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# Modélisation et contrôle de la manipulation dextre multidigitale pour les mains robotisées humanoïdes

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Pour obtenir le titre de docteur de l'université Pierre et Marie Curie (Paris VI)

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# Modeling and Control of Multifingered Dextrous Manipulation for Humanoid Robot Hands

Romain Michalec

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In robotics, when the demands for dexterity and versatility are high, traditional end effectors quickly show their limits and humanoid robot hands look like an appealing alternative. Unfortunately, although such hands can be built nowadays that are mechanically satisfactory, using them still remains problematic because their control is difficult.

In this thesis, we have investigated three problems related to the control of humanoid robot hands: controlling the motion of the grasped object and the forces it is subject to, keeping hold of the object in case of external disturbances, and calculating the stiffness of the grasp, that is to say its elastic behavior.

To manipulate the object, we propose a new control law, based on mathematical programming, that has the advantage of returning control torques which realize a trade-off between the different setpoints, possibly incompatible or unfeasible, and also respect the constraints due to physics and to the mechanics of the robot.

To keep hold of the object when a disturbance happens, we propose a method to compute the tightening forces that make the grasp withstand the largest possible disturbance, in the direction where this largest possible disturbance is the smallest: a kind of critical disturbance for the grasp.

Finally, we model the stiffness of the object as a function of the stiffness of the fingers, in the case when a relative rolling motion is possible between the fingers and the object. We prove that this stiffness is also function of the contact forces and the curvatures of the contacting surfaces.

**Keywords** Humanoid robot hands, multifingered dextrous manipulation, manipulation control, tightening forces, grasp stiffness.

**Research laboratory** This thesis was prepared at the Interactive Simulation Laboratory, Atomic Energy Commission, Fontenay-aux-Roses, France.

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## Modélisation et contrôle de la manipulation dextre multidigitale pour les mains robotisées humanoïdes

En robotique, lorsque les exigences de dextérité et de polyvalence sont élevées, les effecteurs terminaux traditionnels montrent vite leurs limites et les mains robotisées humanoïdes semblent une alternative séduisante. Malheureusement, si l'on sait aujourd'hui fabriquer de telles mains satisfaisantes sur le plan mécanique, leur utilisation pose toujours problème car leur contrôle est difficile.

Dans cette thèse, on s'est intéressé à trois problèmes relatifs au contrôle des mains robotisées humanoïdes : le contrôle du mouvement de l'objet saisi et des efforts qui lui sont appliqués, le maintien de l'objet en cas de perturbations extérieures, et la raideur de la prise, c'est-à-dire son comportement élastique.

Pour la manipulation de l'objet, on propose une nouvelle loi de contrôle, basée sur un problème d'optimisation sous contraintes, qui a l'avantage de synthétiser des couples articulaires moteurs réalisant un compromis entre les différents objectifs de contrôle, possiblement conflictuels ou non atteignables, tout en respectant les limitations de la physique et du robot.

Pour garder prise sur l'objet en cas de perturbation, on propose une méthode pour calculer les forces de serrage qui assurent la robustesse de la prise à la plus grande perturbation possible, dans la direction où cette plus grande perturbation possible est la plus petite : une sorte de perturbation critique pour la prise.

Enfin, on donne une modélisation de la raideur de l'objet en fonction de celle des doigts, dans le cas où un mouvement relatif de roulement est possible entre les doigts et l'objet. On montre que cette raideur dépend aussi des forces de contact et des courbures des surfaces en contact.

**Mots-clés** Mains robotisées humanoïdes, manipulation dextre, contrôle de la manipulation, forces de serrage, raideur de saisie.

**Laboratoire d'accueil** Cette thèse a été réalisée au Laboratoire de Simulation Interactive du Commissariat à l'Énergie Atomique, à Fontenay-aux-Roses.

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# Introduction

## Contents



In robotics, an end effector is a part of a robot that is designed to interact directly with the robot's environment, more precisely with some part of it called the workpiece, or the object. These terms originate from the study and construction of the first serial robotic manipulators, which were meant for industrial applications: "end effector" designates the last link at the end of such robots, where some kind of tool is usually attached and works on the "workpiece". For that reason, the term "end effector" is mostly used for effectors located at an endpoint of a robot [1].

The most typical and widely known robot end effector is probably the two-jaw gripper. It is an end effector designed for prehension, consisting of two mechanized jaws opening and closing around an object. But there are countless other robot end effectors. The nature of each of them depends on the interaction that the robot is supposed to have with its environment.

Among the end effectors designed for prehension, *humanoid robot hands* are striking because they are modeled after our own end effectors, the hands. These devices are artificial, mechanized hands, more or less anthropomorphic, usually around the size of human hands, equipped with three to five jointed fingers attached by their bases to a part called the palm. They are controlled to replicate, as much as possible, the abilities of a human hand.

This thesis is about them. More precisely, it is about some aspects of the control of humanoid robot hands in order to manipulate in-hand objects, that is to say to use the fingers to change the orientation and the position of the grasped object with respect to the palm. This is called *in-hand manipulation*, or *dextrous manipulation*.

1. All endpoint-located environment-interacting parts of a robot are not necessarily end effectors, though. Most notably, the devices that mobile robots use to move around in their environment are not considered to be end effectors: the wheels of a wheeled robot, the feet of a humanoid robot, or the propellers of an underwater or aerial robot for instance.

In this first chapter, we introduce the research issues we have been investigating, and explain where lie the contributions of this thesis to the field of dextrous manipulation control. We also give the outline of the thesis.

## 1.1 What are hands for

When we think about it, the capabilities of our hands are simply stunning. First and foremost, of course, we use them for grasping and manipulation of all sorts of things, in all kinds of ways. But they are not limited to grasping and manipulation: other actions include holding, touching, pushing, feeling, poking, caressing, making signs, and many more.

Humanoid robot hands are meant to emulate those capabilities, particularly the main ones: grasping and manipulation. Their purpose is to make it possible for robots to handle objects in a more precise and versatile manner than is currently possible with standard, specialized end effectors, such as multiple-jaw grippers. The construction of robot hands, their modeling, and the study of their control, began essentially in the United States in the early 1980s, and it quickly became a demanding but promising research topic in humanoid robotics.

In this section, we break down the capabilities of our hands into six functions: prehensile manipulation, restraining, exploration, non-prehensile manipulation, communication, and locomotion. The capabilities of robot hands are ultimately supposed to be the same, however robotics research focuses on the first three ones at the moment. We briefly describe them, with an emphasis on prehensile manipulation as it is the framework of this thesis.

### 1.1.1 Main functions

#### Manipulation

Prehensile manipulation, or just manipulation for short, is the ability to move and relocate objects in space using the prehensile capabilities of one or both hands, that is to say using some kind of grasping or holding. It contrasts with non-prehensile manipulation, by which objects are moved and relocated without the help of prehensility, for instance by poking them with a finger (as in operating a switch) or pushing them with the whole hand (as in moving furniture).

This definition is broad enough to encompass a wide variety of our activities. Everyday, we perform thousands of prehensile manipulations, most of the time without actually paying attention to them. A morning routine examplifies their variety:

| | |
|---|---|
| Squeezing a bottle of shampoo in the shower | Manipulation of a slightly deformable object |
| Putting on clothes | Manipulation of very deformable objects |
| Doing one's hair | Manipulation of a very complex deformable material |
| Pouring milk into cereal | Manipulation of a rigid object whose mass and inertia change during the manipulation |
| Brushing one's teeth | Manipulation of a rigid object with a deformable part |

(a) Opening the side of a small lantern with both hands to put a candle inside

(b) Carefully grasping a live crawfish between thumb and index to tease it with a knife

(c) Playing with an object by tossing it up (this is a pack of hookah tobacco)

(d) Fast manipulation of several objects in a cooperative way: two jugglers passing six blades at a medieval fair in Provins, France

Figure 1.1 – Four very different examples of manipulations

As a matter of fact, manipulations are so diverse that we would have a hard time trying to categorize them. Below are some ideas of criteria that could be used to describe grasps, and form categories of manipulations:

**Characteristics of the grasp** For instance the location of the contact areas on the hand, and their respective surfaces. They make it possible to distinguish between manipulations performed with fingertip grips, such as moving a guitar pick accross the strings of a guitar, and manipulations that require palm usage, such as moving a large box with both hands (Napier 1956).

**Source of the motion** Whether the object is manipulated by finger movements only, or whether the arm contributes too. So-called *fingertip manipulations* have their motion coming from the fingers only, whereas *whole-arm manipulations* move the object with the shoulder, elbow and wrist joints, but not with the fingers. There is no specific name for manipulations between these two extremes.

**Dynamicity of the manipulation** Some manipulations rely more than others on the dynamical properties of the object to complete successfully, in the sense that even a slight error in the estimation of these properties results in the failure of the manipulation. For instance juggling, or adding a few drops of chili sauce to a dish are manipulations that don't allow for any uncertainty about the objects being manipulated. Throwing dirty clothes loose into the washing machine, however, is not so dependent on the dynamics of the clothes to succeed.

**Contact with the environment** There are six directions of possible motion in space: three translations and three rotations. When the object can be moved in all of them, the manipulation is in *free space*: for instance, picking up a pen, or placing a key in front of a keyhole. When one or more directions of motion are not possible for the object, its motion is *constrained*. In that case, the object to manipulate may be attached to the environment: for instance a door knob, a key in a keyhole, a faucet, or a valve. It may be in contact only: a computer mouse on a desk, a pen on paper during writing. It may be attached to another object: for instance lids and corks, or a knife in a watermelon when splitting it open. Or it may be articulated, that is to say the part to manipulate is attached to another part of the same object: for instance the pages of a book.

**Number of hands and persons involved** Some manipulations are performed using one hand, other require both hands, for instance lacing shoes, or doing most knots for that matter. Likewise, certain manipulations are preferably done cooperatively, for instance carrying heavy luggage.

The figure 1.1 shows four examples of manipulations, all different in the sense of the criteria enumerated above. For instance, opening the side of the small lantern illustrated in figure 1.1(a) is a two-handed one-person fingertip manipulation of an articulated object in free space, with the dynamics of the object being not particularly important. The jugglers photographed in figure 1.1(d) are performing a two-handed cooperative whole-arm full-hand manipulation of several objects in free space, with the dynamics of the objects playing a critical role. And so on.

Traditionally, robotic manipulation, as performed by industrial robot manipulators, is single-handed, single-robot, whole-arm, and full-hand. Sometimes, several robot manipulators can cooperate to manipulate large workpieces, but manipulation always remain whole-arm and full-hand: the workpiece is firmly grasped by the end effector and moved using the rest of the robot, not the end effector.

Humanoid robot hands are meant for the opposite sort of manipulation, the kind where the fingers are used to grasp and move the object (figures 1.1(a), 1.1(b), and 1.2). Having a machine autonomously perform such complex manipulations is much more difficult than having it move workpieces with whole-arm full-hand motions. There are several terms that can be applied to such manipulations: *multifingered*, *dextrous*, *in-hand*, *internal*, and *fingertip*. All these terms refer to the same kind of manipulation, but they emphasize a different side of it:

**In-hand manipulation, internal manipulation** These terms underline the fact that the manipulation relocates the grasped object with respect to the hand itself, contrary to whole-arm manipulation which relocates the object with respect to the environment.

**Fingertip manipulation** This term emphasizes the dominant role of the fingertips, even though other phalanges may participate too.

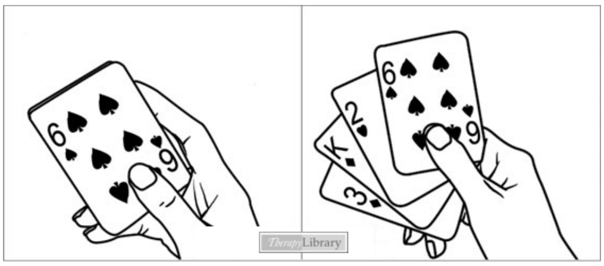
**Multifingered manipulation, dextrous manipulation** The first term speaks for itself, and the second one stresses the dexterity of the manipulation, that is to say its capability to achieve fine and precise changes of the configuration of the manipulated object.

The term “in-hand manipulation” is the most frequently encountered in the litterature about human manipulation, especially in physical therapy and occupational therapy. On the other hand, “multifingered manipulation” and “dextrous manipulation” are the preferred terms in robotics, and indeed, we can say that *multifingered dextrous manipulation for humanoid robot hands* is the subject of this thesis. The figure 1.2 gives additional information about this skill.

**In-hand manipulation** refers to the ability to move and position objects within one hand without using the other hand. The thumb and the fingers are used to adjust the position of the objects correctly. These manipulations are essential in many activities of daily living, and are regarded as “one of the most complex fine motor skills” (L. Johnson, Newton, Greaves, and Rundle 2005).

Three particular skills have been identified as components of in-hand manipulation: translation, shift, and rotation. Some manipulations use only one of these components, others require a combination of them.

**Translation** is the movement of objects between the palm and the fingertips. Examples include picking up change from a flat surface, one coin at a time, while keeping the collected ones in the palm (translation from fingertips to palm), or conversely placing coins into a vending machine slot or a piggy bank, starting with the coins in the palm (translation from palm to fingertips).



**Shift** is the movement of objects between or accross the fingers. An example is “walking” the fingers along the shaft of a pencil to get them closer to the tip, ready for writing. Another example is faning out playing cards. This skill is also used in the fastening of buttons and the lacing of shoes.

**Rotation** consists in turning objects around using the pads of the fingers. In “simple” rotation, the object is moved by less than 90°, and the thumb remains in opposition to the other digits (Exner 2005). This happens, for instance, when adjusting the angle of a pencil during writing. On the other hand, “complex” rotation involves angles between 90° and 180°, and thumb opposition may be lost temporarily as all digits are moved in a voluntary, coordinated, alternating, and independent manner (Exner 2005). This happens when flipping a pencil over to use its eraser end, and then flipping it back, or turning a coin from heads to tails, or twisting open or closed the lid of a toothpaste tube held within the palm of the same hand, and so on.

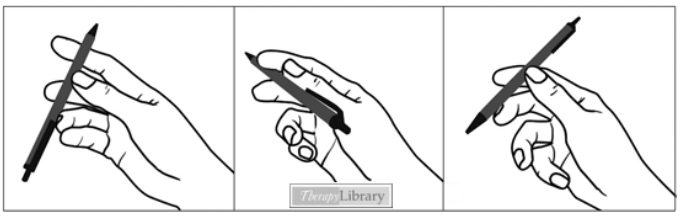


Figure 1.2 – In-hand manipulation, or dextrous manipulation

### Restraining

Restraining is the ability to keep hold of objects and make sure they do not escape the grasp. In the first sense, it is about keeping an object motionless in some place, a task known as “fixturing” in robotics and mechanical design. But it also applies to other situations, for instance:

- Keeping hold of objects despite disturbances, that is to say unexpected external forces. The disturbances may be applied on the object, on the hand, on the arm, or any other part of the body or robot. In all cases they can put the stability of the grasp in jeopardy.
- Preventing an object from slipping between the fingers, usually by appropriate use of friction forces.
- Keeping hold of objects despite their characteristics being wrongly estimated in the first place, be it their mass, mass distribution, rigidity, texture, friction, moistness, or anything else. This happens, for instance, when we seize an empty milk carton while thinking it is full, or the other way round.

So in a more general meaning, restraining is about preventing unwanted motions of the object, in other words ensuring the stability of the grasp. It is not the opposite of manipulation: an object can be restrained and manipulated at the same time. As a matter of fact most manipulations feature some degree of restraining. For instance the kid photographed in figure 1.3 does not only restrain his paper cup with both hands, he also manipulates it to drink, in a two-handed whole-arm full-hand manipulation.

To sum up, the term “manipulation” emphasizes performing an intentional motion of the object, whereas the term “restraining” puts the stress on preventing unintentional motion of the object. Both can be combined.

However, even though they are not antinomic, restraining and manipulation are still often opposed, and in the same vein restraining may be called “grasping” or “prehension”. This is a misnomer to be aware of. Manipulation, at least prehensile manipulation, does feature grasping too and is a modality of prehension just like restraining.

Object restraining can be done by the geometry of the grasp, by the contact forces applied on the object, or both.

**Grasp geometry** A particular arrangement of the fingers, as well as a good choice of contact locations on the object, can help restrain the object more efficiently. So-called “power grips” are especially appropriate here, see section 2.2 in chapter 2 on that matter. Also, grasp configuration optimization makes it possible to choose the best possible contact points on the object, in the sense of some grasp quality measure, see section 6.1.2 in chapter 6.

**Contact forces** Preventively applying larger forces than necessary for the manipulation is a good way to ensure object restraining. It is an anticipatory strategy which can get better outcomes than the reactive strategy of quickly adapting the contact forces to save a manipulation that is about to fail. That said, grip forces should not be excessive either, so that they don’t cause unnecessary fatigue of the hand or damage to the object.

A part of this thesis is dedicated to the study of object restraining by tightening forces applied preventively to the object: this is topic of “robust manipulation” investigated in the chapter 6.

Figure 1.3 – An example of object restraining: two-handed grasping of a paper cup by a three-year-old. At that age, the development of hand function is not complete yet, and the child gains finger independence and hand skills progressively. It will still take a few years before fully mature patterns of grasping and manipulation are observed (Flanagan and Johansson 2002; Exner 2005; Pehoski 2006).

### Exploration

A third important function of our hands is exploration, that is to say the ability to gain knowledge about objects and the environment through sensing. To this aim, our hands are endowed with an enormous amount of sensory nerve endings of different kinds, forming an extremely efficient sensor equipment currently out of reach of artificial reproduction. Sensory nerve fibers end in large numbers in the palmar skin of the hand, for *tactile sensing*, and also in the joints, tendons and muscles, for *proprioception* (sections 2.1.3 and 2.1.5 in chapter 2). In the brain, the areas that process the wealth of information coming from these nerves are among the largest ones of the somatosensory cortex (section 2.3.1 in chapter 2).

Thanks to this sophisticated sensory system, it is possible for us to collect information about an object by touching it (passive sensing), dragging our fingers along its surface (active sensing), or manipulating it (active sensing too) (Tegin and Wikander 2004, 2005). For instance, by sliding our fingers on the object, we have access to its geometry, the sharpness of its edges, the texture and friction condition of its surface. By squeezing it, we can estimate its rigidity, by lifting it, its mass, by tilting it, its mass distribution and center of gravity (Tegin and Wikander 2004, 2005). In many respects actually, tactile sensing outperforms vision in getting information on an object that is relevant to its manipulation. For instance, friction condition or mass distribution are difficult to estimate from vision-based cues only, at least without prior knowledge of the object. Information hidden by occlusions, such as the contact condition (whether there is contact or not) and how is the surface on the back of the object, is even more difficult to obtain with only vision.

Similarly to restraining, exploration is a function that is often blended in manipulation. “Pure manipulation occurs when the object is completely known, pure exploration happens when the object is fixtured and is not known, [and] most dextrous manipulation is a combination of the two", according to Okamura, Smaby, and Cutkosky (2000). This statement is especially true for robots, which have very little knowledge of the world in comparison to humans; therefore, ideally, their manipulations should include a fair amount of exploration for them to learn about the objects they manipulate. We humans, on the other hand, can perform manipulations without exploration more frequently, since we know completely most of the objects we interact with on a daily basis, thanks to a learning process of several years during childhood, continually updated during the rest of our life. At any rate though, even in the case of manipulation without exploration, sensing, the ability at the basis of exploration, remains a critical ability for the success of all manipulations. This is illustrated by the fact that people with anesthetized fingers because of nerve conditions or just because of cold have difficulty in performing fine fingertips manipulations, or at least in completing them in a normal time (Okamura, Smaby, and Cutkosky 2000), whereas on the other hand, people with severe visual impairment can achieve the same manipulations almost normally by using tactile sensing alone (Kemp, Edsinger, and Torres-Jara 2007).

This thesis is about manipulation and restraining, not about exploration. That is to say, we do not investigate further this component of manipulation, and in our mathematical developments, we always assume that the robot hand's controller knows everything about the object that is necessary for the control. However, we do stress repeatedly the importance of sensing, be it for human or robot manipulation (sections 2.1.5 and 2.4.1 in chapter 2; sections 3.2 and 3.3 in chapter 3).

### 1.1.2 Other functions

In the previous section, we described the main three functions of our hands, and by extension the desired functions of humanoid robot hands: prehensile manipulation, restraining, and exploration. These three functions are somewhat entangled: a manipulation can feature restraining and exploration at the same time. In this section, we briefly mention three other functions: non-prehensile manipulation, communication, and locomotion. They are much more independent.

#### Non-prehensile manipulation

Non-prehensile manipulation is the ability to move and relocate objects in space using one or both hands, but without their prehensile capabilities. This may be by pushing or poking with the fingers, hitting or punching with the fist, lifting or smacking with the palm of the hand, and so on. All these actions remain manipulations because of the hand being used: kicking a ball does move and relocate the ball, but it is not a manipulation.

A sizeable class of non-prehensile manipulations is pushing the many switches and buttons of our modern lives: ringing a doorbell, typing on a computer keyboard, switching a light, pressing the controls of electrical appliances such as ovens, washing machines, or alarm clocks, dialing and texting, and the list goes on. In all those cases, the manipulated object is the button, and its motion is constrained in one direction. Other non-prehensile manipulations by pushing or poking include playing marbles (one finger), dribbling the ball in basketball (all fingertips), pressing a door handle (palm), and moving furniture by sliding it on the floor (whole hand). Playing certain instruments such as the piano (and other keyboard instruments) and certain drums (directly with the hands, not with drumsticks) can also qualify as non-prehensile manipulations, with the manipulated objects being the keys and the drumheads. Also, the so-called “platform grasp”, used to carry a tray for instance, can be regarded as a hand posture for non-prehensile manipulation rather than a real grasp.

In any case, non-prehensile manipulations are tasks we do not deal with in this thesis.

### Communication

Hands have a significant role in human communication. Their usage can accompany or replace spoken communication.

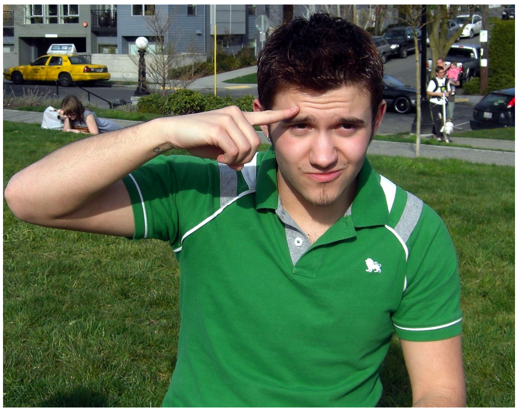
**Verbal communication** Sign languages and manually coded languages are typical examples of hands completely replacing spoken communication. Still, they remain verbal communication, that is to say that they make use of words.

Sign languages, in fact, do not only use the hands: they combine simultaneously hand shapes, orientation and movement of the hands, arms, head, and body, and facial expressions to convey meanings between the signers (figure 1.4). It is worthy of note that they are natural languages, that is to say that they developed by themselves, wherever communities of deaf people exist. Currently, 130 sign languages are identified and in use around the world (P. Lewis 2009). Of course, they are used primarily by people with hearing impairment, but hearing people can learn them too, and communicate with the deaf and hard-or-hearing, act as interpreters, and even communicate with other hearing-and-signing persons in loud environments. Linguists have proven that these languages are as rich, complex, and fast as any spoken language, with the peculiarity of having sophisticated spatial grammars markedly different from the grammars of spoken languages (Stokoe 1960; Klima and Bellugi 1979). Also, similarly to the spoken languages, they are more or less related one another. For instance, American Sign Language, used in the United States and most parts of Canada, emerged primarily from Old French Sign Language [2] and is therefore related to modern French Sign Language, but it is very different from British Sign Language, Australian Sign Language, and New Zealand Sign Language, all of which are related to each other, but distinct (P. Lewis 2009).

Unlike sign languages, manually coded languages are not natural but constructed languages, invented by hearing people. They are often purely manual, and mostly follow the grammars of the written form of the spoken language. In other words, they are representations of a spoken language in a gestural form: signed spoken languages. For instance, there are several such signed encodings of English. Manually coded languages have been mainly used in the education of deaf children until the 1990s, but thankfully the emerging recognition of sign languages by the hearing majority curbs their use in education. Indeed, compared to sign languages, they are unnatural, cumbersome, and much slower. That being said, they have had some influence on natural sign languages.

Very limited manually coded languages also exist for situations where speech is not possible or not practical: for instance while scuba diving, between lifeguards, in television recording studios, or in stock exchanges. The set of signals they use and the set of topics they address are extremely small and specialized (figure 1.5).

2. Not related to medieval Old French: it is the language of the deaf community in eighteenth-century Paris, at the time of the establishment of the first deaf school, by the abbot Charles-Michel



(a) First posture. Also used for the verb "think", and in several other signs.

(b) Second posture

(c) Final posture

Figure 1.4 – The sign "fall asleep" in American Sign Language. This sign is translucent: its meaning makes sense to non-signers once explained. Others can be transparent: non-signers can correctly guess the meaning. But the majority of signs are opaque: their meaning has no apparent relation to the sign itself (Klima and Bellugi 1979, pages 23–26).

**Non-verbal communication** When not replacing spoken communication, hand motions usually accompany it by conveying additional, wordless messages: this is non-verbal communication.

In fact, non-verbal communication occurs through many different channels at once: hand motions indeed, but also posture, facial expressions, eye contact, voice rate, pitch, and volume, speaking style, even clothing and hairstyles. As far as hands are concerned, non-verbal messages are communicated through gestures and touch (Argyle 1988; Knapp and Hall 2009):

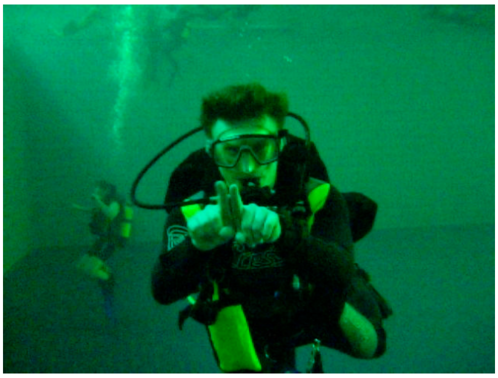
**Gestures** may have a specific meaning, and replace or emphasize a word or an expression, as in hand-waving hello and goodbye, gesturing a "come here" sign, pointing with the index finger, air quoting, facepalming, giving someone the finger, and many more. Other common gestures are those which have no

de l'Épée. The school still exists and is located in the Quartier Latin, under its current name of *Institut National des Jeunes Sourds*.

As a question: Are you okay?
As an answer: I'm okay.

Help! I'm out of air!

I have 100 bar left.
(Half capacity of most diving cylinders.)



Stay together.

Figure 1.5 – Underwater manual communication: four diving signals

meaning by themselves but make sense because they are integrally connected and coordinated with the co-occurring speech: that is to say, when we talk with our hands.

**Touch,** or haptic communication, can also convey a lot of non-verbal meaning, as in handshakes, back slapping, high fives, fist bumps, a pat on the shoulder, a pat on the head, caresses, holding hands, and many more. The meaning is typically highly dependent on the context, the relationship between the communicators, and the way of touching.

The functions served by non-verbal communication through gestures and touch are very diverse. They range from the expression of emotions, personality, and interpersonal attitudes (Argyle 1988, page 5), to rituals like greetings, to the accompaniment of speech, be it by emphasizing it, complementing it, substituting for it, or even conflicting with it (Knapp and Hall 2009, pages 12–17).

Despite its importance to us, the function of communication of the hands is understandably less investigated by roboticists than those related to manipulation. In the future, it might be advantageous that robots be able to communicate with humans not only verbally but also non-verbally: it would surely make communication easier and more natural. But this problematic is not the most topical at the moment, and the critical issue about robot hands remains manipulation.

**Locomotion**

Hands have also a locomotion function, although very minor. This function is not very relevant to humans, but it is much more notable among apes and monkeys, and more generally among all non-human primates. For instance, gibbons, siamangs, orangutans, and spider monkeys can brachiate, whereas gorillas and chimpanzees can knuckle-walk:

**Brachiation** is a form of arboreal locomotion in which some apes and monkeys move by swinging from branch to branch and from tree to tree using only their arms. Gibbons are considered the best brachiators, swinging as far as 6 meters between each handhold, at speeds as high as 55 kilometers per hour.

**Knuckle-walking** is a form of quadrupedal locomotion in which some apes [3] walk on all fours with their hands holding the fingers partially flexed so that the dorsal side of the fingers rests on the ground. More precisely, the knuckle-walking of gorillas and chimpanzees involves carrying their body weight down on the dorsal surface of their middle phalanges (rather than on the knuckles themselves). The interphalangeal joints are flexed but the metacarpophalangeal joints are extended, resulting in the palm being positioned perpendicular to the ground and in line with the forearm.

As far as humans are concerned, this function of the hands is merely anecdotal. A healthy human is able to brachiate clumsily on a limited distance, as can be seen from the monkey bars which are sometimes installed in public parks as an amusement for children and a fitness exercise for adults. Also, wheelbarrow walking, walking on all fours, and walking on hands, are all possible in children's play and in warming up before sport. More significantly, climbing makes extensive use of the hands in their locomotion function.

As for robots, one of the design goals of NASA's Robonaut, a semi-autonomous teleoperated half-humanoid robot launched to the International Space Station in February 2011, was that its hands would enable it to move on the outside of the station in the same way as astronauts do: from handle to handle. This example aside, the locomotion function of robot hands is not currently investigated by roboticists.

## 1.2 The control problems we tackle

In the previous section, we have described the capabilities of our hands by presenting their functions: prehensile manipulation, restraining, exploration, non-prehensile manipulation, communication, and locomotion. This thesis is about the first two functions, for humanoid robot hands. More precisely, we are concerned with the control of multifingered dextrous manipulation for humanoid robot hands.

In this section, we briefly describe the specific problems we have been interested in. That is to say, we summarize the contributions of this thesis to the field of dextrous manipulation control. In short, they are:

1. An optimization-based multi-objective control approach for the manipulation of the object (chapter 5).

3. But also some non-primate mammals: giant anteaters, platypuses, pangolins.

2. A method for determining tightening forces to apply on the object in accordance with a certain restraining objective, in terms of external disturbances to withstand (chapter 6).

3. A model of the elastic behavior given to the object by the elasticity of the fingers in the grasp, in the case that there can be a relative rolling motion at the contacts (chapter 7).

### 1.2.1 Motion

The problem of having a humanoid robot hand autonomously manipulate an object is formulated as a mathematical optimization problem, similarly to the problem of having a humanoid robot keep its balance or walk, in a couple of recent works (Collette and Micaelli 2007a,b; Abe, Silva, and J. Popović 2007). The formulation as an optimization problem makes it possible to find control torques that satisfy a set of equations and inequations, the constraints of the optimization problem, and at the same time realize a trade-off between different and possibly conflicting or unattainable control objectives, the criteria of the optimization problem (assembled into its objective function).

So we get a control law that satisfies multiple objectives, split among the constraints and the criteria of the optimization problem, according to their importance. For instance, the manipulation of the object is a criteria, whereas certain physical and mechanical constraints such as the dynamics of the robot, the Coulomb laws of friction, and the joint limits, are constraints of the optimization problem. Given our choice of criteria and constraints, in fact, the optimization problem we propose is quadratic with linear constraints (a quadratic program), which means that it is not difficult to solve numerically.

This new control strategy was tested in dynamic simulation on a computer model of a robot hand, with a physical engine developed at CEA/LIST [4] and UPMC/ISIR [5], Arboris (Micaelli and Barthélémy 2006–2010).

### 1.2.2 Tightening

If disturbances are likely to happen and jeopardize the grasp, it is appropriate to preventively apply contact forces on the object that are stronger than those needed by the manipulation, in order to ensure object restraining. We propose a method for calculating tightening contact forces, according to a certain robustness objective against disturbances.

The robustness objective is expressed in terms of directions of expected disturbance and a percentage of the maximal robustness of the grasp, defined by the smallest disturbance wrench that the grasp cannot withstand: a sort of critical disturbance for the grasp, or a measure of its quality. So that means that we are looking for tightening forces able to restrain the object against the disturbances that could occur along certain expected directions and with a magnitude up to some percentage of the critical disturbance.

4. *Commissariat à l'Énergie Atomique, Laboratoire d'Intégration des Systèmes et des Technologies*: French Atomic Energy Commission, Systems and Technologies Integration Laboratory (Fontenay-aux-Roses, south of Paris, France).

5. *Université Pierre et Marie Curie, Institut des Systèmes Intelligents et de Robotique*: Pierre and Marie Curie University, Institute for Intelligent Systems and Robotics (Paris, France).

We find such tightening forces in a two-step approach. First, we determine the critical disturbance, thanks to a linear optimization problem with linear constraints (a linear program). When solving this optimization problem, we also get tightening forces that ensure the robustness of the grasp to the disturbances that could occur along the directions of expected disturbance and with a magnitude equal to the magnitude of the critical disturbance: that is to say, we find tightening forces for the maximal robustness. After this first step, we are able to compute tightening forces for a lesser robustness (directions of expected disturbance and a percentage of the maximal robustness). This is done with a quadratic optimization problem with linear constraints (a quadratic program).

Our method returns forces that can be integrated into control schemes of multifingered dextrous manipulation, as desired values for the contact forces. We have done so with our optimization-based control law; this achieves robust manipulation. We report dynamic simulations of dextrous manipulation with the object being restrained in spite of disturbances, using the physical engine Arboris.

### 1.2.3 Stiffness

When we tighten an object, our fingers do not only apply larger contact forces, but also stiffen, making it difficult to move the object with the other hand, or with a disturbance for that matter. Stiffening the fingers is also possible without applying any additional force on the object; in that case, it still makes it harder to move the object with an external force. This provides a second approach to ensure object restraining: stiffness.

Robots can stiffen their fingers too, if the control of their hands has been designed for that purpose. The stiffness of their fingers gives the object an elastic behavior, characterized by a certain stiffness too. We calculate the analytical expression of this stiffness, as a function of the stiffness of the fingers. This is not a trivial issue, because of the possibility of rolling motion at the contacts between the object and the fingers. We show that the object stiffness depends not only on the finger stiffnesses, and of course on the grasp configuration (location of the contact points), but also on the contact forces and on the local geometries of the contacting surfaces (their curvatures at the contact point). We validate our modeling of the object stiffness by numerical tests, still in dynamic simulation with the physical engine Arboris.

This work has led to many open questions and research ideas for the future, either theoretical issues such as the structure and the properties of the stiffness matrix representing the elastic behavior of the object, or practical topics such as the stiffness control of the object, that is to say the control of the object stiffness through adjustment of the finger stiffnesses.

## 1.3 Outline of the thesis

Before this thesis deals with the problems presented in the previous section, it brings in some background about robot hands, and also about human hands, a subject worthy of interest since they form the basis of our expectations for robot hands. Here is the outline of the remaining chapters.

It is good to know that all the chapters are relatively independent, and may be read in any order, or skipped. This is especially true for the first two ones, chapters 2 and 3: they give interesting context about human and robot hands but are not critically important to the understanding of the following chapters. Chapter 4 should be read before chapters 5, 6, 7 though, because it defines most of the notations used in the mathematical developments of these chapters. But the reader familiar with rigid body mechanics and screw theory will only have to skim through it. Chapter 6 is best read after chapter 5.

**Chapter 2**
**About the human hand**

We begin by presenting basic knowledge about the anatomy of our hands, as well as some insight about their importance over the course of human evolution. We also describe the different types of grasps involved in prehensile manipulation. In the light of all that, we explain the gap to bridge between robot hands and their human models, in actuation, sensing, and control.

**Chapter 3**
**About humanoid robot hands**

Then we present some background about humanoid robot hands. First, we discuss the relevance of anthropomorphism for robot end effectors, that is to say the reasons that may lead to the choice, or not, of humanoid hands as end effectors for a robot. Then we review the eventful history of artificial hands, for prostheses and for robots, from the beginnings to the present day.

**Chapter 4**
**Mathematics and mechanics for robot modeling**

This short chapter provides an overview of the concepts and results of rigid body mechanics that we use to model humanoid robot hands. The general framework is that of screw theory: we recall what is a twist (generalized velocity), what is a wrench (generalized force), and so on. We define a lot of the notations we use in the following three chapters.

**Chapter 5**
**Dynamic optimization-based control of dextrous manipulation**

This chapter presents our new, optimization-based control scheme of multi-fingered dextrous manipulation we were talking about in section 1.2.1. We start by modeling the hand/object system we want to control, then review the field of robotic manipulation control, and proceed with formulating the control problem as a constrained optimization problem.

**Chapter 6**
**Optimal tightening forces for robust manipulation**

In this chapter, we complement our optimization-based control scheme with the robustness study mentioned in section 1.2.2. An introduction in pictures explains our approach of grasp robustness, and how it compares to related notions in the robotics litterature. Then we expose our two-step method for determining tightening contact forces: first, those for the maximal robustness of the grasp, second, those for a lesser robustness.

**Chapter 7**
**Stiffness modeling for grasping with rolling contacts**

This chapter is about the stiffness analysis mentioned in section 1.2.3. Here again we start by explaining in detail and in pictures our approach of the modeling of grasp stiffness. Then we put in place all the equations and hypotheses we need, especially those about the kinematics of rolling contacts between the object and the fingers, and we calculate the expression of the object stiffness as a function of the finger stiffness.

In the end, the chapter 8 concludes the thesis by summing it up very briefly and reminding the main research perspectives that could be developed in the future, as a continuation of the ideas of this work.

# 2

# About the human hand

## Contents



The chief specific feature of the human hand, and the hand of primates in general as opposed to the forelimb appendages of non-primate mammals, is the opposability of the thumb. The key to this distinctive trait is to be found in the anatomy of the thumb, which is structurally differentiated from the other digits by the particular nature of its articulation between the carpal and metacarpal bones, and by a dedicated set of muscles that realizes its movements.

Thanks to this opposition, the hands are the main organs for prehension and manipulation, in both a coarse and a precise manner: they prove useful anywhere from gross motor skills (such as moving large objects) to fine motor skills (such as hand-sewing). They are also richly innervated, with the fingertips being one of the densest areas of nerve endings in the body. Consequently the hands are also the main organs for the sense of touch.

This chapter starts by providing in section 2.1 basic knowledge about the anatomy of the human hand, which is simultaneously complex, intricate, effective and fascinating. Then it presents how we grasp objects in section 2.2, that is to say the different types of grasps involved in prehensile manipulation. Then section 2.3 provides some insight into the history of our hands over the course of human evolution. In the light of these three sections, section 2.4 explains the gap to bridge between robot hands and their human models.

## 2.1 An intricate and effective anatomy

The hand consists of a broad palm to which five digits are attached: four fingers and a thumb. The hand is itself attached to the forearm by a joint called the wrist. The back of the hand is called the dorsum.

Each finger is made of three phalanges. The thumb however has two phalanges, the distal one wider than the proximal one, unlike those of the fingers. Figures 2.1 and 2.2 present the anatomical terms that are used to refer to the various parts of the hand.

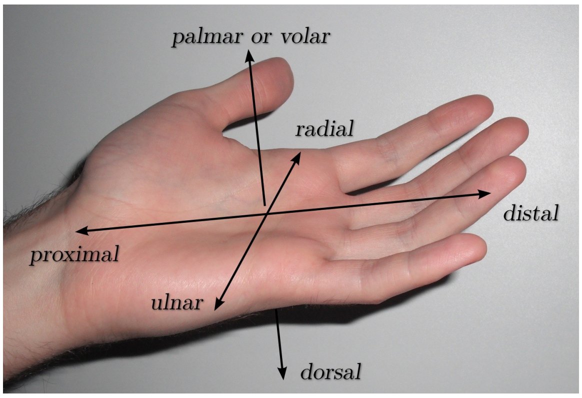



Figure 2.1 – Anatomical terms of location. Distal refers to the end of an appendage, proximal to where it joins the body. Radial and ulnar refer to the two bones of the forearm, the radius and the ulna, respectively on the side of the thumb and on the side of the little finger.

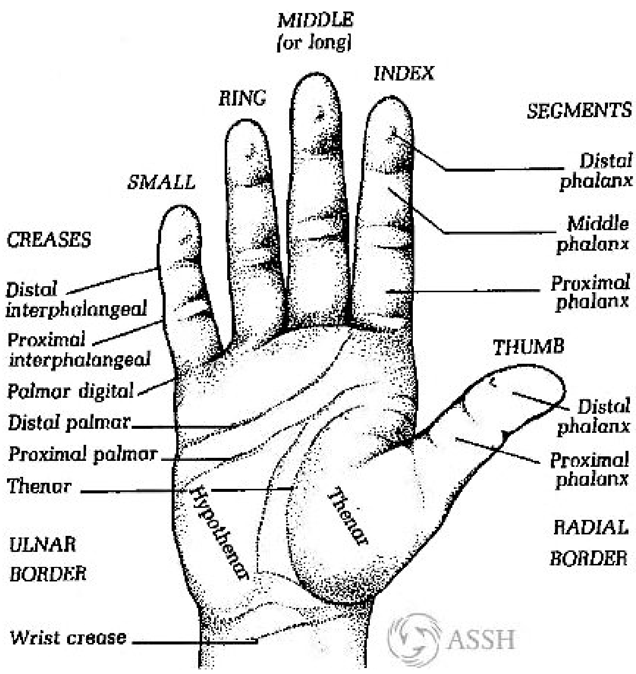



Figure 2.2 – Surface anatomy of the palmar aspect of the hand (i.e. its palmar side). The terms thenar and hypothenar refer respectively to the thumb and the little finger, for instance the thenar muscles are the small muscles moving the thumb.

Apart from amputations, exceptions to the normal number of digits are congenital physical anomalies, often of genetic origin (figures 2.3 and 2.4). Polydactyly is the presence of more than five digits [1], oligodactyly of less than five, and syndactyly is when several digits are fused together, either by the bones or by soft tissue. These anomalies are often accompanied by other congenital anomalies, not necessarily of the musculoskeletal system only.

This section presents the anatomy of the hand in broad outline, starting with the bones and the joints (2.1.1), then the muscles and the tendons (2.1.2), the nerves (2.1.3), the blood vessels (2.1.4), and in the end the skin and its sensory capabilities (2.1.5). Most of the material for this section stems from various readings in anatomy, medicine and surgery, in particular Gray (1918), C. Taylor and Schwarz (1955), Chevallier (1998/2002), Seiler (2001), Wilhelmi, Marrero, and Sahin (2009), and Lisi (2010, chapter 1).

(a) Pre-axial polydactyly: extra digit on the radial side in the right hand of a child

(b) Post-axial polydactyly: extra digit on the ulnar side in the left hand of a ten year old boy

(c) Oligodactyly: two fingers missing in the hand of a newborn (ring and little fingers)

(d) Syndactyly: middle and ring fingers joined in the hand of a newborn. This one is “complex” (the bones are fused) and “complete” (they are fused all the way to the fingertip).

Figure 2.3 – Physical anomalies of the hand

### 2.1.1 Bones and joints

The skeletal elements of the hand consist of twenty-seven bones, divided into three groups: the carpals (eight short bones), the metacarpals (five long bones), and the

1. The extra digits are rarely complete and functioning. Often it may be a small piece of soft tissue without bones in it, or it may have bones but no joints. Most commonly it is a fork in another digit. More rarely it originates at the wrist like a normal digit.

The subject of these photographs is right-handed with a normal right hand, and he reported no other congenital anomaly whatsoever. He mentionned having more reach and more strength in the ring finger on his left hand than on his right hand, and being able to reach further in narrow places. Aside from that, the hand behaves like a normal hand. The drawbacks he reported were having to "reassign some actions on some video games" and to tuck inside the last finger of left gloves "so it doesn't hang uselessly", as well as being "picked on by other kids during childhood".

Figure 2.4 – Oligodactyly in the left hand of a twenty-one year old boy.

phalanges (fourteen long bones). They are illustrated on figure 2.5, together with the names of the joints between them. The dorsal surfaces of the long bones are easily palpable subcutaneously, and the whole skeleton is observable by radiography (figure 2.6).

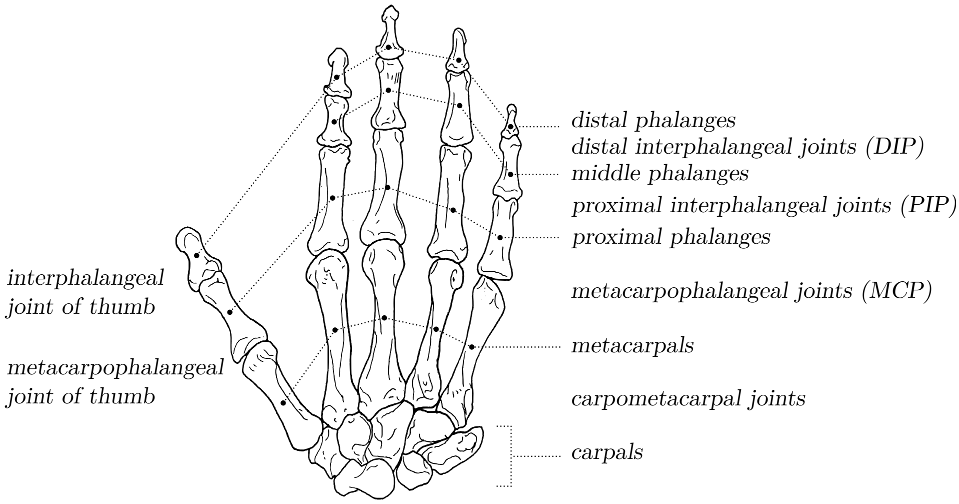



Figure 2.5 – Bones and joints, dorsal view

### Carpals

The carpals are organized into two rows of four bones, with very restricted motion between them. They form an arch, convex on the dorsal side and concave on the palmar side. The groove on the palmar side is closed by a strong fibrous band connected to the outer carpal bones: the transverse carpal ligament, or flexor retinaculum. The space between the carpals and this ligament is called the carpal tunnel. One nerve and nine flexor tendons come from the forearm and pass through the carpal tunnel into the hand (figure 2.7).


(a) X-ray of the hand of an adult. It seems that the carpals are articulated only with the radius at the radiocarpal joint, but it is not exactly the case: the space between the ulna and the carpals is occupied by a thick and flat fibrocartilage, transparent to X-rays, which takes part in the radioulnar joint by one face and radiocarpal joint by the other (it extends the articular surface of this last joint on the ulnar side). As a side note, the ring metacarpal is fractured.

(b) X-ray of the hand of a boy. All the long bones seem severed at one of their extremities, but it is not the case: the space between the two osseous parts of these bones is occupied by a cartilage, the growth plate, responsible for the longitudinal growth of the bones. This cartilage is transparent to X-rays, like all cartilages. It will become ossified at the end of teenhood, around twenty for the bones of the hand.

Figure 2.6 – X-ray photographs of the hands of an adult and a boy

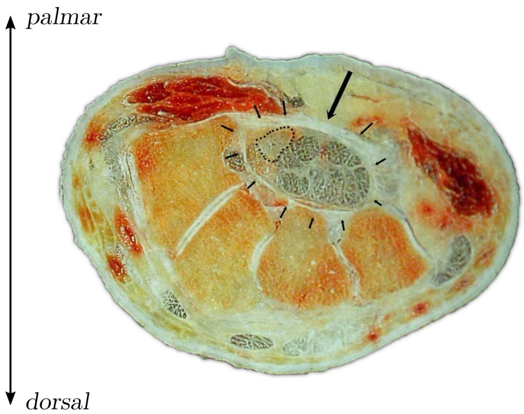



Figure 2.7 – Transverse section of the wrist across the distal row of carpals in a human cadaver. The four carpal bones are clearly visible, as well as the transverse carpal ligament (large arrow). Together they limit the carpal tunnel (small arrows), which encloses the median nerve (dashed circle) and nine flexor tendons (in gray color).

### Metacarpals and phalanges

Each long bone has a base, a shaft and a head, except the distal phalanges which end in a flat and wide apical tuft (figure 2.5). This bony tuft supports the fleshy pad of the fingertip on the palmar side (the finger pulp) and the nail on the dorsal side.

The metacarpals and phalanges are not totally straight, but slightly concave on the palmar surface. The metacarpals have a triangular section, flat on the dorsal side and edgy on the palmar side.

### Radiocarpal joint

The carpal bones provide “a firm yet elastic link between the bones of the arm and those of the hand” (Connolly and J. Elliott 1972/1976). To realize this articulation, they form a condyloid joint with the radius, called the radiocarpal joint: the distal end of the radius forms an elliptical cavity into which the ovoid shape of the proximal row of carpals is received (this is quite visible on figure 2.6(a)). The condyloid joint allows two degrees of freedom to the palm of the hand: flexion-extension and radio-ulnar deviation (figure 2.8), with a wide range of motion in all directions. The third degree of freedom of the palm, prono-supination, is actually realized by the whole forearm: it is the result of a complex relative motion of the ulna and radius, allowed by their mutual articulations at both ends.

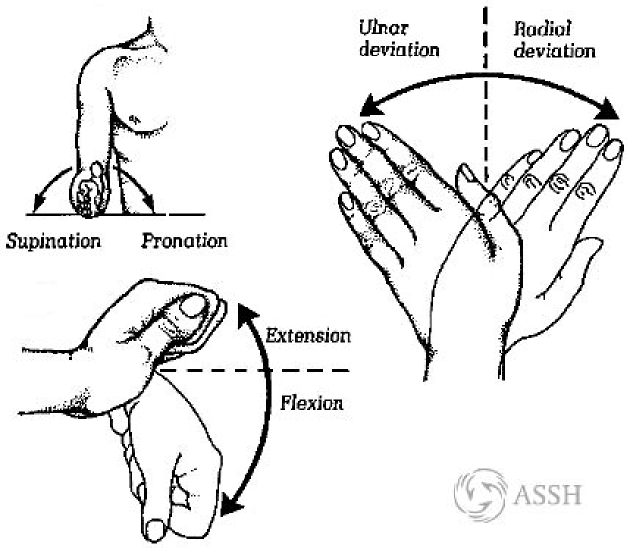



Figure 2.8 – Anatomical terms of motion for the wrist

### Midcarpal joint

The two rows of carpals are articulated together as two functional units: this is the midcarpal joint. Because of the many bones involved, the articular cavity of this joint is very complex and irregular: as a result the motion between the two rows of carpals is more restricted than the motion between the proximal row and the bones of the forearm. Actually, the midcarpal joint articulates only in flexion-extension. It participates as follows to the very wide range of flexion-extension of the wrist: on the 85° of flexion of the wrist, 50° are achieved by the radiocarpal and 35° by the midcarpal, while on the 85° of extension of the wrist, 35° are achieved by the radiocarpal and 50° by the midcarpal. In addition to mobility, the midcarpal joint also participates in the stability of the wrist, thanks to the sophisticated geometry of its articular surfaces.

### Carpometacarpal joints

The third and last joint of the wrist is provided by the carpometacarpal joints. The carpometacarpal of the thumb, or trapeziometacarpal, differs significantly from the other four carpometacarpals, as explained below.

**Index, middle, ring, and little carpometacarpals** These four joints articulate two functional units of several bones, similarly to the radiocarpal and midcarpal joints. These functional units are the metacarpals of the four fingers on the one hand, and the distal row of carpals on the other hand. Their articulation is actually very restricted: the ring and little carpometacarpal joints offer a limited but still perceptible amount of flexion-extension, but the index and middle carpometacarpal joints are essentially immobile. Instead, they provide the other three carpometacarpal joints with a fixed and stable axis. To complicate further, the metacarpals of the four fingers also articulate with their neighbors by their bases, forming three intermetacarpal joints, of very limited mobility however.

**Thumb carpometacarpal** Contrary to the other carpometacarpal joints, the thumb carpometacarpal is a very mobile joint. First, its metacarpal bone is not engaged into an intermetacarpal joint with the index metacarpal: it is independent of the other metacarpals, and this independence is one of the reasons of the great mobility of the thumb. Second, it articulates with only one bone of the carpals, the trapezium, by a saddle joint that allows two degrees of freedom (figure 2.9) with a large range of motion in both flexion-extension and abduction-adduction. These four basic movements are combined to form the complex movements that characterize the opposable thumb: opposition (moving the thumb into anteposition) and retropulsion (moving the thumb into retroposition), palmar abduction and palmar adduction, radial abduction and radial adduction (figure 2.10). The thumb carpometacarpal joint plays therefore an irreplaceable role in the normal functioning of the thumb and is of critical importance to the usability of the hand. Any damage to or pathology of this joint is a severely disabling condition.

### Joint capsules and ligaments

All the articular surfaces of the carpal bones are, of course, covered with cartilage, as all the articular surfaces of the body. The joints and their cartilages are enclosed in fibrous capsules lined on the inside by a synovial membrane (the synovium), that secretes the synovial fluid necessary to the proper lubrication of the articular cartilages (the synovia). These articular capsules are loose and lax enough to accomodate the necessary movements of their joints. Actually, the radiocarpal, midcarpal, intercarpal, carpometacarpal, and intermetacarpal joints often share a single, common synovial cavity, of very irregular shape, surrounded by the various interconnected synovial membranes of the carpal joints.

The carpal joints are held in place by a complex set of ligaments whose role is threefold: first, they keep the bones together, as they are the primary link between

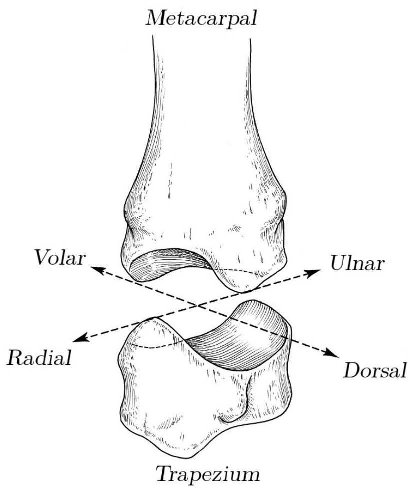



Figure 2.9 – The saddle joint at the thumb carpometacarpal level: articulation by reciprocal reception

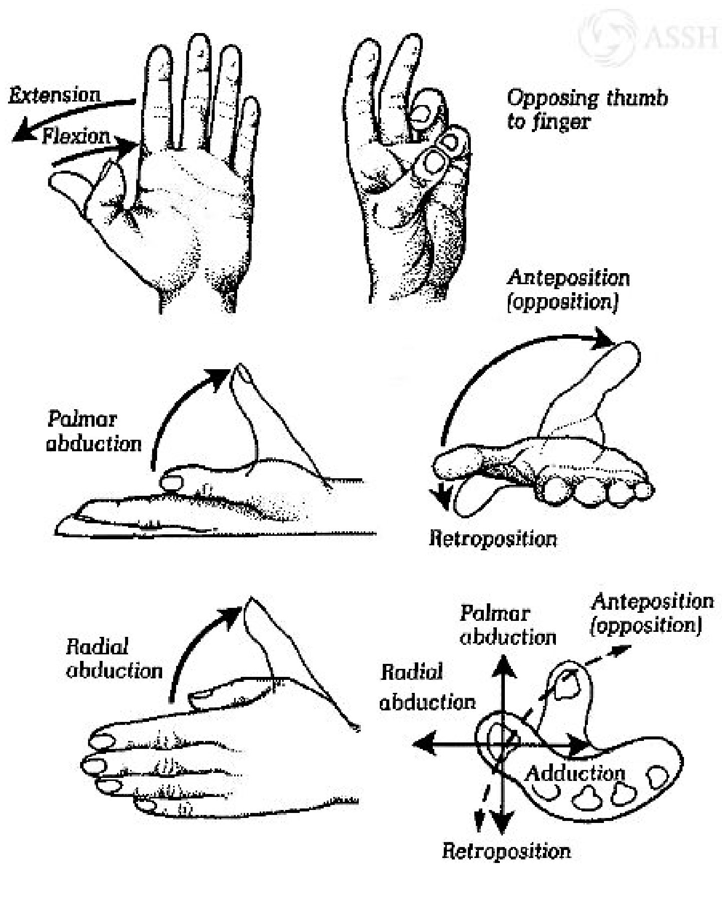
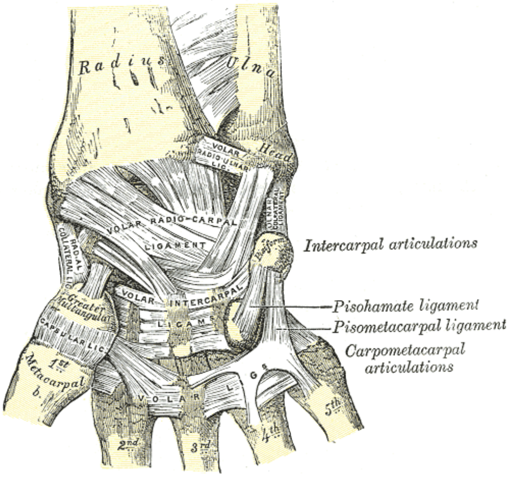
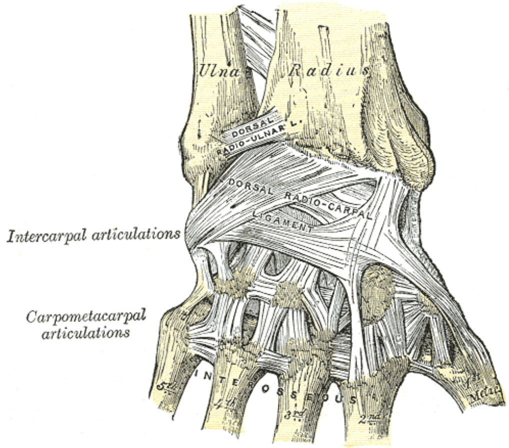



Figure 2.10 – Anatomical terms of motion for the thumb

bones[2]; second, being non-extensile, they define and limit the articular range of motion of their respective joints; third, they surround, protect, and strengthen the articular capsules. The carpal ligaments are either intrisic or extrinsic to the carpal bones, that is to say between carpals or between carpals and neighboring bones (radius, ulna, metacarpals). They are located on all four sides of the wrist: palmar, dorsal, and lateral (figure 2.11).




(a) Palmar view




(b) Dorsal view

Figure 2.11 – The ligaments of the wrist

The role of these ligaments must not be underrated: they hold the joints in place and provide stability to the wrist. The integrity of the short intercarpal ligaments, for instance, is "critical to normal wrist motion", and their disruption lead to "loss of synchrony between adjacent carpal bones, altered wrist motion, and pain" (Seiler 2001).

### Metacarpophalangeal joints

The metacarpophalangeals are formed by the articulation of the heads of the metacarpals with the bases of the proximal phalanges. The articular surface of each head is rounded, almost spherical, and is received into a congruent cavity on the proximal end of the phalanx. This interlocking of surfaces realizes a condyloid joint (like the radiocarpal joint) with two degrees of freedom: flexion-extension and abduction-adduction (figure 2.12). The thumb metacarpophalangeal joint, however, is more like a hinge joint, and consequently it is only capable of one degree of freedom, flexion-extension. As usual, a fibrous capsule with synovial membrane lining encloses each metacarpophalangeal joint, and is protected and strengthened by ligaments.

The proximal phalanges may be flexed by 90° on the metacarpals and extended by 45° (hyperextension). The ranges of motion of the metacarpophalangeal joints in abduction-adduction is much more limited, with 20° to 30° of each. This is because of two strong and short ligaments, located on the radial and ulnar sides of each metacarpophalangeal joint. These ligaments are called collateral ligaments and limit lateral motion (figure 2.13).

2. The other link between bones is the muscles and their tendons. Ligaments are passive links, muscles are active links.

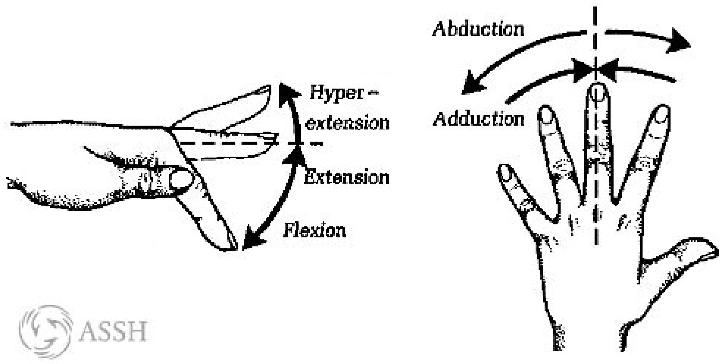
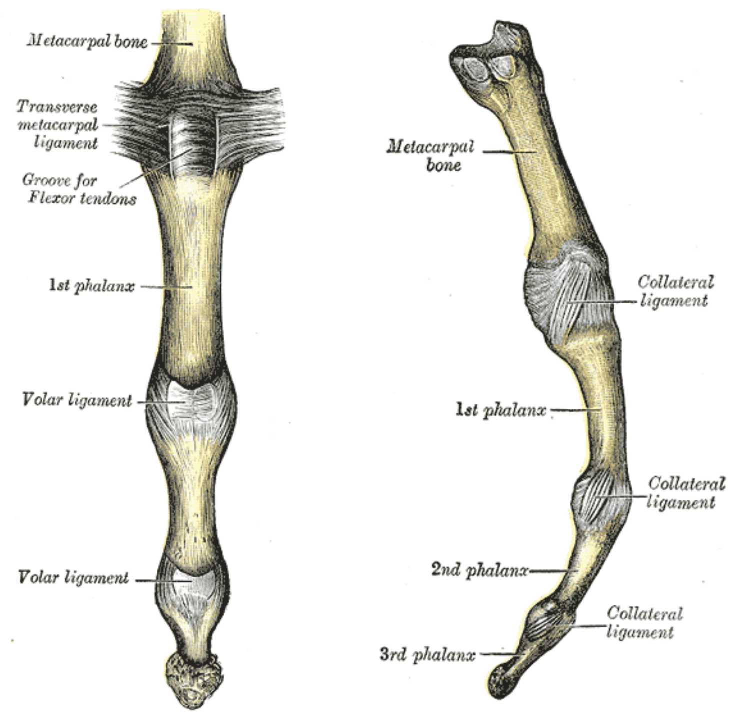



Figure 2.12 – Anatomical terms of motion for the fingers




(a) Palmar view (b) Ulnar view

Figure 2.13 – The ligaments of the fingers

It is striking to note that flexion-extension and abduction-adduction at the metacarpophalangeal joints are not totally independent degrees of freedom: the movements of abduction and adduction cannot be performed when the fingers are flexed. This is one of the articular interdependencies of the hand. It results from ligament interaction at the metacarpophalangeal level. The volar ligament of this joint is indeed connected to the collateral ligaments and blends also intimately with the transverse metacarpal ligaments (intermetacarpal ligaments that connect together the heads of the index, middle, ring and little metacarpals). These connections at ligament level result in flexion-extension and abduction-adduction being somewhat interdependent.

#### Interphalangeal joints

The interphalangeals occur between the head of one phalanx and the base of the next. They are hinge joints with one degree of freedom, flexion-extension. The articular capsules of these joints are very thin and lax dorsally, and so is the skin too, with characteristic folds on the interphalangeal knuckles: this facilitates a very wide range of motion in flexion, up to 100° for the proximal interphalangeal and 80° for the distal interphalangeal. On the contrary, extension is very limited: thick volar and collateral ligaments stop extension of the proximal interphalangeal at straightness, and the distal interphalangeal may have only about 15° of hyperextension. Both proximal and distal joints exhibit great lateral stability, thanks to the shapes of the articular surfaces, which are not adapted to laterality, and to the collateral ligaments, which remain tight through their whole range of motion (contrary to those of the metacarpophalangeals), therefore preventing any lateral motion.

The sum of the flexion angles of the metacarpophalangeal joints (90°), proximal interphalangeal joints (100°) and distal interphalangeal joints (80°) amounts to 270° and makes it possible for the fingers to touch the palm of the hand and seize thin objects between the palm and the fingertips.

### 2.1.2 Muscles and tendons

Many of the muscles that operate the hand and the fingers are actually not in the hand, nor in the fingers, but rather in the forearm. As a matter of fact, the majority of the muscles located in the forearm, with the exception of those controlling its prono-supination, are muscles of the hand. They attach proximally to the radius or ulna, or even as high as the humerus just above the elbow, and distally to the bones of the hand by long tendons. It is easy to feel these muscles work when we move the hand or digits, by putting the other hand around the forearm.

Because one of their points of attachment is located outside the hand, these muscles are called extrinsic muscles of the hand, whereas the much smaller muscles that are located in the hand itself, with all their attachments in it, are called intrinsic muscles of the hand. Since the strength of a muscle is related to its thickness, the extrinsic muscles serve primarily in gross motor skills requesting power and the application of large forces, while the intrinsic muscles are used for fine motor skills demanding delicate finger movements and fine force control (see section 2.2.1 for more about this distinction between power and precision). In total, there are 15 extrinsic muscles and 19 intrinsic muscles.

The muscles of the hand are connected primarily with the bones, but not always: generally speaking, muscles may also attach to cartilages, ligaments, tendons, or skin [3], and those of the hand are no exception. The attachments may be direct, or indirect through the intervention of tendons or aponeuroses. Tendons are tough bands of fibrous tissue, usually cord-like, almost entirely made of collagen fibers like ligaments, and similarly devoid of elasticity. Aponeuroses are flattened thick fibrous membranes, ressembling sheet-shaped tendons, tough and inextensile since made of dense collagen fibers too. An example of aponeurosis is the superficial palmar aponeurosis, which is the distal ending of the palmar long muscle (figure 2.16).

When a muscle is attached to a bone, its muscular fibers do not actually enter into the bone, but end upon the periosteum, which is a membrane that covers the outer surface of all the bones and contains the blood vessels, lymph vessels and nerves intended for them [4]. So the muscle or the tendon is attached to the periosteum, and the periosteum is itself attached to the underlying bone tissue by strong collagenous fibers.

Speaking about membranes, it is worthy of note that the muscles are themselves wrapped into collagenous membranes, contrary to what one may think from looking at anatomy écorchés, where they are not drawn for clarity. These fibrous membranes are called fasciae, and their fonction is to minimize friction between the muscles to allow them to glide over each other. So each muscle is wrapped in a fascia, and groups of muscles may themselves be surrounded by another fascia [5]. For instance in the hand, the thenar and hypothenar muscles are respectively grouped into two specific fasciae (called the thenar compartment and the hypothenar compartment).

The rest of this section about muscles briefly describes the muscles of the hand, extrinsic first, then intrinsic, with figures illustrating their position. In the description of a muscle, the term origin is meant to imply its more fixed attachment, and the term insertion refers to the more mobile one, for instance a finger flexor may originate in the forearm and insert into one or several finger bones. The muscles of the hand vary extremely in shape and position, and they are named according to their action (flexor, extensor), their form (long, short), their closeness to the bones or the skin (deep, superficial), their situation (radial, ulnar, interosseous), or the part they act

3. The muscles of the face are a straightforward example of muscles attached to the skin. As for muscles attached to the tendons of other muscles, the lumbricals of the hand are a good example. Each lumbrical muscle attaches indeed on the deep flexor tendon of a finger by one end and on the extensor tendon of the same finger by the other. These muscles have no osseous attachment at all.

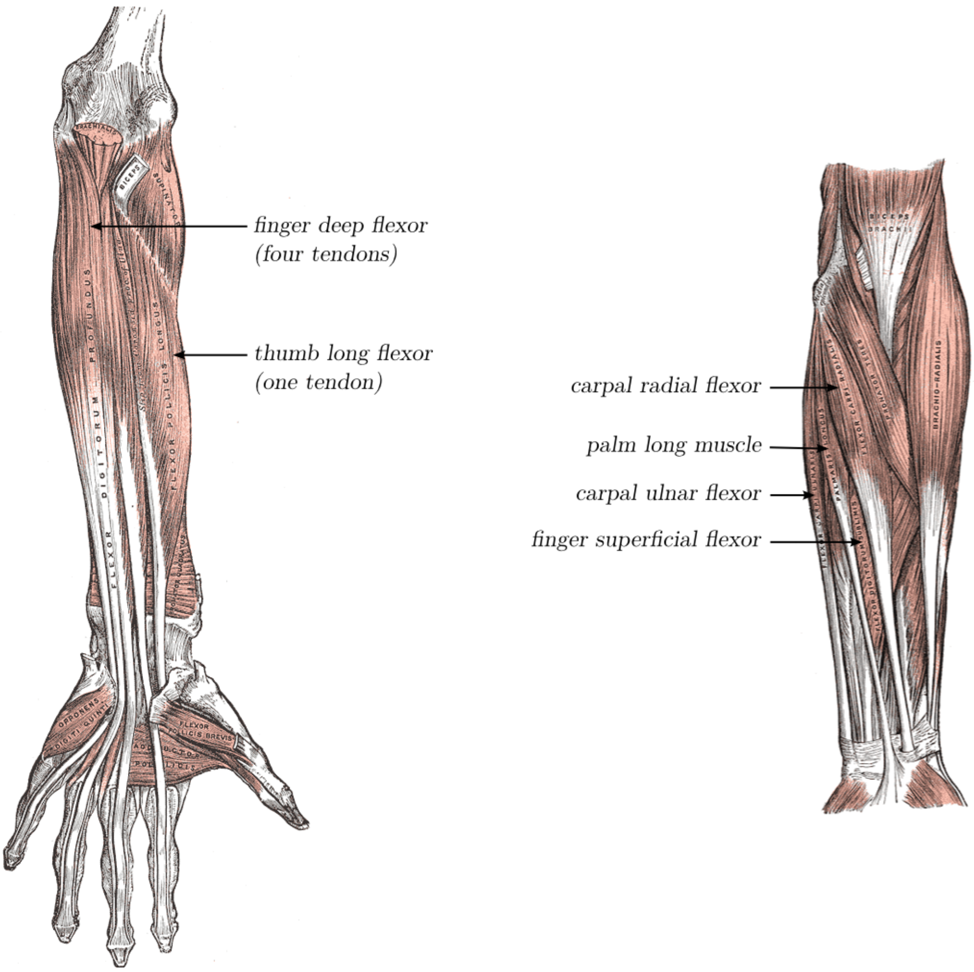
4. Bones may appear static, but they are far from being so. Albeit hard and mineralized, they are living body organs, constantly renewed, and their cells require nutrient and oxygen supply, hence the blood vessels. Not to mention that the marrow they store, which produces erythrocytes (red blood cells), leukocytes (white blood cells) and thrombocytes (platelets), obviously requires an interface with the blood system. As for the nerves of the bones, they innervate the periosteum (especially at the insertions of ligaments, tendons and articular capsules), the bone tissue and the marrow. Their observation in bones is fairly recent, and their role is still unclear (McCredie 2007). It is already obvious though that they participate in proprioception and nociception: proprioception is the sense of position of the various parts of the body in relation to each other, and nociception is pain perception. Pain is sensed by free nerve endings called nociceptors, whose electrical signals are interpreted by the brain as pain: the presence of nociceptors in bones explains why bone fractures, or osseous illnesses such as bone cancer, are so painful. It could also be that the nerves of the bones play a role in their growth and/or their healing after a fracture, by stimulating cell division: this action has been observed in amphibians, but remains to be observed in humans.

5. Actually, the whole body is permeated with fasciae, which are virtually everywhere. They surround, separate and protect the muscles, the blood vessels, the nerves, or they bind these structures together, or they suspend the organs within their cavities, and so on.

upon (carpal, palm, thumb), for instance: the carpal radial long extensor, or the finger deep flexor[6].

### Extrinsic volar muscles

The extrinsic volar muscles are six flexors: closer to the bones, the finger deep flexor and the thumb long flexor (figure 2.14(a)); closer to the skin, the finger superficial flexor, the carpal radial and ulnar flexors and the palm long muscle (figure 2.14(b)).




(a) Deep plane. The flexor retinaculum is removed to show the tendons of the finger deep flexor.

(b) Superficial plane. The flexor retinaculum is present at the wrist.

Figure 2.14 – Extrinsic volar muscles of the hand

The finger deep and superficial flexors originate both close to the elbow (from the ulna for the deep one, from the humerus, radius and ulna for the superficial one) and divide into four tendons each, two for each finger. They are thus muscles whose flexor action is common to all the fingers. The tendons first pass under the flexor retinaculum (transverse carpal ligament) through the carpal tunnel. When they arrive under the proximal phalanges, each superficial tendon divides into two strips between which the associated deep tendon passes to insert into the base of the distal

6. English normally uses Latin names for muscles, so these two muscles would be respectively "extensor carpi radialis longus" and "flexor digitorum profundus", but we use translated names for clarity and simplicity.

phalanx, while the two strips of the superficial tendon pass dorsally to the deep tendon to insert into the middle phalanx (figure 2.15 for a side view, figure 2.20(b) for a palmar view). As indicated by their names, the finger deep and superficial flexors are primarily flexors of the phalanges, however they also assist in flexing the wrist.

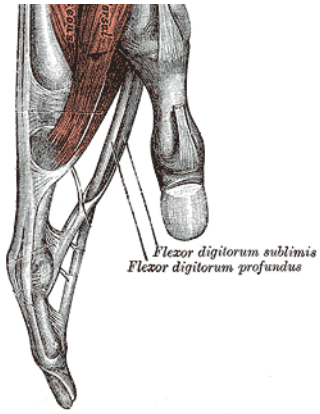



Figure 2.15 – Distal insertions of the finger deep and superficial flexors (radial view). The deep flexor tendon runs through the opening in the superficial tendon to reach the distal phalanx.

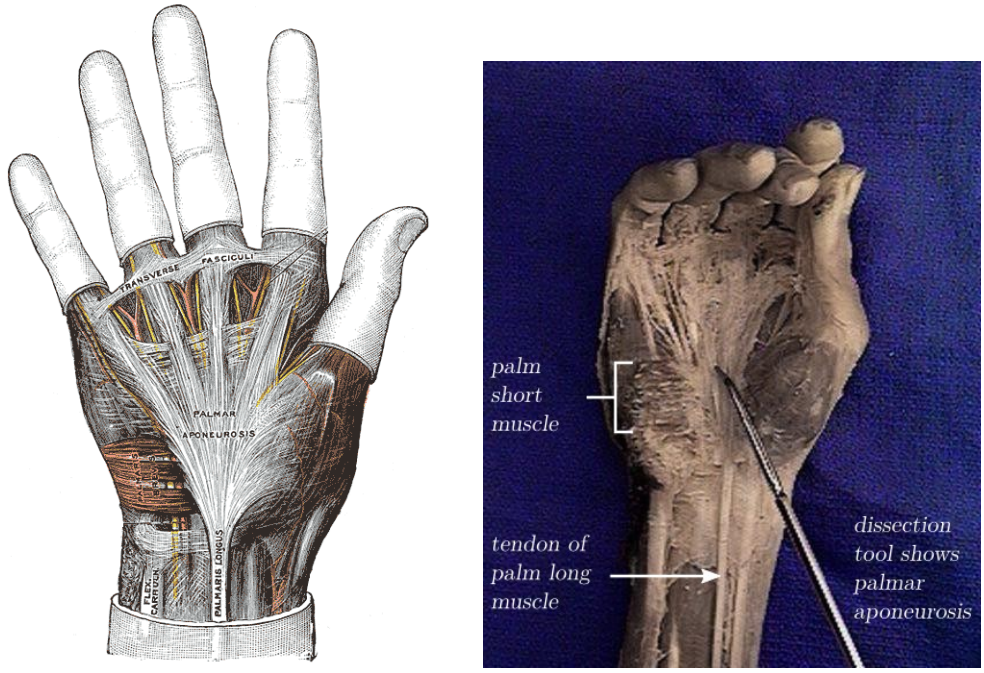
The thumb long flexor originates from the radius, forms a tendon that passes through the carpal tunnel, between the two heads of the thumb short flexor (an intrisic muscle which has two heads i.e. two layers of fibers), and inserts into the base of the distal phalanx of the thumb. It is a flexor of the phalanges of the thumb, but when the thumb is fixed it may also assist in flexing the wrist.

The carpal radial and ulnar flexors have their origins at the elbow, and their insertions on certain metacarpals and carpals. The radial muscle is a flexor and abductor of the wrist, the ulnar muscle is a flexor and adductor of the wrist.

The palm long muscle is a variable muscle: it is absent in 15% of the population (without known effect on prehension), and when present it is subject to many variations from one individual to the other: muscular above and tendinous below is the most common configuration, but it may be tendinous above and muscular below, or muscular in the middle with a tendon above and below, or it may present two muscular bundles with a central tendon, or it may be only tendinous. In any case it originates from the base of the humerus and ends in a thin, flat, superficial tendon, which passes over the flexor retinaculum and forms the superficial palmar aponeurosis (figure 2.16). It is a flexor of the wrist.

### Extrinsic dorsal muscles

The extrinsic dorsal muscles are a total of nine, eight extensors and one abductor: in the deep plane, the thumb long abductor, the thumb long and short extensors and the index extensor (figure 2.17(a)); in the superficial plane, the carpal radial long and short extensors, the carpal ulnar extensor, the finger extensor and the little finger extensor (figure 2.17(b)). They are the direct antagonists of the flexor extrinsic muscles of the palmar side.



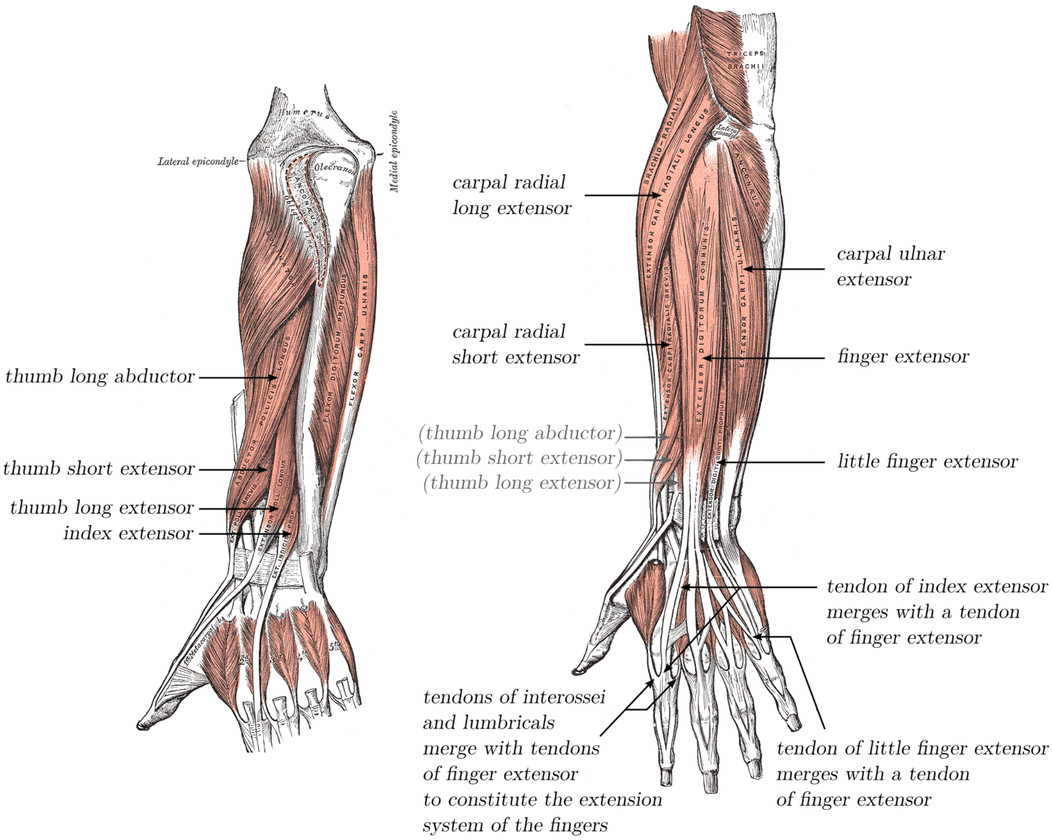

(a) Anatomical drawing (b) In a human cadaver

Figure 2.16 – Subcutaneous plane of the palm. The palmar aponeurosis ends the tendon of the palm long muscle in a triangular fin. The palm short muscle is visible on its side; it attaches to the palmar aponeurosis by one end and to the underneath surface of the skin by the other.

The muscles of the deep plane arise from the radius and/or ulna, as well as from the interosseous fibrous membrane that is stretched between these two bones. From top to bottom, we find the origins of the thumb long abductor, the thumb short extensor, the thumb long extensor, the index extensor. The first three muscles give tendons for the thumb which insert respectively into the bases of the thumb metacarpal, proximal phalanx and distal phalanx. The index extensor turns into a tendon which does not insert into a bone but merges with one of the tendons of the finger extensor (figure 2.17(b)). The main actions of these four deep muscles are suggested by their names; they also assist in extending and abducting the wrist.

In the superficial plane and on the radial side, the carpal radial long and short extensors arise from the base of the humerus and give tendons that insert into the index and middle metacarpal, respectively. They are extensors of the wrist but also radial deviators of the hand. On the ulnar side, the carpal ulnar extensor has two origins, one on the humerus and another on the ulna; it inserts into the base of the little metacarpal. It is an extensor of the wrist, but when acting alone it deviates the hand in the ulnar direction.

Between the radial and the ulnar sides, still in the superficial plane, the finger extensor originates at the elbow and splits into four tendons, one for each finger (figures 2.17(b) and 2.18). Each extensor tendon inserts successively into the bases of the proximal, middle and distal phalanges, by three fibrous splits. They are joined at the proximal phalanx level by the tendons of the interosseous and lumbrical muscles (intrinsic muscles, visible on figure 2.17). This forms the very complex extension system of the fingers: in comparison, the flexion system is simpler, since it consists




(a) Deep plane (b) Superficial plane

Figure 2.17 – Extrinsic dorsal muscles of the hand

solely of two tendons per finger, one running through an opening in the other, each with a single attachment on a phalanx.

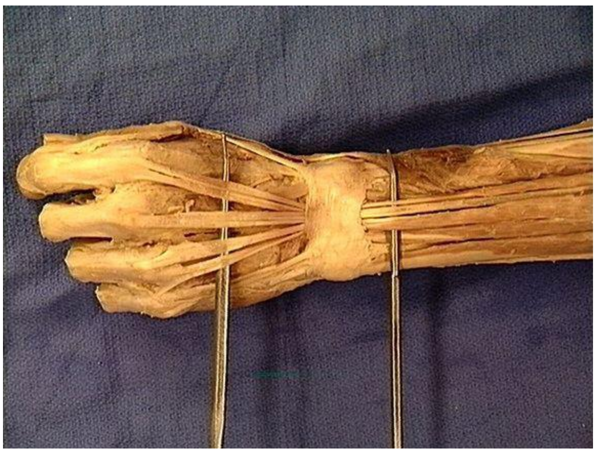


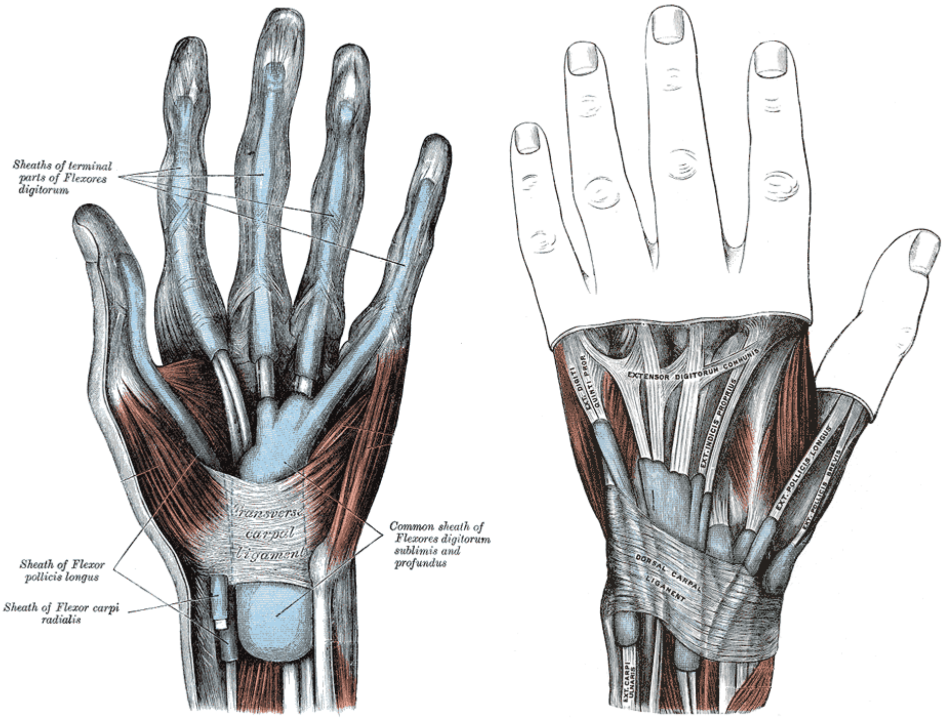
Figure 2.18 – The tendons of the finger extensor muscle. They pass under the extensor retinaculum, a structure similar to the flexor retinaculum, but more superficial and on the dorsal side of the wrist.

The little finger extensor often shares its tendinous origin with the finger extensor. Similarly to the index extensor, it does not insert into a bone but merges with a tendon of the finger extensor, the one intended for the little finger (figure 2.17(b)).

As its name suggests, it is a specific extensor of the little finger: owing to it, the little finger can be extended while the others are flexed, a movement that is on the contrary impossible for its immediate neighbor the ring finger.

### Mucous sheaths of the flexor and extensor tendons

Since the tendons of the extrinsic muscles are so long and important, they are protected by sheaths which surround them in part and lubricate them by secreting synovial fluid. These sheaths are illustrated in figure 2.19. The carpal sheaths are common to several tendons; for instance on the palmar side there is one common flat sheath for the eight tendons of the finger deep and superficial flexors.

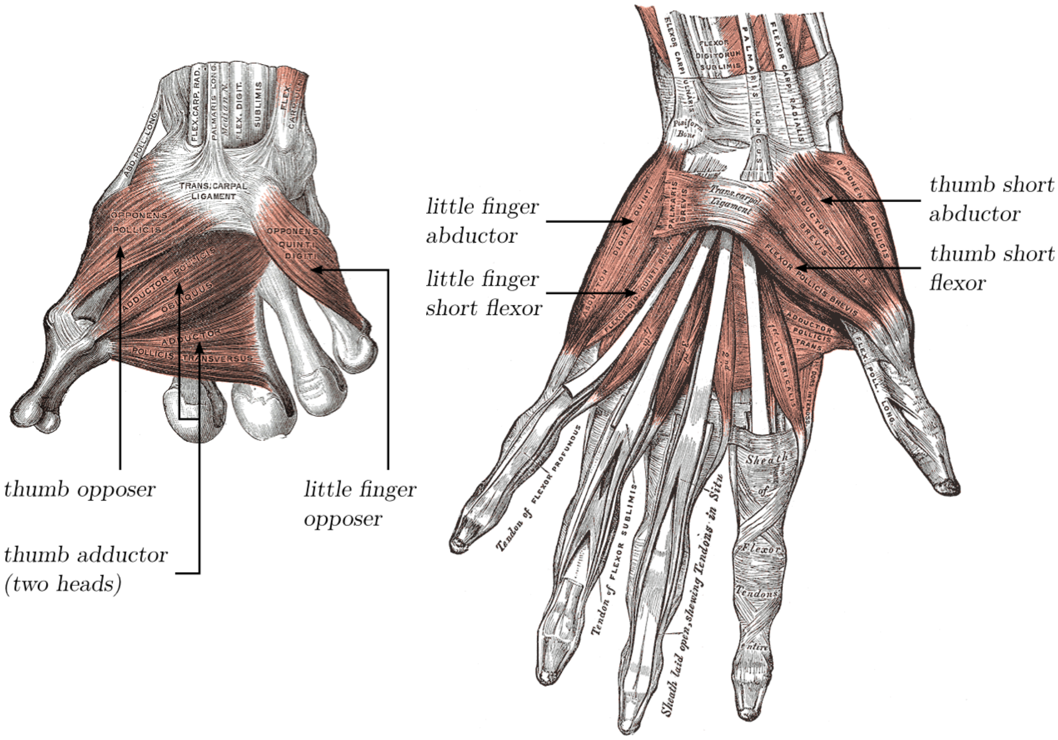



(a) Palmar view (b) Dorsal view

Figure 2.19 – Synovial sheaths of the flexor and extensor tendons (in blue color)

### Thenar muscles

There are four intrinsic muscles taking part into the mobility of the thumb. They are called the thenar muscles: the thumb adductor, the thumb short flexor, the thumb opposer and the thumb short abductor (figure 2.20). These muscles arise from various carpal bones and from the flexor retinaculum (transverse carpal ligament); they all have several origins. The thumb adductor has two heads, that is to say two bundles of fibers: one is attached on carpal bones, the other on the middle metacarpal. The thumb short flexor also has two heads, one on top of the other. All these muscles insert into the base of the thumb proximal phalanx, except the thumb opposer that inserts into the metacarpal.




(a) Deep plane (right hand) (b) Superficial plane (left hand)

Figure 2.20 – Thenar and hypothenar muscles, palmar view

### Hypothenar muscles

There are three intrinsic muscles dedicated specifically to the mobility of the little finger. From depth to surface, these hypothenar muscles are: the little finger opposer, the little finger short flexor and the little finger abductor (figure 2.20). They all arise from carpal bones and from the flexor retinaculum (transverse carpal ligament). The opposer inserts into the outer side of the little metacarpal; it draws this metacarpal forward during opposition of the fingers, in order to deepen the hollow of the palm. The short flexor and abductor insert into the base of the proximal phalanx, on the outer side too.

On top of the hypothenar muscles and close to the wrist lies subcutaneously a short and flat square muscle called the palm short muscle. It attaches to the superficial palmar aponeurosis by its radial side and to the dermis of the skin by its ulnar side (figure 2.16).

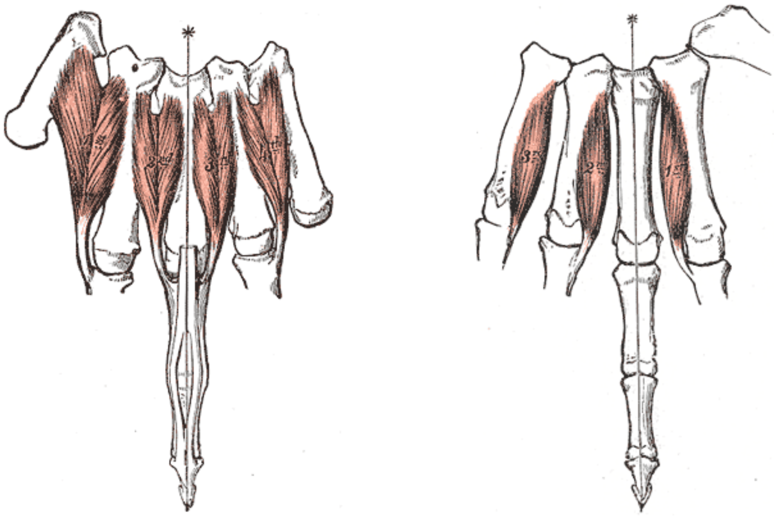
### Interosseous and lumbrical muscles

The lumbrical muscles are four small muscular bundles, located in the palm of the hand. They are visible on figure 2.20(b), on the radial side of each of the four tendons of the finger superficial flexor. They arise in the palm from the radial sides and volar surfaces of the tendons of the finger deep flexor [7]. Then they enter radially into the fingers, and insert into the four tendons of the finger extensor, which run dorsally to

7. The first and second lumbricals have one origin each, on the tendons of the index and middle fingers respectively. The third and fourth lumbricals have two origins each: on the tendons of the middle and ring fingers for the third, and on the tendons of the ring and little fingers for the fourth!

the finger bones. So they are particular in that they have no osseous attachment, they are instead associated with tendons.

The interosseous muscles are located in the intervals between the metacarpal bones, some of them more dorsally, the four dorsal interossei (figure 2.21(a)), the others more palmarly, the three palmar interossei (figure 2.21(b)).



(a) Dorsal view (left hand) (b) Palmar view (left hand)

Figure 2.21 – Interosseous muscles

The dorsal interossei have two heads each, each one attached to the side of a metacarpal. They insert primarily into the bases of the index, middle and ring proximal phalanges, and are abductors of these fingers (the abduction of the thumb and little finger is done by thenar and hypothenar muscles, plus the extrinsic thumb long abductor).

The palmar interossei arise from the sides of the metacarpals too, and insert into the bases of the index, ring and little proximal phalanges. They are adductors of these fingers (the middle finger doesn't need any since the second and third dorsal interossei are antagonists: when one abducts the middle finger from the axis of the hand, the other one is used to adduct the finger back).

In addition to their primary abduction-adduction action, the interossei, in conjunction with the lumbricals, are flexors of the first phalanges and extensors of the second and third phalanges. This is the consequence of the attachments of the lumbricals on tendons, and also because the interossei also insert into the extensor tendons, like the lumbricals.

The lumbricals, interossei, as well as the other intrinsic muscles and a couple of other structures of the hand are visible and recognizable on the palm section of figure 2.22.

### Muscle interactions and synergies

As we have reviewed, most muscles do not have only the action that their name suggests: additional actions are present. For instance, the thumb long flexor is also a flexor of the wrist, when the thumb is fixed. This is because the intricacy of the muscular system, in its complex routing of muscles and tendons and in its wealth of

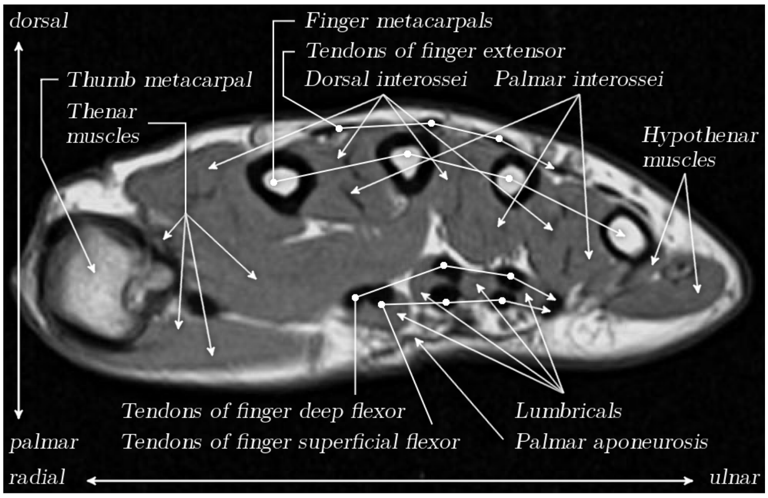



Figure 2.22 – Magnetic resonance image of the palm: transverse section accross the metacarpal bones and the intrinsic muscles

origins and insertions, gives birth to various interactions and synergies. It is not as simple as "one muscle, one action, one motion".

Actually, the importance of the relations of each muscle with its surrounding parts was already emphasized by Gray (1918), who noted that "the action of the muscle deduced from its attachments [...] is not necessarily its action in the living".

In his own words: "it is impossible for an individual to throw into action any one muscle; in other words, movements, not muscles, are represented in the central nervous system. To carry out a movement a definite combination of muscles is called into play, and the individual has no power either to leave out a muscle from this combination or to add one to it. One (or more) muscle of the combination is the chief moving force; when this muscle passes over more than one joint other muscles (synergic muscles) come into play to inhibit the movements not required; a third set of muscles (fixation muscles) fix the limb [...] and also prevent disturbances of the equilibrium of the body generally".

Speaking about fixative and inhibitory actions, we can illustrate this matter of muscle interactions with a straightforward example in the hand: when we voluntarily contract the muscles of the hand (intrinsic and extrinsic) to make it hard, stiff and motionless. Indeed, we can even control the amount of stiffness in our fingers by contracting more or less the muscles of the hand. The synergy at work here is called muscle coactivation; it is the simultaneous and coordinated activation of the agonist and antagonist muscles. This cancels any motion and stiffens the joints.

### 2.1.3 Nerves

The hand and the forearm are innervated by three nerves called the median, ulnar and radial nerves, according to their relative positions. All three nerves have both motor and sensory fibers. The median and ulnar nerves bring both types of fibers to the hand, but the radial nerve brings only sensory fibers: its motor fibers supply instead various muscles in the forearm.

As can be seen in figure 2.23, the median and ulnar nerves run volarly while the sensory branch of the radial nerve runs dorsally to the hand. They all divide past the wrist into smaller and smaller branches which serve the muscles and skin of the hand until the fingertips. The branches that innervate the digits are called digital nerves; they are all sensory nerves since there are no muscles in the digits. At palm level, the branches of the median and ulnar nerves are also easily identified in dissection (figure 2.24).

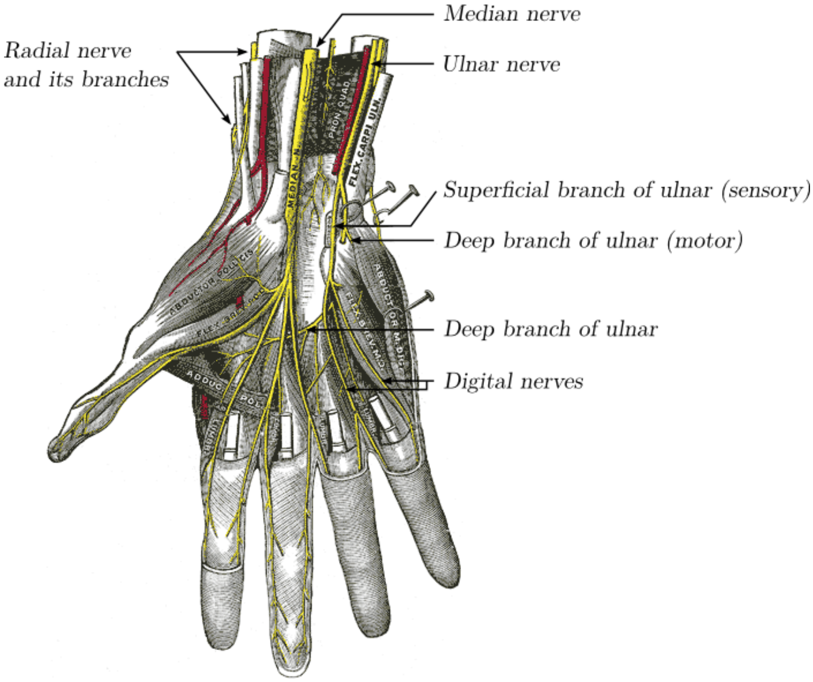
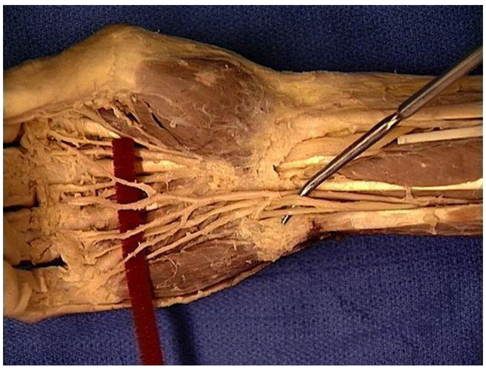



Figure 2.23 – Nerves of the hand, palmar view

(a) Median nerve



(b) Ulnar nerve

Figure 2.24 – Nerves of the hand, dissection

Wilhelmi, Marrero, and Sahin (2009) note that “variations from the classic nerve distribution are so common that they are the rule rather than the exception”. The patterns of branching are not even the same for both hands of an individual. Gupta (2009) notes however that “generally, the sensory fascicles are considered to sit more superficially and the motor fibers more dorsal”: this reflects the importance of the skin of the hand in the sensory input.

### Median nerve

Along its course in the forearm, the median nerve sends off branches that supply all the extrinsic volar muscles of the hand (flexor muscles), except the carpal radial flexor and the ulnar half of the finger deep flexor (both under ulnar innervation). At the wrist, it runs very superficially, protected only by the thin tendon of the palm long muscle. Then it enters the hand through the carpal tunnel, together with the flexor tendons. Once clear of the flexor retinaculum, it serves two and a half thenar muscles and the first two lumbricals. Because its motor territory includes the extrinsic flexors and the thenar muscles, the median nerve is of critical importance to the prehension and pinch functions of the hand.

The sensory branches of the median nerve consist of one cutaneous branch for the palm and four digital nerves. The palmar cutaneous branch arises from the median nerve in the distal part of the forearm and passes over the transverse carpal ligament; it provides sensation to the palm and the thenar eminence. The four digital nerves originate directly in the hand (figure 2.23) and provide sensation to the thumb, index finger, middle finger, and radial side of the ring finger.

The superficial position of the median nerve at the wrist makes it very vulnerable to injuries, while its possible compression in the carpal tunnel causes "carpal tunnel syndrome". Figure 2.25 documents these cases of nerve damage, that lead to disability of an otherwise anatomically intact hand (Chevallier 1998/2002, pages 170, 212–215; Danikas, Neumeister, and Nolan 2010; Amirlak, Upadhyaya, Ahmed, Wolff, Tsai, and Scheker 2010).

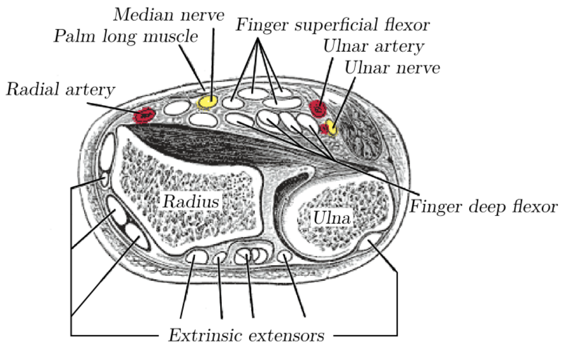
### Ulnar nerve

In the forearm, the ulnar nerve innervates only the extrinsic volar muscles that are not already served by the median nerve: namely, the carpal radial flexor and the ulnar half of the finger deep flexor. In the hand, it sends off a deep motor branch which itself distributes successively several motor branches (figure 2.23): to the hypothenar muscles, to the last two lumbricals, to all the interossei, and finally to one and a half thenar muscles.

The sensory branches of the ulnar nerve consist of one cutaneous branch for the palm, one dorsal branch for the skin of the dorsum, and two digital nerves. The palmar cutaneous branch arises from the nerve trunk in the forearm and ends in the skin of the palm, where it provides sensation to the hypothenar eminence. The dorsal branch arises at the wrist and supplies sensibility to the ulnar portion of the dorsum and to the dorsal surfaces of the small finger and ulnar side of the ring finger. In the hand and volarly, the superficial sensory branch of the ulnar nerve divides into two digital nerves (figure 2.23) which provide sensibility to the small finger and ulnar side of the ring finger.

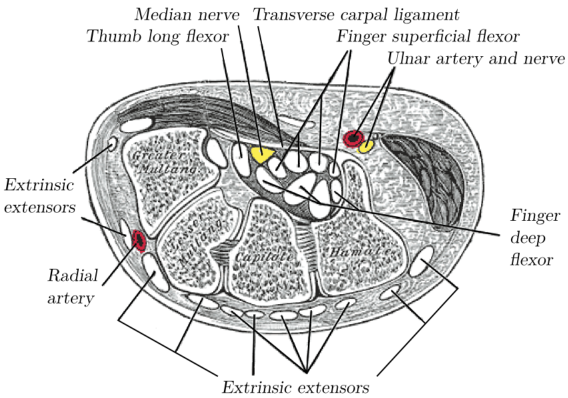
The ulnar nerve has relatively little protection from the muscles in the forearm and at the wrist, so injury is not uncommon and may lead to various disabilities. Figure 2.26 documents the consequences of damage to this nerve at wrist level (Chevallier 1998/2002, pages 212–215; Danikas, Neumeister, and Nolan 2010).

**Severing of the median nerve** at the wrist is a possible outcome of accidents or attempted suicides by wrist slashing, because the subcutaneous position of this nerve at the wrist makes it very vulnerable even to relatively minor lacerations. This severe injury results in paralysis, and atrophy over time, of the median-innervated muscles, namely the first and second lumbricals and three thenar muscles: the thumb short abductor, the thumb opposer and the superficial head of the thumb short flexor. The lumbricals are flexors of the metacarpophalangeal joints and extensors of the interphalangeal joints: the loss of the first two causes the lack of flexion at the metacarpophalangeal joints of the index and middle fingers when the patient tries to make a fist, thereby hindering prehension. But most importantly, the loss of the thenar muscles commanding abduction and opposition of the thumb means that these movements are no longer possible and that the patient's thumb is restricted to the plane of the palm, a disability known as "ape hand". Since it cannot oppose the fingers any more, the thumb loses most of its usefulness.




Transverse section of the forearm across the distal ends of the radius and ulna. The superficial position of the median nerve is clearly visible, protected only by the thin tendon of the palm long muscle.

**Compression of the median nerve** as it travels through the carpal tunnel is the cause of a wide variety of sensory-motor symptoms, known collectively as "carpal tunnel syndrome". The nerve may be compressed because of any condition that causes pressure to increase in the carpal tunnel. As nine flexor tendons pass through the carpal tunnel together with the median nerve, this pressure elevation is often caused by inflammations of the tendons (tendinitis) or of their synovial sheaths (tenosynovitis), that cause them to swell and compress the nerve. Rheumatoid arthritis for instance causes inflammation of the flexor tendons; fluid retention in tissues, common during pregnancy or caused by thyroid dysfunction, swells the tenosynovium. The symptoms vary from mild to extreme and include abnormal sensations and numbness in the thumb, index and middle finger, which are innervated by the sensory branches of the median nerve. The main motor branch serves three thenar muscles, and consequently the motor symptoms are weakness and clumsiness of the thumb, lost of gripping strength and dropping of things. The symptoms worsen over time, up to atrophy of the thenar muscles. If the condition remains untreated, permanent nerve damage may occur, leading to hand disability even after surgery.




Transverse section of the wrist across the distal row of carpals. The carpal tunnel is limited by these bones and the transverse carpal ligament. Nine flexor tendons and the median nerve pass through this space roughly as large as the thumb.

Figure 2.25 – The consequences of median nerve damage

Ulnar claw in a patient with ulnar nerve injury who tries to open his hand.

**Injuries to the ulnar nerve** at the wrist cause various degrees of paralysis of the ulnar-innervated muscles of the hand, namely the third and fourth lumbricals, all seven interosseous muscles, the thumb adductor, the deep head of the thumb short flexor and the three hypothenar muscles: little finger short flexor, little finger abductor, little finger opposer. The result of the loss of the interossei is that the patient cannot adduct or abduct the fingers any more. Paralysis of thenar and hypothenar muscles means loss of mobility and strength of the thumb and little finger. As for the loss of the last two lumbricals, it causes the lack of flexion at the metacarpophalangeal joints of the ring and little finger and the lack of extension at the interphalangeal joints of the same fingers: as a result, the antagonist action is unopposed and makes these fingers hyperextended at the metacarpophalangeal joints and flexed at the interphalangeal joints. This condition is called “ulnar claw” because of the shape of the fingers.

Figure 2.26 – The consequences of ulnar nerve damage

#### Radial nerve

As written previously, the radial nerve brings only sensory branches to the hand. Its motor branches supply instead all the extrinsic dorsal muscles of the hand (extensor muscles), in the forearm.

The sensory branches of this nerve are three in number and innervate most of the dorsum of the hand: its radial portion and the dorsal surfaces of the thumb, index finger, middle finger and radial side of the ring finger.

The sensory territories of all three nerves of the hand are summed up in figure 2.27.

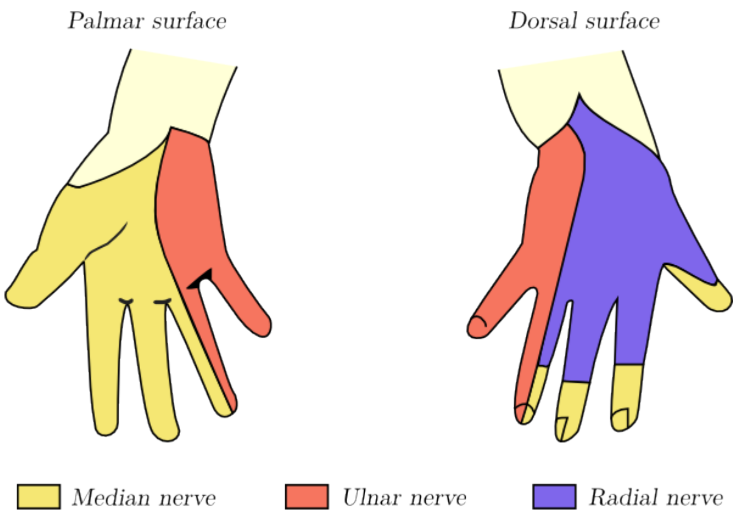



Figure 2.27 – Sensory territories of the nerves of the hand

### 2.1.4 Blood supply

The vascular network of the hand is rather complex. It presents moreover a lot of variations from one individual to the other, and even between both hands of the same person. Unlike bones, muscles or nerves, blood vessels are not very relevant to prehension and manipulation, so this section only presents very basic facts about them, for the sake of completeness.

### Arteries

The blood supply of the hand is mainly provided by two arteries coming from the forearm, named from their locations the radial and ulnar arteries. As illustrated on figure 2.28, these arteries split into several branches which meet one another, forming four arches: a deep palmar arch, a superficial palmar arch, a palmar carpal arch and a dorsal carpal arch. These arches give rise to several arteries which supply blood to the fingers, and to multiple branches to intrinsic muscles and skin. The deep palmar arch is the major blood supply to the thumb.

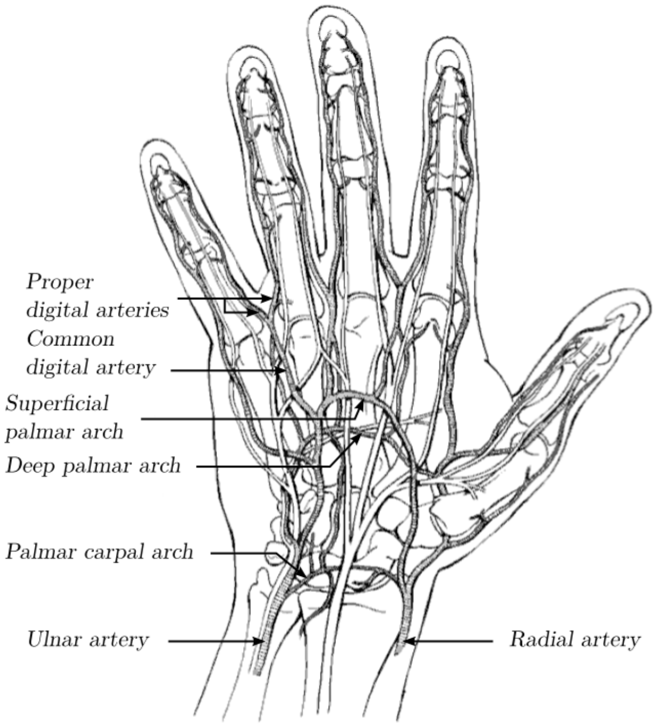



Figure 2.28 – Arteries of the hand, palmar view. In gray, the arteries, in white, the nerves. The dorsal carpal arch and the dorsal arteries of the hand are not visible (since they are dorsal).

### Veins

Similarly to the arterial network, the venous network is divided into two sets of vessels, superficial and deep. The deep veins generally follow the deep arterial system as "accompanying veins", that is to say they run in pairs along an artery, in close proximity to it, one vein on each side of the artery [8].

The superficial veins are very numerous, especially on the dorsum of the hand, whose venous network is much more developed than on the palmar side. This network is

8. This is common with small arteries and veins, especially those in the extremities. The pulsations of the artery aid venous return.

illustrated on figure 2.29: the dorsal digital veins connect one another at metacarpal level, forming dorsal metacarpal veins, which drain blood further upward in the forearm to the cephalic and basilic veins (superficial veins, respectively radial and ulnar). All these veins interconnect a lot, forming a network that is very variable from one individual to the other and presents also variations between the hands of the same person.

Since they run mostly in the subcutaneous fat, the superficial veins are often visible through the skin of the forearm and dorsum of the hand, especially in older people.

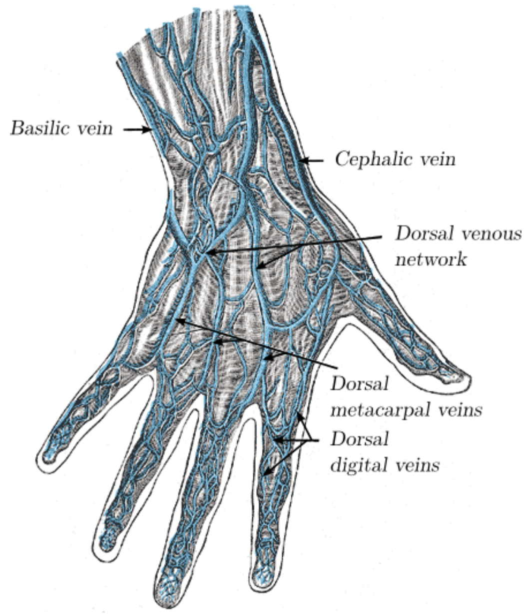



Figure 2.29 – The veins on the dorsum of the hand

### 2.1.5 Skin and tactition

In a study about prehension and manipulation, the skin of the hand deserves special attention. It is indeed a full-fledged sense organ that plays the key role in the sense of touch. Its palmar surface embeds most of the sensory nerve endings which enable the sharpness of tactile perception, in a density unequaled anywhere else on the body; and "the fact that individuals with numbed digits have great difficulty handling small objects even with full vision illustrates the importance of somatosensory information from the fingertips" (Flanagan and Johansson 2002).

#### Skin of the dorsal surface and nails

The skin that covers the dorsum of the hand and digits is greatly different from the skin that covers the palm and the volar surface of the digits. Contrary to the later indeed, the skin of the dorsal aspect is thin, pliable, and attached very loosely to the underlying tissues. This feature enables it to move and stretch as much as necessary during the motion of the digits. Characteristic folds in the skin are even present on top of the interphalangeal knuckles, to account for skin extension during flexion of the digits.

The dorsal skin has no particular sensory role; in this respect it is similar to the skin covering most of the rest of the body.

It is endowed with specialized appendages at the distal extremity of the digits, derived from the epidermis: the nails. Each nail is implanted by a hidden portion, called the root, into a groove in the skin, which extends several millimeters into the phalanx. The exposed portion of the nail is called the body or nail plate. Both the root and the body rest on an underlying tissue called the nail bed or nail matrix. The proximal part of this matrix is called the germinal matrix because it produces most of the cells that become the nail plate. It generates indeed about 90% of the nail plate, and is responsible for nail growth in length. The distal part of the matrix is called the sterile matrix, it thickens the nail and provides an adherent surface to which the nail is firmly attached. It produces the remaining 10% of nail plate volume.

The germinal matrix lies under the nail root and a small part of the nail body which corresponds to the lunula, the pale semi-circular shape visible at the proximal end of the nail body. Distal to the lunula, the sterile matrix is very vascular, which explains the color seen through the translucent nail tissue. The nails are hard because of the high amount of keratins their cells contain [9].

Functionaly speaking, the nails protect the fingertips and rigidify their cutaneous covering, which adds stability to precision grasps and enhances the sensitivity of the fingertips through counter-pressure exerted on the pulp of the fingers when they touch an object or a surface.

**Skin of the palmar surface and cutaneous sensory receptors**

The palmar skin exhibits features characteristic of its special functions. First, it is thick and tough, devoid of hair, and not as pliable as the dorsal skin. It is strongly attached to the underlying fibrous fasciae by numerous vertical fibrous fibers, and most firmly anchored at the palmar and digital creases. These features enhance its stability, a useful quality for proper grasping function.

Various fibrofatty pads are located under the palmar skin to accomodate the grasps to uneven surfaces and distribute pressure during grasping. Of noticeable importance are the hypothenar pad (the thickest of them, covers the hypothenar muscles), the thenar pad (on the internal part of the thenar eminence), the metacarpophalangeal pad (located accross the distal end of the palm), and of course the pulps of the digits.

The skin of the palmar surface of the hand and digits is also equipped with an enormous amount of sensory nerve endings of different kinds, which enable it to play an extraordinary sensory role. The density of these sensory receptors "increases in the distal direction of the hand and is exquisitely high in the fingertips" (Flanagan and Johansson 2002).

Simply put, there are three types of cutaneous sensory receptors. Thermoreceptors detect heat or cold in the innocuous range (two kinds of thermoreceptors, heat-sensitive and cold-sensitive), mechanoreceptors respond to mechanical deformations in the skin (various kinds of mechanoreceptors), and nociceptors detect noxious heat, noxious cold, excessive mechanical stress, as well as damage to tissues, for instance cuts in the skin or cutaneous inflammations (various kinds of nociceptors too). These three classes of sensory receptors are the source of three senses called somatic

9. Keratins are a family of fibrous proteins which form strong unmineralized tissues, such as hair and nails in humans, as well as claws, horns, scales, shells, beaks and quills in other animals.

senses: thermoception or temperature perception, nociception or pain perception and tactition or touch [10].

Thermoreceptors and nociceptors are both free nerve endings: the nerve fibers [11] branch a lot at their extremity and send their unmyelinated terminal branches free throughout the tissue elements. Mechanoreceptor however are special end-organs that encapsulate the end of the nerve fiber. There are four types of mechanoreceptors in the skin of the hand: they respond to different types of cutaneous motion and deformation, by producing action potentials that are then conveyed along their nerve fiber to the central nervous system. The structures of these four mechanoreceptors are briefly described in figure 2.30, and their roles are roughly summarized below from K. Johnson (2001). It is the sum of the distinctive perceptual functions of the mechanoreceptors that constitutes tactile perception as we feel it.

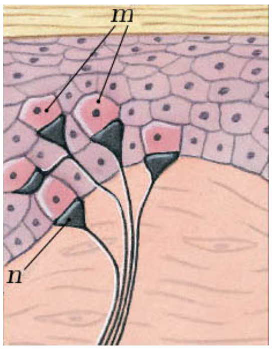
**Merkel disks** respond to constant skin pressure and very low frequency mechanical vibrations, up to about 15 Hz. They produce action potentials as long as pressure is present, thereby informing the central nervous system about contact with an unvarying stimulus. Their spatial resolution is high (they discriminate at 0.5 mm), they may detect skin indentations of less than 1 µm and up to 1500 µm without saturating, and they have been shown to be remarkably sensitive to “edges, corners, and curvatures”. These characteristics make them particularly suited to the tactile exploration of fine surface patterns and object shapes.

**Meissner corpuscles** are insensitive to constant skin deformation, but sense dynamic skin deformation better than Merkel disks: they respond to relatively low-frequency mechanical vibrations, with highest sensitivity to vibrations below 50 Hz. Therefore, when subject to a continuous, unvarying mechanical stimulus, they do not fire action potentials during the stimulus as Merkel disks do, but only at its onset and offset (the varying parts, containing higher-frequency changes). The spatial resolution of these corpuscles is poor (a few millimeters). They have been recognized quite recently as responsible for detecting slip between the skin and a grasped object. They also seem to be the most effective of the four mechanoreceptors at “signaling sudden forces that act on objects held in the hand” (disturbances). As a result of all these characteristics, their most important function seems to be “the provision of feedback signals for grip control”.

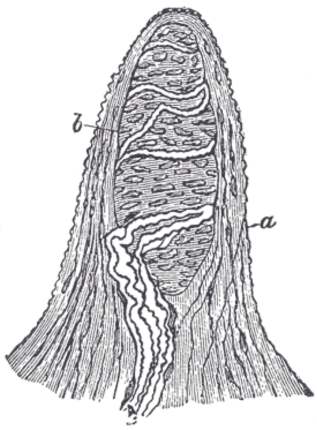
**Pacinian corpuscles** are sensors of high-frequency vibrations. They form action potentials when they are rapidly distorted, from 80 Hz to 400 Hz, with maximal sensitivity to vibrations around 250 Hz. When subject to sustained pressure, they do not fire action potentials, except at the onset and offset of the stimulus. They have virtually no spatial resolution (several centimeters) and are extremely sensitive, responding to deformations in the nanometer range if these deformations have sufficient frequency (for instance, amplitudes of 10 nm may be detected at 200 Hz). These distinctive features make Pacinian corpuscles have an important function in “the perception of distant events through transmitted vibrations when we grasp an

10. There are other somatic senses, for instance proprioception, the sense of position of the various parts of the body in relation to each other. Proprioception also stems from thermoreceptors, nociceptors and mechanoreceptors, but located elsewhere than in the skin: most notably, they are in the muscles, around the tendons, in the articular capsules and in the periosteum.

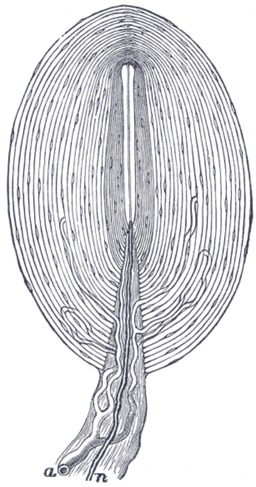
11. As a reminder, a nerve fiber is the axon of a neuron (here a sensory neuron).



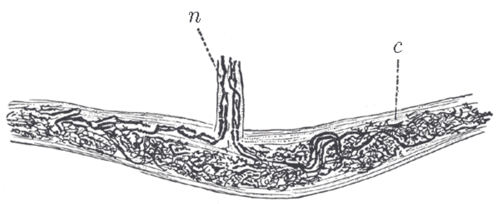

(a) Merkel disks. The sensitive nerve fiber divides into dozens of terminal branches, which end into nerve terminals ($n$) in close apposition with large cells of the epidermis, called Merkel cells ($m$). For this reason, Merkel disk receptors are also referred to as Merkel cell-neurite complexes. The branching of each Merkel nerve fiber covers a skin area of about $5\,\mathrm{mm}^2$, and at the fingertip, there are about 100 of these nerve fibers per $\mathrm{cm}^2$.




(b) Meissner corpuscles are oval-shaped bodies ($b$), made of flattened supportive cells arranged horizontally, and surrounded by a capsule of connective tissue ($a$). One sensitive nerve fiber passes through the capsule and makes several spiral turns around the body of the corpuscle, while branching a few times. Like Merkel discs, Meissner corpuscles lie just beneath the epidermis. They are around 100 µm in length and 40 µm in diameter; their density is about 150 per $\mathrm{cm}^2$ at the fingertip, but it drops fourfold between the ages of 12 and 50.




(c) Pacinian corpuscles are oval-shaped and visible to the naked eye because of their length of 1 mm. They have an onion-like structure of 20 to 70 concentric capsules of fibrous connective tissue, separated by gelatinous fluid, and enclosing a fluid-filled cavity with the end of the nerve fiber ($n$), unmyelinated and unbranching. An arterial twig ($a$) also enters the corpuscle, forming capillary loops in some of the intercapsular spaces. Pacinian corpuscles are located deep in the skin and are far less numerous than Merkel disks or Meissner corpuscles: they amount to about 350 per finger and 800 in the palm. The skin of the fingertips features specific Pacinian-like corpuscles, found only there and called the Golgi-Mazzoni corpuscles. They are smaller, thinner and feature a branching nerve fiber in the cavity.




(d) Ruffini corpuscles are spindle-shaped, relatively large, and made of connective tissue sheaths ($c$) inside which sensitive nerve fibers ($n$) divide into numerous branches. They are located deep in the skin and are firmly anchored to the surrounding dermis by collagen fibers. This attachment transmits the stretch of the skin to the corpuscles.

Figure 2.30 – The cutaneous mechanoreceptors in the skin of the hand

object in the hand". For instance, "when we become skilled in the use of a probe or a tool, we perceive events at the working surface of the tool or probe as though our fingers were present". The Pacinian corpuscles bear responsibility for this perceptual capacity.

To achieve their high-frequency sensitivity, Pacinian corpuscles filter out the low-frequency stimuli of the large stresses and strains accompanying many manual tasks of everyday life. Otherwise, they would be completely overwhelmed by this constant low-frequency noise. This is what the multi-layered, fluid-filled structure is about: it realizes a high-pass filter, attenuating low frequencies aggressively at almost 60 dB per decade (third-order filter).

**Ruffini corpuscles** are similar to Merkel disks in that they respond to constant, unvarying stimuli, contrary to Meissner and Pacinian corpuscles. They are quite insensitive to skin indentation but much more sensitive to skin stretch, which suggests that they are sensors of the horizontal tensile strain of pressure fields, whereas Merkel disks would detect the vertical component. Experimental studies have identified their role as "the perception of the direction of object motion or force when the motion or direction of force produces skin stretch". It appears that they also contribute to "the perception of hand shape and finger position through the pattern of skin stretch produced by each hand and finger conformation", since simply stretching the skin has been shown to activate them and produce the illusion of finger flexion.

## 2.2 Grasping for manipulation

The previous section has made it clear that our hands have a very complex anatomy. This intricacy underlies extremely diverse and varied abilities: when we think about our hands in everyday use, it is easy to realize how severely disabled we would be if a stroke of bad luck impaired them – see, for instance, the consequences of nerve injury in figures 2.25 and 2.26, as well as the description of our hands' functions in chapter 1, section 1.1. The present section is about one of those abilities, the main one actually: prehensile manipulation. It presents how we grasp objects to manipulate them.

### 2.2.1 Two fundamental types of grasps

A lot of our daily hand usages are, of course, prehensile activities, reflecting the fact that our hands are "primarily adapted to serve the requirements of prehension" (Connolly and J. Elliott 1972/1976). But they are also used in non-prehensile ways, as in pushing or lifting objects with the whole hand or with fingers, or in hitting or clubbing with the fist or the edge of the hand, or in poking or scratching with the fingers, and so on (see chapter 1, section 1.1.2).

Thus we categorize hand usages as *prehensile* or *non-prehensile*. Such a classification requires, of course, a definition of what prehension exactly is. We will go by the common definition that prehension is "the ability to pick up an object in one hand" (Connolly and J. Elliott 1972/1976). Prehensile movements are then "movements in which an object is seized and held partly or wholly within the compass of the hand", whereas non-prehensile movements are those "in which no grasping or seizing is involved but by which objects can still be manipulated" (Napier 1956), by pushing, lifting, hitting, and so on.

Surprisingly enough perhaps, the prehensile activities of the human hand can be grouped into two fundamental types of grasps only, despite the extremely wide range of prehension situations. These grasps were first identified, described and analysed by British anatomist and primatologist John Napier (1956, and subsequent publications on that matter). He called them the *power grip* and the *precision grip*. These two patterns of grasp are fundamentally different, anatomically and physiologically speaking. They provide the basis for all prehensile abilities of the hand, because they may be divided into several subcategories each, that is to say subtypes of precision grips and subtypes of power grips. This forms a tree-like classification of grasps: a grasp taxonomy. But before going into this detail, let us review the differences between the power and precision grips.

#### Anatomical differences between the power and precision grips

On an anatomical point of view, in the power grip the object is "held in a clamp formed by the partly flexed fingers and the palm, counter pressure being applied by the thumb lying more or less in the plane of the palm" (Napier 1956) (figure 2.31). Sometimes, the thumb may instead be wrapped over the dorsal side of the fingers, where it acts as a buttress to reinforce the grip. In any case, it is not involved in any kind of opposition with the other fingers.

In the precision grip the object is "held pinched between the flexor aspects [12] of the fingers and the opposing thumb" (Napier 1956) (figure 2.31). Contrary to the power grip, the palm of the hand is not involved: although the object may still touch it in certain cases, for instance if it is large enough, the palm is not an active part of the precision grip (figures 2.31, 2.32(a) and 2.32(b)). Another anatomical difference with the power grip is that the precision grip clearly involves opposition of the thumb, the object being clamped between the fingers and the opposing thumb. Large objects held in a precision way usually involve all the fingers, with a possible "spreading (abduction) of the fingers" (Connolly and J. Elliott 1972/1976), but "smaller ones require only the thumb, index and middle fingers with the fourth and fifth fingers providing lateral stability" (Young 2003). Two-finger precision grips are also possible, usually between the thumb and the index.

The term "precision grip" is sometimes taken for "fingertip precision grip", i.e. a precision grip involving only the distal tips of the digits (see e.g. Flanagan and Johansson 2002, glossary). Precision grips do not necessarily use only the fingertips, for instance relatively large or heavy objects may be held securely in a precision way by a clamp of the whole fingers and the whole opposing thumb (see figure 2.32). To sum it up, as long as there is opposition of the thumb and no active involvement of the palm, a grip qualifies as a precision grip, according to Napier's definition.

#### Functional differences between the power and precision grips

On a physiological point of view now, the power grip and the precision grip are functionally different. In the precision grip, the mobility allowed by the use of the digits, especially in a fingertip grasp, makes the grip better suited when precision of movement is required, in fine and precise manipulations of the object for instance. On the contrary, the dominant characteristic of the power grip is the application of force, at the expense of mobility. Precision grips are thus a better choice to manipulate

12. That is to say, the part of the fingers on the side of flexion: the palmar side, not dorsal.

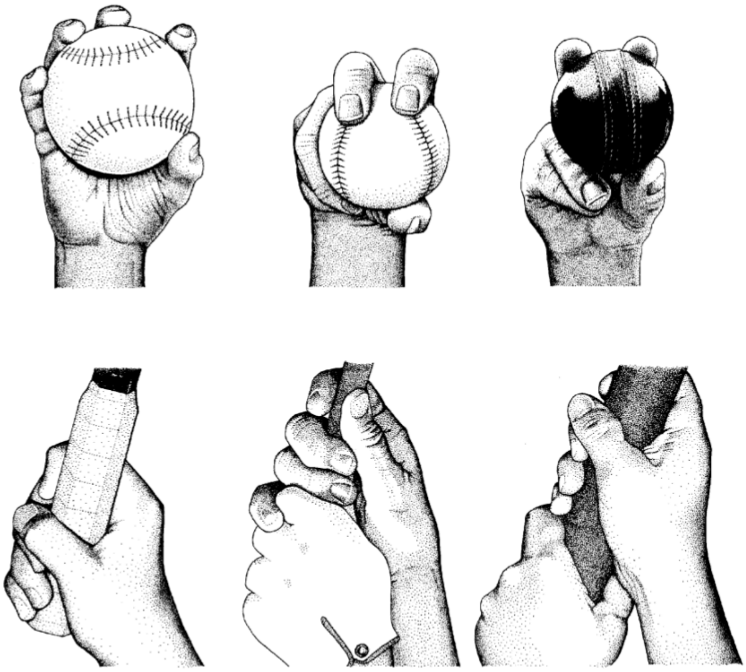
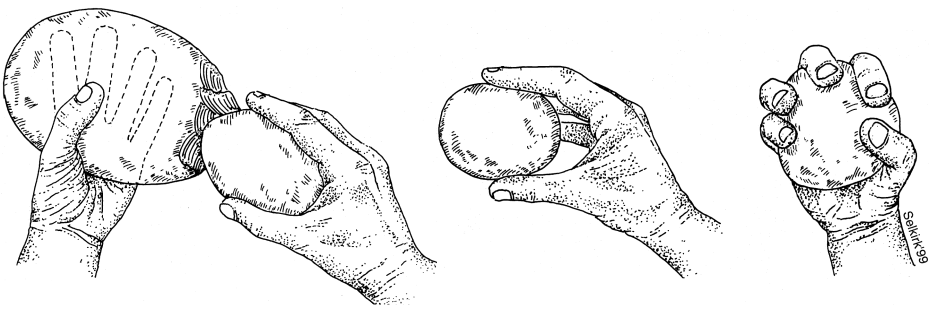


Figure 2.31 – Precision grips and power grips in sports. Above, a softball, a baseball and a cricket ball held in precision grips. Below, a tennis racket, a golf club and a cricket bat held in power grips.




(a) (b) (c) (d)

Figure 2.32 – The grasps in (a) and (b) are precision grips, although the object is quite large and touches the palm. Removing flakes from the stone would not be possible with the fingertip precision grip (c), which is not able to resist the impact. It would not be possible either with the plain power grip (d), since it exposes the fingers to crushing.

objects in-hand, that is to say to change the position and orientation of objects with respect to the palm or the wrist, while power grips are better employed in grasping without manipulation, to restrain firmly an object for instance (see figures 2.33, 2.34 and 2.35). Of course, precision and power "are not mutually exclusive concepts" (Napier 1956), but when they are both present in manual operations, Napier remarks that one of them is usually pre-eminent. This provides the ground for naming the grips after those two functions.

Figure 2.33 – Power grasping in a crowded subway

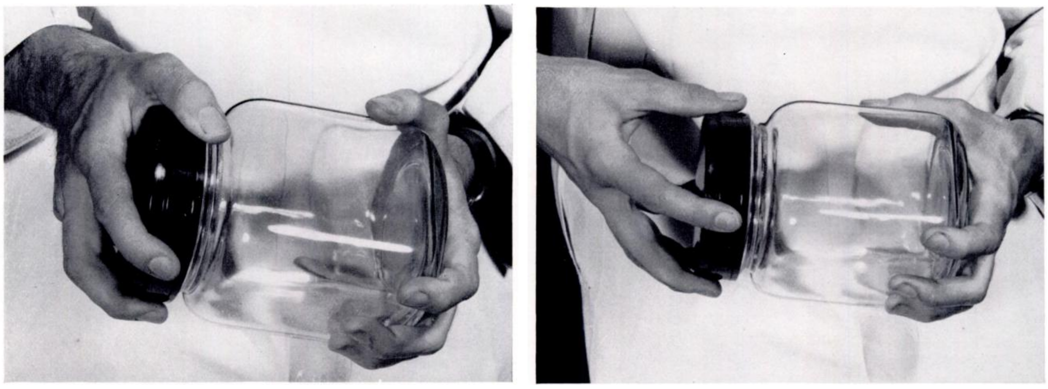


Figure 2.34 – Opening the lid of a jar. As the lid is started, the right hand is in a power grip posture to apply a large force and unblock the lid. As the lid becomes loose, the right hand assumes a precision grip posture to turn the lid open more easily and faster. Photographs given as examples by Napier (1956).

The functional analysis of these two classes of grasps enables Napier (1956) to conclude that "it is the nature of the intended activity that finally influences the pattern of the grip", rather than the shape of the object. This, he says, is one of the reasons to prefer using the function-related terms of "precision" and "power" rather than the previous attempts at classifying the prehensile activities of the


Figure 2.35 – Restraining versus manipulation: roughly speaking, power grips are better adapted to firm restraining and precision grips are better employed for fine manipulation. Between both, no clear border.

hand according to the shape of the object: those classifications had no functional and sometimes no anatomical basis. Schlesinger (1919), for instance, proposed a classification [13] into cylinder grip, spherical grip, tip grip, hook grip, palmar grip and lateral grip (figure 2.36), according to the form of the hand and the size of the object; Griffiths (1943) classified into cylinder grip, ball grip, ring grip, pincer grip and pliers grip. Such classifications are unsatisfactory in Napier's eye as they suggests that the grip is mainly dependent on the shape of the object, with cylinders having to be seized in a cylinder grip (similar to a power grip) and balls in a ball grip (similar to a precision grip). Actually, both balls and cylinders may be grasped by power and precision grips, depending on the nature of the task to be performed with the ball or the cylinder…

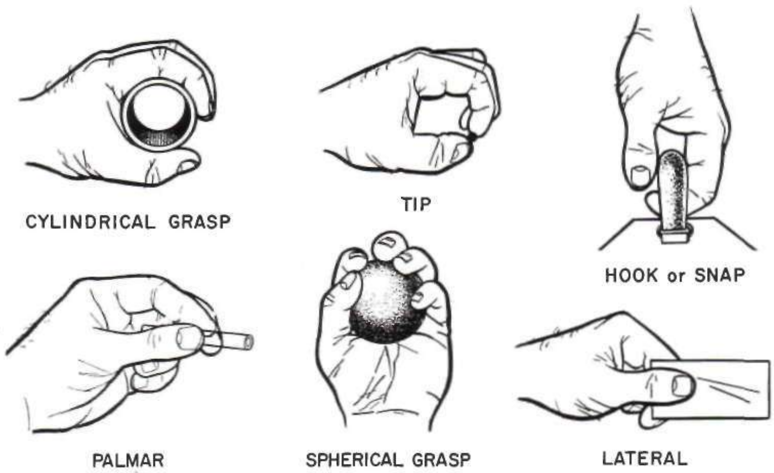



Figure 2.36 – An historical grasp classification, by Schlesinger (1919). Later taken up by C. Taylor and Schwarz (1955).

### Combined grips

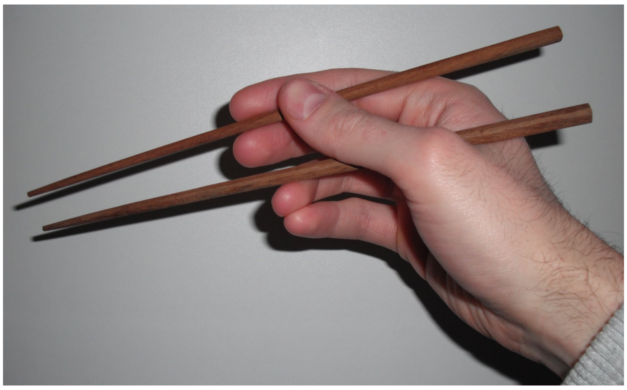
Napier (1956) also remarks that there are certain activities of the hand in which the power and the precision grips are combined at the same time. For instance, it is the case when two objects are small enough to be seized, one in a precision manner between the index and the thumb, and the other in a power grasp formed by the palm and the three other fingers (figure 2.37(a)). Another example occurs when tying a knot in a piece of string with the first two or three digits of the hands,

13. This was actually, if not the first classification of human grasps, at least one of the very firsts. World War I had lead to a dramatic increase in the number of limb amputees in Europe (Neumann 2010), and as a result medical research on prostheses was very active. Investigation on human prehension was part of this effort. The practical goal was to design better, more functional limb replacements.

while the other digits hold the string in a power way (figure 2.37(b)). Napier calls such situations "combined grips" or "composite grips", and notes that usually the precision element is dominant, with the last two or three fingers "utilised in a purely supplementary role". However, in certain tasks, the precision and power aspects of the combined grip may be equally essential to the success of the task (figure 2.37(c)).

(a) The example of composite grasp given by Napier (1956)

(b) Lacing a shoelace: the first digits of each hand are in a precision posture, while the extremities of the shoelace are kept clear from the knot by the other fingers arranged in a power posture.



(c) Holding chopsticks: one chopstick is moved by the precision grip formed by the thumb, index finger and middle finger; the other is held in place by the power grip made by the ring finger, little finger and the base of the thumb.

Figure 2.37 – Combined grips are the association of a precision grip and a power grip at the same time

Connolly and J. Elliott (1972/1976) also encounter combined grasps in an experimental survey on spontaneous tool using by children (the tool being a paintbrush). They describe them as "mixtures of the two basic hand configurations" that do not fit easily into one of the precision or power categories, since they exhibit characteristics of both. Actually, depending on the context, they may be interpreted as power or precision grasps. This observation further asserts that the concepts of precision and power grasps are really better defined by reference to the function of the grasp, i.e. to the demands of the task to be performed, rather than according to the anatomical configuration of the hand or shape of the object.

### The origin of the precision and power grips

As an end remark on the precision and power grips, let us note that biological anthropologist Richard Young (2003) underlines the role of early weapons in the morphological evolution of the human hand. Those weapons, he assumes, would have been rocks and wooden clubs thrown and swung at adversaries, in the early ages of our evolution. As a result, “the human hand should be adapted for throwing and clubbing”, and he explains that the precision and power grips identified by Napier are indeed, respectively, throwing and clubbing grips. The precision grip is indeed suited to grasping a stone and precisely controlling its release, a required condition for accurate throwing and hitting of the target. On the other hand the power grip is adapted to firmly holding a club and absorbing the reaction force of impact without letting the weapon go. Young supports his hypothesis through paleoanthropological evidence and extensive comparison of the chimpanzee hand and the human hand. His theory provides a possible evolutionary explanation for the existence of the two grip categories.

Section 2.3 will provide more insight about the origins of our hands and their importance in human evolution.

### 2.2.2 Grasp taxonomies

Starting with Napier’s general categories of power and precision grips, it is possible to subcategorize grasps successively over various criteria, for instance the size and shape of the object, the appearance of the grasp, the number of contacts between the hand and the object or the size of the contact areas. The subcategories obtained are subtypes of precision grips and subtypes of power grips, and the tree-like classification resulting from this approach is a grasp taxonomy.

Roboticits Mark Cutkosky and Paul Wright were the firsts to derive a grasp taxonomy from Napier’s general categories (Cutkosky and Wright 1986; Cutkosky 1989). They classified grasps into fifteen subtypes, illustrated on figure 2.38.

Because of its relatively high-level formulation, this taxonomy is easily understandable by humans, but rather unsuited to automated grasp recognition by robots. Yet this later point is of interest for practical applications such as machine learning by observation (e.g. Ikeuchi and Seuhiro 1994; Ekvall and Kragić 2005) or human-computer interaction, and more generally for reconstruction of human hand posture from vision-based tracking (Erol, Bebis, Nicolescu, Boyle, and Twombly 2007; Romero, Kjellström, and Kragić 2010). To alleviate this problem, Kang and Ikeuchi (1991, 1992) proposed another taxonomy, based on low-level criteria that a computer system can recognize in visual observations: the contact points between the object and the fingers (number, location). This model, which they called the “contact web”, resulted in the grasp taxonomy of figure 2.39. Although it might look as if the “power” and “precision” informations were lost, they are actually preserved: each of the grasp subtypes is either a power grip or a precision grip. Therefore, the “contact web” taxonomy is compatible with Napier’s functional categories, and more adapted than Cutkosky’s taxonomy to the problem of automated grasp recognition from observations (Kang and Ikeuchi 1993a,b).

When describing their “contact web” model, Kang and Ikeuchi (1991, 1992) make use of the concepts of “virtual fingers” and “opposition type”. These concepts are two abstract tools of grasp description and analysis, introduced in the 1980s. Virtual

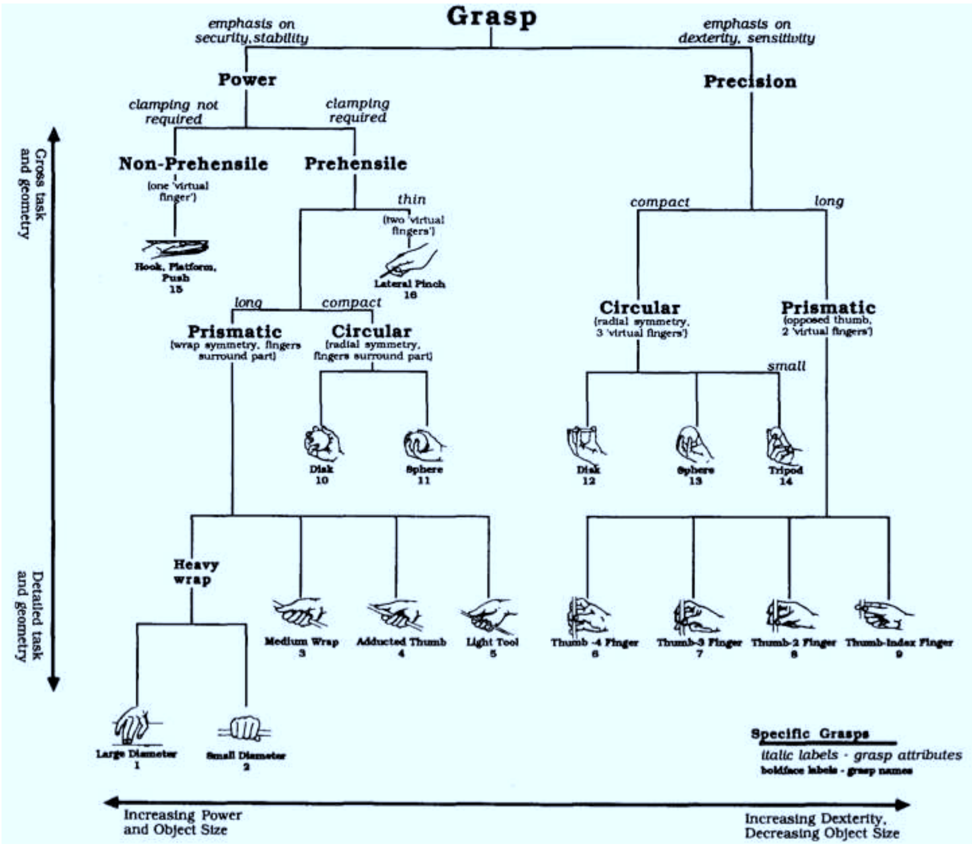



Figure 2.38 – The grasp taxonomy derived from the "power" and "precision" categories by Cutkosky and Wright (1986), Cutkosky (1989)

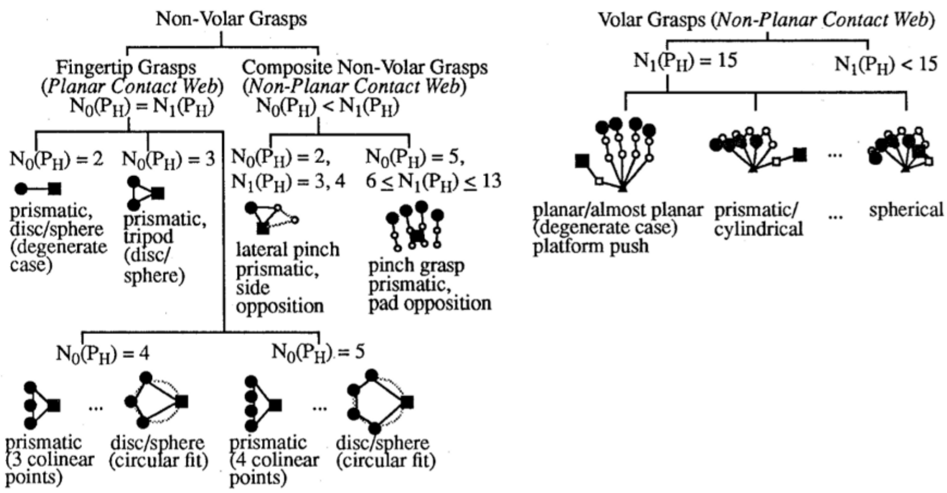



Figure 2.39 – The grasp taxonomy derived from the "contact web" of Kang and Ikeuchi (1991, 1992). The black square is the thumb, the black circles are the fingertips.

fingers, defined by Arbib, Iberall, and Lyons (1985), are groups of digits and/or the palm that act as a single functional unit in a given grasp. For instance, when picking up a small object with three fingers, the thumb can be “virtual finger 1” and the index and middle fingers can form “virtual finger 2”. In a cylindrical power grasp, the palm may act as “virtual finger 1”, the fingers as “virtual finger 2” and the thumb as “virtual finger 3”. Building on this concept of virtual fingers, Iberall, Bingham, and Arbib (1986), Iberall (1987), Iberall and MacKenzie (1988, 1990) argue that in most grasps, the object is held in opposition between two virtual fingers, and that three types of opposition between virtual fingers may be found: if one virtual finger is the palm, we have “palm opposition”, if not we have either “pad opposition” or “side opposition” depending on whether the pulps of the digits are used, or their sides (see figure 2.40). Consequently grasps get classified into three main groups, providing finally the basis for another grasp taxonomy, based on opposition patterns.

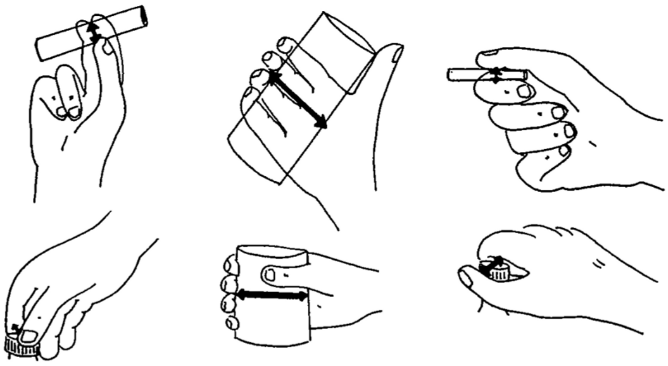


Figure 2.40 – Classifying grasps according to opposition types (Iberall, Bingham, and Arbib 1986). Left to right: pad opposition, palm opposition, side opposition.

To conclude this short and incomplete review of grasp classifications, the recent work of Feix, Pawlik, Schmiedmayer, Romero, and Kragić (2009a,b) must not be forgotten. In a laudable effort, they wrote the synthesis of the grasps classifications proposed so far, by analyzing 147 grasp descriptions found in a review of 17 publications and arranging them in a comprehensive taxonomy of 33 unique grasps, grouped into 17 grasp types. Their taxonomy is based on Napier’s distinction, the type of opposition, the virtual fingers involved, and the position of the thumb as an additional attribute (abducted or adducted). This work is a good entry point for further reading on the subject of grasp classification. The review on grasp taxonomies made by Iberall (1997), while older, is also interesting.

Future research directions in the study of human grasping include grounding classifications on experimental data and taking into account the whole grasp sequence to better characterize grasps (Ekvall and Kragić 2005; Feix, Romero, Kjellström, and Kragić 2010; Romero, Feix, Kjellström, and Kragić 2010). Current taxonomies are indeed based primarily on the intuition of their respective authors, and have not really been experimentally compared or evaluated with respect to how effectively they describe human grasping. Data-driven approaches from experimental tracking of subjects performing grasps should provide valuable insight in and understanding of our grasping actions. Also, current taxonomies are static, based solely on the final grasp pose: the pre-grasp approach phase is totally ignored, while it may convey useful information, starting with the grasp intention. There again, experimental recordings seem to be able to provide us with more understanding of the actions of our hands, and consequently benefit to prosthetic and robotic hand research.

## 2.3 The evolution of the human hand

"Man could not have attained his present dominant position in the world without the use of his hands", British naturalist Charles Darwin wrote in 1871 in *The Descent of Man* (volume 1, chapter 4), his second book on evolutionary theory after his 1859 work *On the Origin of Species*. He was of course not the first one to wonder about the particular place of humans in the world, and to try to explain it by what sets us apart from other animals: our hands and their capabilities, among other things.

To be fair however, the development of upright posture and permanent bipedalism on the hind limbs should be given more credit as a prime mover in hominid evolution than the realizations of the hands. After all, lemurs too have hands with opposable thumbs, and most primates too, and even some non-primates animals to a certain extent [14]. Still, their evolution is nowhere near the one of our species.

The early role of bipedalism is widely agreed upon among biological anthropologists, and there is clear "evidence that an early hominid behavior was bipedal gait, which would have freed the hands for greater use of tools" (Young 2003). Progressively relieved from weight-bearing, a fundamental function in arboreal and quadrupedal locomotion, the hands of our distant ancestors could slowly adapt to other usages. Eventually, as written by anthropologist Josef Biegert (1963/2007), "the attainment of the highest evolutionary perfection of the hand, i.e. its development in the hominids as an organ for culture, resulted from the total emancipation of the hand from use in locomotion through the development of upright posture".

This is not to say, of course, that the development of hands did not play a critical part in human evolution too; actually, it did. In the rest of this section about the evolution of the human hand, we will review on the whole the evolutionary relations between hands and brains (2.3.1), hands and tools (2.3.2), hands and language (2.3.3). It will appear that the evolution of those typically human characteristics are strongly related together, with the hands in a central role.

### 2.3.1 Hands and brains

The relation between our hands and our mind, two of our most distinctive features among other animals, has probably been in dispute from the very beginning of the history of ideas. Anaxagoras of Clazomenae for instance, a Greek presocratic philosopher, argued that their hands was the cause of the intelligence of humans. Aristotle, a more famous philosopher whose ideas lasted through the whole European Middle Ages, later refuted this opinion. As he put it in his work *On the Parts of Animals* (book 4, chapter 10): "Now it is the opinion of Anaxagoras that the possession of these hands is the cause of man being of all animals the most intelligent.

14. Tarsiers and marmosets are primates with non-opposable thumbs, and giant pandas and many polydactyl cats are non-primates with some degree of opposition in their forelimbs. Cat polydactyly is a mutation most commonly found in South West England and along the East Coast of the United States, especially Boston, Massachusetts. These cats have been extremely popular as ship's cats during the important sailing past of these two nations. Their extra toes and claws were believed to give them better balance during rough weather and improved skills as ratters and mousers (besides, as all cats, they were also thought to bring good luck when at sea).

But it is more rational to suppose that his endowment with hands is the consequence rather than the cause of his superior intelligence. For the hands are instruments or organs, and the invariable plan of nature in distributing the organs is to give each to such animal as can make use of it; nature acting in this matter as any prudent man would do. For it is a better plan to take a person who is already a flute-player and give him a flute, than to take one who possesses a flute and teach him the art of flute-playing".

The current general view among present-day biological anthropologists is that the evolution of the hand and the evolution of the brain were continually linked and strongly interrelated, especially through the use and later the elaboration of mankind's first tools. Neither of them was a first cause of the other: the evolution of the hand was more probably both one of the causes, and one of the effects, of the evolution of the brain. As stated by anthropologist Mary Marzke (1996/1999): "It is becoming clear now that changes in both hand structure and cortical control of its movements have been factors in the refinement of hominid dexterity". Connolly and J. Elliott (1972/1976) for instance, when reviewing the range of primate hand function, note that in all primate species, but especially in humans, "neuroanatomy has evolved to meet the demands of prehension", and that "the evolution of the hand was concomitant with the evolution of the brain, and as greater manual dexterity was achieved, additional neurological advances occured".

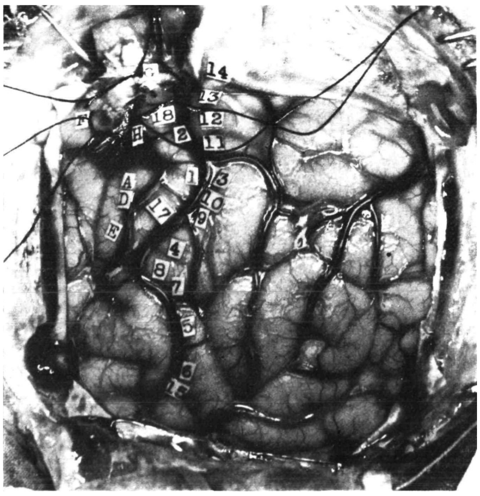
Details about the evolution of the human brain are difficult to be certain about, as evidence is difficult to obtain: cerebral structures do not fossilize and as a result "there are no brains to study except those of the living" (Holloway 1996/1999). Consequently and despite its questionable significance, overall size of the brain, preserved in the internal volume of fossil skulls, is the most available feature of once-living brains [15] and "the most reliable evidence of evolutionary change" (Holloway 1996/1999). Valuable knowledge is also drawn from the comparative study of nowadays human brains with those of other apes and monkeys: as neurophysiologists Randall Flanagan and Roland Johansson (2002) put it, "in addition to structural factors, a major contributor to differences in hand movement capacity among primates is the neural machinery underlying hand movement".

From these two sources of evidence, paleoanthropology and comparative studies, it has been understood that "the motor and tactile capacities of the primate hand are accompanied by a special enlargement and differentiation of the pre-central motor and post-central sensory regions of the cortex, along with their mutual interconnections" (Connolly and J. Elliott 1972/1976). M. Marzke (1996/1999) relates that in order to account for "the initial increase in area of the cortex related to the hand", neurophysiologist William Calvin (1983) proposes that "the rewards of rapid, one-handed throwing of small rocks may have been an important factor in selection for redundant timing circuits, increasing brain size". Faster, farther, more powerful throwing of stones at preys or attackers was indeed very probably a valuable adaptive advantage for archaic humans and proto-humans. This, among other factors, would have selected for encephalization.

Nowadays, as a result of this evolution, a large part of the human cortex is dedicated to grasping and manipulation. This is well known since the pioneering works of

15. "Cerebral asymmetries" are also sometimes reliably preserved, but "convolutional details of the brain's surface" are not, because the intervening tissues between the brain and the skull make it seldom for these details to be clearly expressed on the inside surface of the skull (Holloway 1996/1999).

Canadian neurosurgeon Wilder Penfield, who wrote down the first functional maps of the human brain, and discovered that hands, lips, and the face, despite their small size in the body, correspond to areas of the brain as large as the rest of the body. Starting in the late 1920s and for many years onwards, Penfield, helped by various fellow neurologists, conducted more than four hundred brain operations on patients suffering from severe epilepsy. The aim of these operations was to destroy nerve cells in the brain where the seizures originated. The operations began by electrical stimulations of the patient's brain using an electrode directly applied to its surface. The patient, under local anesthesia, was then to explain the effect of each probe to the surgeons. When operating in the sensorimotor cortex, the patient's responses could be such as "I feel a numbness in my finger", "My right thumb is tickling", "I felt as though I could not speak" or "My tongue seemed to be paralyzed" (figure 2.41); when operating in other areas of the brain, the patients could experiment visual phenomena, hearing of sounds, recalling memories, even out-of-body experiences (Penfield and Rasmussen 1950). In this way, the surgeons were able to identify precisely the abnormal tissue to remove and delineate the surrounding, healthy areas, which were not to be touched. Operation after operation, Penfield was able to create maps of the sensorimotor cortex, showing "the areas of motor and somatosensory cortex devoted to each part of the body, and their proportions relative to one another" (Costandi 2008). These maps were soon known worlwide as the "motor homonculus" and the "sensory homonculus", because of the drawing of a little man with disproportionate hands, lips, and face in the original publication (Penfield and Rasmussen 1950). The bigger the part of the homonculus, the larger the corresponding area in the cortex (figure 2.42).



**Right: primary somatosensory cortex**
(3) Numb feeling in hand and forearm up to just above the forearm. (10) Tingling feeling in the fifth or little finger. (9) Tingling in first three fingers. (4) Felt like a shook and numbness in all four fingers but not in the thumb. (8) Felt sensation of movement in the thumb; no evidence of movement could be seen. (7) Same as (8).

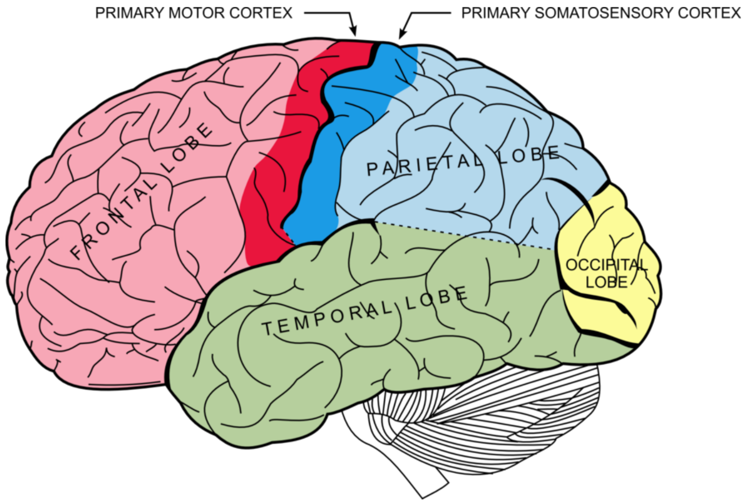
**Left: primary motor cortex**
(18) Slight twitching of arm and hand like a shock, and felt as if he wanted to move them. (A) Extreme flexion of wrist, elbow and hand. (D) Closure of hand and flexion of his wrist, like an attack. (17) Felt as if he were going to have an attack, flexion of arms and forearms, extension of wrist. (E) Slight closure of hand.

Figure 2.41 – Cerebral cortex of a boy undergoing brain surgery by Wilder Penfield (Penfield and Boldrey 1937). The photograph shows a part of the boy's left hemisphere, whose epilepsy was in the right side of the body. The tickets relative to the hand are described in the text.

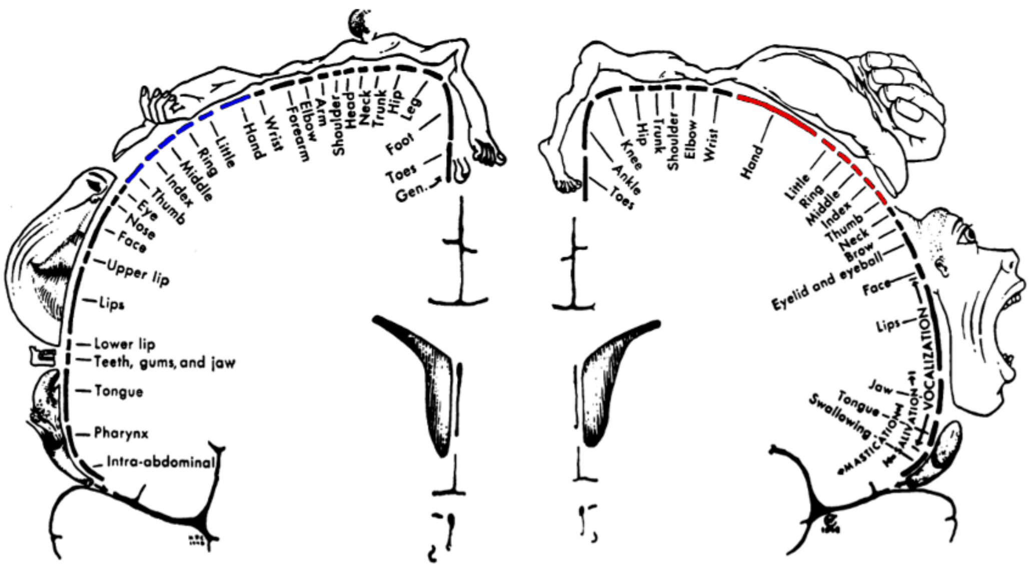
### 2.3.2 Hands and tools

The reciprocal co-evolution of human hands and brains is also of course closely bonded with tool behavior, that is to say tool use and tool making.

"Ever since Darwin", state Mary Marzke and Robert Marzke (2000), "there has been a discussion of whether the evolution of tools played an important role in the




(a) The main parts of the sensorimotor cortex, mapped below. The left hemisphere, pictured here, is relative to the right side of the body. The same regions exist in the right hemisphere and are relative to the left side of the body.




(b) Left: map of the primary somatosensory cortex and sensory homonculus. Right: map of the primary motor cortex and motor homonculus. Original drawing (Penfield and Rasmussen 1950).

Figure 2.42 – Sensory homonculus and motor homonculus

evolution of human morphology". This debate became especially active following the identification, at the beginning of the 1960s, of an early species of our human genus, *Homo habilis*[16] (Leakey, Tobias, and Napier 1964). Indeed, the first discovered fossils of this species, found in 1960 at Olduvai Gorge in Tanzania, included, "at the same level as primitive stone tools", a remarkable set of hand bones which had "an ape-like pattern" but also a thumb "quite similar to the modern human thumb, in its range of motion and in its ability to flex strongly at the tip" (M. Marzke and R. Marzke 2000). It seemed reasonable to suppose that the archaic human hand was the maker of the associated tools, hence the name given to the newly discovered species.

The debate about the role of tools in the evolution of the human hand "has persisted to the present day" according to Mary Marzke and Robert Marzke (2000), with a general consensus "hampered by disagreements about how to translate experimental data from living species into models for predicting the performance of fossil hands". But despite these unavoidable disagreements, the general view among biological anthropologists acknowledges tool behavior, in particular stone tool making, in the anatomical modifications of the hand during human evolution (Young 2003, see page 171 for examples of studies that make this point).

However, the realisation of stone implements alone does not explain entirely the changes in anatomy and the increase in dexterity over the course of hand evolution. Young (2003) points out that the hand of *Australopithecus afarensis*[17] "shows many features of the modern human hand, yet antedates the earliest identified stone tools", and that by the time these tools first appear, "the hominid hand had already closely approached its current state". Therefore he proposes the theory that the first tools ever used, at the origin of the hominid lineage, were "hand-held weapons that were hurled or swung as bludgeons at adversaries during disputes, providing the aggressors with advantages that in various ways promoted reproductive success". To support his theory, he details how performance at throwing stones and clubbing with wooden sticks could provide reproductive advantages, reviews the anatomical characteristics of the modern human hand and wrist that indicate adaptation to throwing and clubbing (as opposed to the chimpanzee hand "taken as a model for the hand of the hominid ancestor"), and also provides paleoanthropological evidence. His conclusion is that natural selection for improved throwing and clubbing, prolonged over millions of years, would have increasingly adapted the hand "for grasping spheroids in a manner that allows precise control of release and for gripping clubhandles with strength sufficient to withstand a violent impact". This would be how the precision and power grips (Napier 1956), respectively, would have emerged. Eventually, at the end of this long anatomical evolution, the hands would have been pre-adapted for the fabrication of the first hand-made tools.

The fact that most paleoanthropological studies about tools focus on the interrelation between hands and tools must not hide the fact that they also indirectly pertain to the interrelation between brains and tools, for as we told previously, the evolution of hands and brains are closely intertwined. Indeed, as archaic humans developed more elaborate tools over the course of human evolution, and as their hands became

16. *Homo* is the genus that comprises our species *Homo sapiens* (anatomically modern humans) and other closely related species, all extinct, among which the most well-known are probably *Homo habilis*, *Homo ergaster*, *Homo erectus*, *Homo heidelbergensis* and *Homo neanderthalensis*.

17. Like *Homo*, *Australopithecus* is a genus of hominids. It includes the famous species *Australopithecus afarensis* and *Australopithecus africanus*, a specimen of the former, discovered in 1974 in the Afar Depression in Ethiopia, is world-renowned as "Lucy". All the species of this genus are extinct.

progressively more adapted to tool making, their brains also became more elaborate for tool use and production. In a positive correlation, the gradual evolution in size and complexity of their brains led in turn to more sophisticated and more efficient techniques of tool making. It also led, very probably, to a greater ability to learn from others by replicating their techniques and to learn to others by passing knowledge down from one generation to the next, a social behavior that greatly shortens the learning time required for tool realization, and accelerates the pace of innovation.

### 2.3.3 Hands and language

The existence of links between the evolution of hands, the evolution of brains and the development of tools is of course hardly surprising. More unexpectedly, there may also be a relation between the evolution of hands and the emergence of human spoken language.

Of course, the debate about the origins and evolution of language is not new. It became especially lively after the publication of Darwin's *On the Origin of Species* in 1859, but at that time, it was greatly disengaged from the requirements of scientific discourse, and appeared more like unfounded theorizing with a lot of conjecturing and speculating (Christiansen and Kirby 2003). It was not until the last decade of the twentieth century that research on language origins and evolution finally acquired solid theoretical grounds from brain sciences and cognitive sciences. There was then a notable increase in serious, scientific activity, contrasting with the "armchair speculation that has been all too characteristic of debate in this area in the past" (Dunbar 1998).

Christiansen and Kirby (2003) list the current points of consensus and the remaining controversies among researchers in language origins and evolution. It is commonly agreed, for instance, that the ability to use symbols was a necessary pre-adaptation for language, symbol usage meaning "a capacity for linking sounds or gestures arbitrarily to specific concepts". On the other hand, the precise role of those sounds or gestures in the origin of language is very controversial, and it is not known whether language "evolved from manual gestures, gradually incorporating vocal elements" (Corballis 2003b) or originated exclusively in the vocal domain, from primate vocal calls.

Corballis (e.g. 1992, 2003a,b, 2009), Kimura (e.g. 1993), Armstrong, Stokoe, and Wilcox (e.g. 1995) are figures of the theory according to which gesture-based communication predated oral communication and played a major part in the emergence of human language. As we have just explained, this theory is by no means a consensus, and it has fierce detractors (see for instance the commentaries on Corballis 2003b). Nevertheless it sheds interesting light on the relations between hands, brains and language.

Indeed, Corballis (2003a,b) explains that a tight interrelation between manual gestures and spoken language is visible in the comparative study of human and monkey brains. In monkeys, a region of the cortex was found in 1992 to contain "mirror neurons" related to active motor control of the hands (Pellegrino, Fadiga, Fogassi, Gallese, and Rizzolatti 1992), that is to say neurons that activate "for both the production of manual reaching movements and the perception of the same movements performed by others" (Corballis 2003b). Further research by Fadiga, Fogassi, Pavesi, and Rizzolatti (1995, see also their subsequent research) suggested that a similar, unexpected mirror system for gesture recognition "also exists in humans and includes Broca's area"

(Rizzolatti and Arbib 1998; Arbib 2002), a left-hemispheric region of the human brain related to the motor control of speech [18]. The monkey mirror system, however, appears to have "nothing to do with vocal control" (Corballis 2003b) and to be limited to manual motion control and recognition.

If we take present-day monkeys for an approximation of our common ancestors, these findings suggest that Broca's area "has been involved in manual action well before it was involved in vocalization" (Corballis 2003b), a conclusion that supports the hypothesis of a manual origin to language. This theory is further supported by fossil "evidence that Broca's area is enlarged in *Homo habilis*, suggesting that a link between gesture and vocalization may go back at least two million years".

As an end remark, let us note that the prolonged association of vocalization, controlled from the left side of the brain in humans, with manual gesture, is suggested by Corballis (2003b) to be a reason why the motor control of manual movements is far more predominantly left-hemispheric in humans than in monkeys. This long correlation between language and hand motion, he concludes, would have "left us a legacy of right-handedness".

## 2.4 Human hands as a model and aim for robot hands

The previous three sections have covered some aspects of human hand anatomy (2.1), function (2.2), and evolution (2.3), at an entry level. While far from comprehensive (they are the matter of numerous specialized works, and still on-going research topics), these introductory materials are hopefully sufficient to realize the impressive complexity of the human hand, the significance of its link with the brains, and the sophistication of the movements and actions that they achieve. Consequently, setting the human hand as a model and aim for a robot hand is setting but an easy target.

In this section, in light of the preceding presentation of human hands, we explain on the whole what are the main aspects of humanoid robot hands that need to be improved, if these hands are one day to measure up to the human models.

### 2.4.1 The complexity of design, actuation and sensing

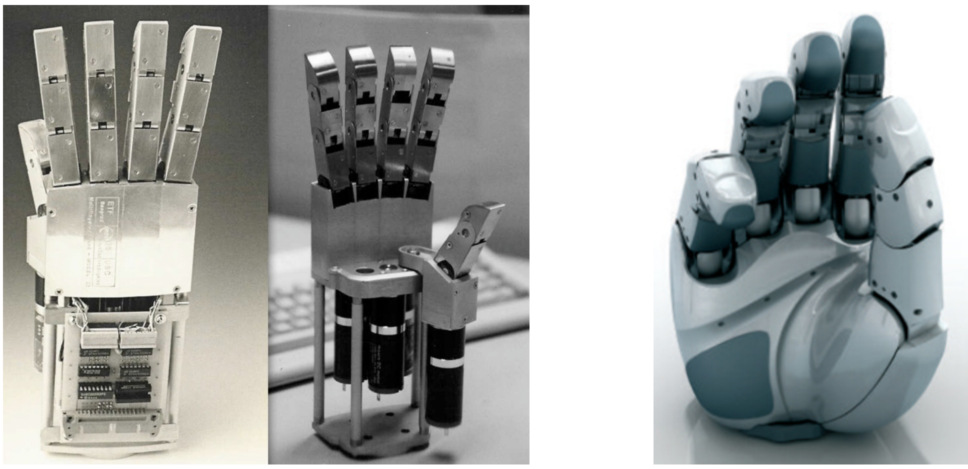
Were it only the anatomy, it would already be its share of technological hurdles to try and realize a perfect robotic equivalent of the human hand. The particular arrangement of the bones and their unique articulation, especially at the thumb carpometacarpal level, the large number of muscles and their actioning synergies, the complex routing of the tendons to their insertions on the bones they move (possibly several at a time), the elasticity and the sensitivity of the covering skin, all of it, and the rest, participate in the human hand being currently, on the whole, beyond the possibility of an exact robotic duplicate. Therefore, since complete reproduction as a robotic device is presently out of reach, a more realistic occupation is the elaboration of robot hands that emulate, as well as possible, as large as possible a subset of the abilities of the human hand, without necessarily translating literally its composition, actuating or sensing into perfect artificial equivalents. In other words, bio-inspiration

18. This area is named after Paul Broca, the French physician who identified this region in 1861 from the autopsies of two speech-impaired patients. Broca's area is one of the two main cerebral regions involved in language processing, the other being Wernicke's area (named after its identifier Carl Wernicke, a Prussian physician). Broca's area is responsible for the articulation of words while Wernicke's area is responsible for their comprehension.

may certainly be present, but in the shape and functional abilities rather than in the mechanical construction.

### Hand design and kinematic structure

In this respect, robotics research has already progressed to a fairly advanced level, with the realization of some stunning humanoid robot hands, at least in terms of kinematics properties and aesthetic appearance. Both these aspects are now much closer to those of a human hand than they were in the first robot hands of the 1970s and 1980s. Present-day humanoid robot hands no longer have that heavy, bulky, square look of their ancestors (see figure 2.43). Most of them use four or five human-like digits arranged in a human-like fashion, with an opposing thumb, and an important number of controlled degrees of freedom. Improvements have been made in the shape, the weight, the outer appearance, and although all design decisions, most importantly the number of degrees of freedom, the number of actuated degrees of freedom, and the arrangement of the digits, are ultimately made "depending on which is the field of research of the hand" (Alba, Armada, and Ponticelli 2005), roboticists Luigi Biagiotti, Fabrizio Lotti, Claudio Melchiorri, and Gabriele Vassura note in a technical review on the state of the art in anthropomorphic robot end effectors (2002) that the human hand "has become a model for the majority of the researchers in the field of robotic manipulation, even if the projects, in which they are involved, do not explicitely require anthropomorphism as design specification". They go on with the remark that "the kinematic structure of robotic hands becomes more and more close to the human model, and the dissimilarity with our hand mainly concern the size and the skin".



(a) The Belgrade/USC Hand, developed in the 1980s at the University of Belgrade in Yugoslavia (now Serbia) and the University of Southern California in Los Angeles, California. A milestone in the history of robot hands.

(b) The DLR/HIT Hand II, developed in the 2000s at the Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center), Oberpfaffenhofen, Germany and the Harbin Institute of Technology, Harbin, China.

Figure 2.43 – Twenty years apart: two examples of robot hands

### Finger actuation

As regards the size of current robotic hands, it is mainly the fault of the actuators, which have to be a certain size if they are to output a certain power. In this respect, Melchiorri and M. Kaneko (2008) recognize that when actuators are placed in the fingers, close to the joints they drive, “the size of the finger is imposed by the dimension of the actuators, and for technological reasons it is quite difficult to obtain both an anthropomorphic size and the same grasp strength as the human hand. Furthermore, the motors occupy a large space inside the finger structure, making it difficult to host other elements, like sensors or compliant skin layers”.

Miniaturization of actuators without loss of performance is thus needed. In this respect, if progress is still made regarding conventional actuation techniques such as electric motors and pneumatic or hydraulic artificial muscles, newer actuators based on shape memory alloys or electroactive polymers show much promise: they have a high power-to-weight ratio, and besides, operate silently. These next-generation actuators are being actively researched (e.g. Selden, K. J. Cho, and Asada 2006; Vertechy, Babič, Berselli, Parenti-Castelli, Lenarčič, and Vassura 2009) and are now implemented in some prototype robot hands (K. J. Cho, Rosmarin, and Asada 2006, 2007; K. Yang and Gu 2002, 2007, 2008; Maeno and Hino 2006; K. J. Kim and Tadokoro 2007; Chuc, Vuong, D. S. Kim, Koo, H. R. Choi, Y. K. Lee, and Nam 2009), as well as in some prototype prosthetic hands (DeLaurentis and Mavroidis 2002; O’Toole and McGrath 2007; Bundhoo, Haslam, Birch, and E. Park 2008; Andrianesis, Koveos, Nikolakopoulos, and Tzes 2010).

In the meantime, to achieve human-like size and human-like force at the same time, a common workaround is to place the actuators in the palm and forearm, far from the joints they drive, just like it is the case in our anatomy (see section 2.1.2 on muscles). That way, powerful actuators may be used, analogous to our powerful extrinsic muscles, that are too big to be placed close to the fingers (the force of a muscle is function of the thickness of its muscular bundle). Motion and power must then be transmitted from the actuators to the joints by some kind of transmission chain. Most commonly, it consists of cables that get called “tendons”, after their biological counterpart (see figure 2.44); sometimes gears and screws may be used with or without tendons (Alba, Armada, and Ponticelli 2005). But if this design approach solves the problem of size, it also introduces coupling issues, control difficulties, tendon routing problems and additional wear: all sorts of drawbacks that are not present when actuators are placed closer to their joints.

### Sensing capabilities

Another main disparity between human hands and robot hands concerns the skin (Biagiotti, Lotti, Melchiorri, and Vassura 2002). This is not so much about the cosmetic covering of the articulated mechanism: such coverings have already improved significantly and are now quite advanced. Actually, numerous types of cosmetic gloves for articulated prosthetic hands are commercially available, and the most advanced of them, custom-made high-definition silicone covers, are nearly impossible to tell apart from real skin on visual observation only [19] (W. Hanson 2001; Bowers 2002). The main issue about skin concerns the tactile sensitivity of current robot hands (be it for use on a robot or as a prosthesis). This artificial sensitivity comes nowhere near the sensitivity of human skin.

19. Unfortunately, they are also difficult and time-consuming to manufacture, and are made on a one-of-a-kind basis, therefore they are very expensive: from above a thousand dollars to several thousand dollars, compared to a few hundred dollars for more common, off-the-shelf PVC gloves.

Figure 2.44 – The epitome of tendon-driven robot hands: the Shadow Dextrous Hand, manufactured by the Shadow Robot Company, London, United Kingdom. The joints are driven by tendons actuated by forty pneumatic artificial muscles placed in the forearm.

Tactile sensing is critical to our everyday manipulations. We can see it for ourselves, as Okamura, Smaby, and Cutkosky (2000) point out, when our fingers are cold and numb: “simple tasks like buttoning a jacket become difficult”. The problem is “not with the muscles (which are mainly in the forearm, and comparatively warm), but with the cutaneous sensors which have become anesthetized”. Various experiments involving finger anesthesia have actually been conducted by physiologists to quantify the consequences of the loss of cutaneous sensation (e.g. Augurelle, A. Smith, Lejeune, and Thonnard 2003; Monzée, Lamarre, and A. Smith 2003). These studies are of interest because when the central nervous system is deprived of cutaneous feedback, it must achieve the manipulation tasks by relying solely on the knowledge gained from prior experience: what are called the “internal models”, that is to say patterns of neural activity, learned from experience, that simulate and anticipate the dynamics behavior of our body and the world, i.e. in our case, those of the hand and the hand-held object (Flanagan and Wing 1997; Jordan and Wolpert 1999; Kawato 1999; McIntyre, Zago, Berthoz, and Lacquaniti 2001). Blocking cutaneous sensation enables therefore to gain insight into how dependent on feedback and feedforward human manipulation is. For instance, Augurelle, A. Smith, Lejeune, and Thonnard (2003) found out that anesthesia of the index and thumb made the subjects of their experiment increase grip force significantly to compensate for feedback absence, but nevertheless the object “was dropped on 36% of the trials, and a significant slip occured on a further 12%”: even though the internal model of the hand-held object make manipulation possible, the absence of cutaneous feedback greatly hampers the security of the grip.

To achieve tactile perception, our hands make use of a rich sensory innervation in the palmar skin. In particular, they are endowed with four types of mechanoreceptors which are very specialized and extremely efficient (see section 2.1.5 for their functions and characteristics). In comparison, available sensor technology for robot hands seems pretty primitive: as Biagiotti, Lotti, Melchiorri, and Vassura (2002) put it, "if the sensing system of the human hand is the desired target, unfortunately current technologies are still far from their biological models". Improvements must be made in sensor technology in order for robot hands to have richer information on the grasped object, about the location of the contacts, their areas, the properties of the surface at the contacts (friction, compliance [20], texture, moistness, temperature), the contact forces, the shape of the object (edges, corners, curvatures: the role of Merkel disks in the human skin), the slip condition and potential disturbances (the role of Meissner corpuscles in the human skin), and the list goes on. Basically, the lack of richer, more comprehensive, more varied tactile feedback for robot hands makes them comparable to human hands with anesthetized digits. It impedes control of grasping and manipulation, and also hinders the creation or improvement of hand-held object models by the robot's artificial intelligence.

In this respect, Kemp, Edsinger, and Torres-Jara (2007) regret that "current [force] sensors rarely provide directional information and tend to perform poorly when the incident angle of contact deviates significantly from the direction that is normal to the sensing surface". This, and "a lack of sensitivity and dynamic range" make "many traditional tactile sensing technologies [...] not fit to the requirements of robot manipulation in human environments". Melchiorri and M. Kaneko (2008) remark that drawbacks common to all extrinsic tactile sensors (see further) are "the size of these sensors, which are usually quite large in comparison with the available space, and the necessity of a large number of electrical connections". Indeed, each tactile element of these sensors requires electrical wires for signal, and the sensor as a whole also requires wires for power. If we equate a tactile element with a biological cutaneous mechanoreceptor, we can liken these wires to single nerve fibers: however thin the wires are nowadays, they are still much thicker than their biological counterparts. Other common current limitations of sensor technology are sensitivity to electromagnetic noise, non-linear phenomena (hysteresis), poor resolution, delicacy and poor long-time stability, difficulties in manufacturing and cost (Okamura, Smaby, and Cutkosky 2000; Biagiotti, Lotti, Melchiorri, and Vassura 2002; Tegin and Wikander 2004, 2005). These drawbacks are found in almost all sensors, at various levels. However, they do not prevent clever ingeneering, good choice of sensors and advanced sensor data analysis to result in robot hands with relatively good sensing abilities, or at least good enough for the research the hand is used for. Besides, scientific "advances in materials, microelectromechanical systems (MEMS) and semiconductor technology" make it possible for researchers to develop better and more efficient tactile sensors.

A detailed review of robot hand sensors, with their respective functioning, assets and drawbacks, is out of the scope of this section, however fascinating it would be. It may be found in appropriate references. The above-cited works are a good place to look for such information; articles by Howe (1994), Saad, Bonen, K. Smith, and Benhabib (1999), Upasani, Kapoor, and Tesar (1999), and C. Choi, Shin, S. Kwon, W. Park, and J. Kim (2008) are also of interest. In summary, tactile sensors for robot hands may be classified into three types (Tegin and Wikander 2004, 2005): intrinsic sensors, extrinsic sensors, and compliant sensors.

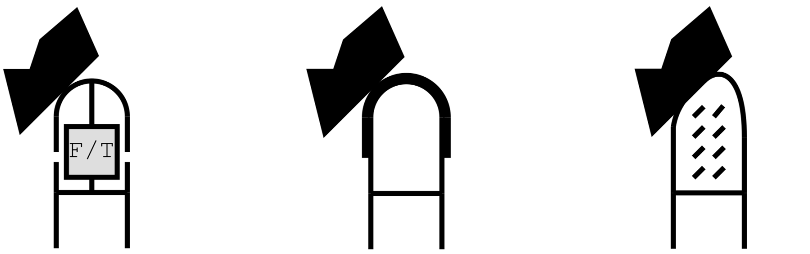
**Intrinsic sensors** measure interaction forces from within the inside of the hand, where they are placed. The typical intrinsic sensor is a small force/torque sensor

20. Compliance is the inverse of stiffness.

mounted inside the fingertip (figure 2.45(a)). It uses several strain gauges, miniature deformable metallic circuits whose electric resistance changes according to local deformation. From these changes it is possible to deduce the force acting on the sensor, which is also the contact force acting on the fingertip. It is even possible to deduce the position of the contact point on the surface of the fingertip, except when there are several contact points (it is also not possible to find out the shape and area of the contact surfaces).

**Extrinsic sensors** measure interaction forces directly at the surface of the hand and digits, where they are placed (figure 2.45(b)). Usually, they consist of a matrix of small sensing elements, called tactile elements (taxels). They are very diverse in the physical principles they use to measure the contact forces, but usually it involves some kind of measurable change in the electrical, magnetical or optical properties of the surface of the sensor when it is deformed by the contact forces. In that way, the overall sensor is not unlike the touchpad of a laptop computer. It provides a map of the forces acting on it, sampled over the tactile elements. From this map it is possible to deduce the position and shape of the contacts, local mechanical properties (e.g. friction coefficient) and motion of the contacts (e.g. slip).

**Compliant sensors** may be used when the fingertips are made from soft, deformable material (figure 2.45(c)). Such sensors are less common than intrinsic and extrinsic sensors. The deformations of the compliant material must be recorded in some way and analyzed to derive information about the cause of the deformation: position of the contacts, force intensity, local shape of the object, and so on. For instance, Y. Ito, Y. W. Kim, and Obinata (2009) present a transparent fingertip membrane marked with a grid pattern: an optical sensor placed inside the fingertip records the deformation of the grid, from which the authors deduce the slip condition of the contact and an estimation of the friction coefficient (figure 2.46).




(a) Intrinsic sensor (b) Extrinsic sensor (c) Compliant sensor

Figure 2.45 – Types of tactile sensors (from Tegin and Wikander 2004)

Tactile sensors are exteroceptive: they provide information related to the environment of the robot (in that case, the object). In addition to these sensors, robot hands are also built with proprioceptive sensors, which measure data related to the state of the device itself (the robot hand). The most common are joint position/velocity sensors, often Hall-effect transducers or potentiometers, placed in the actuated joints or on the actuator itself, or both. They are seldom absent since joint position/velocity measures are always necessary to robot hand control. If the hand features a tendon-based transmission system, tendon tension sensors are also employed: most commonly, they consist of strain gauges placed at flexible pulleys along the course of the tendon (Melchiorri and M. Kaneko 2008). The biological equivalent of those proprioceptive

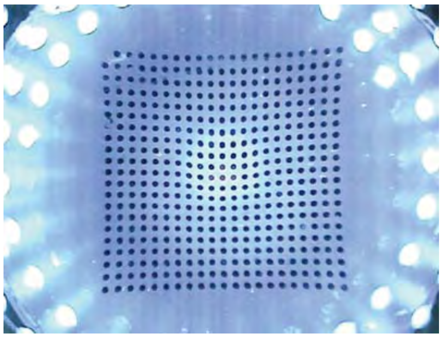


Figure 2.46 – The compliant sensor by Y. Ito, Y. W. Kim, and Obinata (2009). View from inside the fingertip.

sensors are, of course, the proprioceptors found in the muscles, tendons, joint capsules and at the surface of the bones.

### 2.4.2 The importance of control

In any case, all the hardware issues about design, actuation and sensing are only half of the problem, and still, the most advanced half. The other half is the control of this hardware.

Indeed, whatever its degree of sophistication or its likeliness to a human hand, the finest of all robot hands remains nothing more than an useless mechanism without a proper, adequate control, in the very same manner that our hands are nothing without their control by our brains. As pointed out by neurophysiologists Randall Flanagan and Roland Johansson (2002), "the highly versatile functions of the human hand depend on both its anatomical structure and the neural machinery that supports the hand".

In this connection, injuries or illnesses of this "neural machinery" are possible causes of impairment or disability of the hand, but causes of another nature than those affecting the anatomical integrity of the hand (such as accidental amputation of a hand or digits, degenerative bone or joint diseases such as osteoporosis or rheumatoid arthritis, and many more). The unlucky ones to whom the misfortune of hand-relative neural damage happens find theirselves paradoxically fitted with functional hands from an anatomical point of view, that they progressively or suddenly cannot use any more because of motor and sensory loss. Trivial-looking tasks of daily routine become ordeals: brushing their teeth, shaving, buttoning up their clothes, cutting up their food, and so on. Such afflictions may be of course injuries or illnesses of the central nervous system, in the regions related to the hands, but they may also concern the nerves. Figures 2.25 and 2.26 in section 2.1.3 on nerve anatomy give three examples of such nerve conditions.

This importance of control has not escaped the minds of roboticists. Biagiotti, Lotti, Melchiorri, and Vassura (2002) make the distinction between the "potential dexterity" of a humanoid robot hand, resulting from its mechanical structure and sensory equipment, and its "real dexterity", the product of its control algorithms and task planning strategies. They remark that "because of its control system, the human hand can fully exploit its complex structure; the same does not happen for robot hands: [...] their actual dexterity is considerably lower than the dexterity given by their structure and paradoxically some simple devices with suitable control strategies may be more dextrous than a complex robot hand". In other words, there is room for improvement on the control side of robot hands to fully exploit the complexity of present humanoid robot hands, some of them being potentially very dextrous. Advances in this area will help catching up with the hardware and realize the expected applications of robot hands.

However this is not exactly an easy task: if robot hand hardware has the human hand anatomy as a model, then it is coherent that robot hand control takes the human brain as a model. Obviously not the easiest organ to imitate, if we recall that the current state of brain control of our hands took millions of year of evolution to develop (section 2.3.1 on that matter). Actually, the complexity of this biological control is examplified by the fact that it requires several years of training to master. On this subject, Connolly and J. Elliott (1972/1976), in order to investigate the development of hand usage in children, conducted an experimental survey in two nursery schools about spontaneous tool usage by children aged three to five (the tool was a paintbrush). On ground of the analysis of their experimental data, they concluded that "in several important respects the use of the hand is not fully developed in children within this age range", and that "while the sixty week old infant may be able to grasp an object in an essentially adult manner, the development of hand function is by no means complete even by the fourth year". According to neurophysiologists Randall Flanagan and Roland Johansson (2002), this development is eventually complete at eight: "fully mature patterns of grasping, lifting, and holding objects are not observed until about eight years of age; during this period, there is gradual improvement in grasping behavior as well as qualitative improvements in the capacity to produce independent finger movements".

Nevertheless, whatever the difficulty to emulate the brains' control of the hands, it is a necessary work to aim for if we want one day truly dextrous humanoid robot hands, for it is finally in the intelligence of the control that lies most of the dexterity of a hand, be it robot or human. As a conclusion on this matter, the end of John Napier's first publication on the power and precision grips (1956) is a must-read: "The human hand is little better endowed, in a purely material sense, than that of any generalised primate in whom the thumb is present and specialised. In this connection Wood Jones (1941) wrote: "We shall look in vain if we seek for movements that man can do and a monkey cannot, but we shall find much if we seek for purposive actions that man can do and a monkey cannot". The heart of the matter lies in the term "purposive actions", for it is in the elaboration of the central nervous system and not in the specialisation of the hand that we find the basis of human skill".

In face of so much difficulty and work ahead to realize humanoid robot hands, and while knowing in advance that our impatience at equaling the human hand will be disappointed, we could actually doubt and wonder if it is worth the effort. To shed some light on this issue, the next chapter will explain why humanoid robot hands are desirable, and what for.

3

# About humanoid robot hands

## Contents



In the previous chapter, we have discussed the human hand from the point of view of its anatomy (2.1), its functional abilities (2.2) and its evolutionary history (2.3). We have also reviewed in which aspects it stands way ahead of the robotic attempts to emulate it (2.4): the robotics community reckons that actuator size and sensing abilities need improvements, but more importantly, that control of the hardware is the main difficulty. On this particular point, humanoid robot hands simply do not stand up to their brain-controlled biological models.

This chapter deals more extensively with robot hands. It starts in section 3.1 by explaining why they are desirable, and what for; that is to say, what are the reasons that justify anthropomorphism for robot end effectors. Then, sections 3.2 and 3.3 provide a wide state of the art of past, current and future artificial hands, divided somewhat arbitrarily between the hands meant for prosthetic applications and those meant for robotic applications (they tend to have more and more things in common and less and less differences).

## 3.1 The case for humanoid robot hands

In the collective imagination, the very image of a robot is a humanoid robot, even though such robots are perfectly known to be much unlike the present-day reality of robotics, made of industrial robots, army drones and automated vacuum cleaners. Still, the humanoid vision of robotics remains pregnant, and sets humanoids as the ultimate goal of roboticists. And a humanoid robot is definitively going to need humanoid hands.

For this reason, we start this section by providing a short historical survey of this expectation of humanoid robots so characteristic of humankind: a craving for our robotic selfs that could almost explain by itself all research on humanoid robots, hands included (3.1.1). Then we give more rational reasons for humanoid hands, by comparing them to traditional grippers, in the main application fields of robotics: industrial robotics (3.1.2) and service robotics (3.1.3). This comparative study enables us to understand how and when humanoid hands for robots are useful and relevant.

### 3.1.1 Humanoid hands and humanoid robots

Our bias toward humanoid robots is exemplified by a history of humanoids much older than robotics itself. Artificial humans may be traced back to myths and legends. In greco-roman mythology for instance, they are often animated creations of gods and goddesses. Homer tells in the *Iliad* that the god of metalwork Hephaistos created golden handmaids who worked for him, and were like real young women, with sense, reason, voice and strength [1] (*Iliad*, book 18, verse 419). Hephaistos is also said to have made Talos, a giant of bronze given by Zeus to Europa to protect her in Crete: Talos would circle the island's shores three times a day and throw rocks at any approaching ship. In the legends of the Phoenician prince Kadmos and of the Greek hero Jason, fully armed ferocious warriors sprang from dragon's teeth sown into the ground. As for the Cypriot sculptor Pygmalion, who desperately fell in love with a statue he had carved, Ovid tells that the goddess of beauty Aphrodite took pity on him and made the statue come to life (*Metamorphoses*, book 10). Another humanoid is reported in Norse mythology, the giant Mökkurkálfi made of clay and a mare's heart by the other giants, to assist the giant Hrungnir in a fight against Thor, the god of thunder. It was a complete failure: Hrungnir was crushed by Thor's hammer Mjölnir and Mökkurkálfi was slain by Thor's servant Thjalfi (the Icelandic historian and poet Snorri Sturluson wrote an account of this legend in the *Skáldskaparmál*, in the *Prose Edda* around the year 1220) [2].

Besides these mythological reports, humanoids are found as automatons around the world. The Chinese *Lie Zi*, a taoist text of the -IIIrd century, tells that an astonishing automaton was presented to Zhou Mu Wang, the fifth sovereign of the Zhou dynasty, by a mechanical engineer known as Yen Shih. Life-size, human-shaped, the figure walked rapidly, sang in tune, "went through any number of movements that fancy might happen to dictate", and even "made advances to the ladies in attendance". Once opened, it turned out to be "only a construction of leather, wood, glue and lacquer", with "all the internal organs complete" and modeled after their anatomical

1. It stands to reason that Hephaistos, the god of blacksmiths and craftsmen, also be the first roboticist.

2. Another ancient instance of would-be robots is sometimes seen in an episode of the Bible, when the prophet Ezekiel has a vision of a valley full of dry bones over which God makes him prophesy. Then the bones come together, are covered by flesh and skin, and come back to life (Book of Ezekiel, chapter 37, verses 1 to 14). But seeing pre-robots here is a gross out-of-context misinterpretation: those resurrected bones are in no way comparable to artificial human-like creatures. First, they are a vision, and second, the rest of the story makes it very clear that they are a metaphor for the jews of Jerusalem, which were at that time scattered after the fall of Jerusalem and of the kingdom of Judah before Babylonian king Nebuchadnezzar II. Ezekiel was one of those held captive in Babylon, and his prophecies were a message of hope for his fellow exiles, emphasizing God's sovereignty which will bring about restoration of Judah.

counterparts (Needham 1956/1991, page 53). The scene took place in the -IXth century, and even though the technology of ancient China is renowned, the striking abilities of this automaton cast some doubt on the reality of this story and indicate that the tale should more likely be interpreted in its taoist context. Real automatons would eventually be built much later, from the eighteenth century on, in Japan and in Europe. The Japanese *karakuri ningyo* are delicate mechanized puppets [3], pictured on figure 3.1. Those meant for theater and festivals are quite tall and operated by strings pulled by hidden puppet masters (up to three or four per puppet); those used at home for amusement are smaller and powered by a concealed spring mechanism with cams and levers. In Europe, the making of automatons was a result of progress in mechanical engineering, especially clockmaking (see section 3.3.1 for more on this subject).

(a) Karakuri ningyo on top of a festival float in Nagoya, Japan, 2008. The puppet masters are hidden below them, and the wooden float is pulled by men through the streets. The float also usually carries musicians.

(b) Tea-serving karakuri ningyo and its mechanism. The automaton brings the tea cup while moving its feet as though it walked, although it actually rolls.

Figure 3.1 – Karakuri ningyo in Japan

Last but not least, humanoids have been present in various popular tales and works of fiction throughout the centuries. Carlo Collodi's *Pinocchio*, written in 1883, has left a deep impression on generations of kids worldwide, even more since the classical 1940 Disney animated movie (see figure 3.2). Speaking of Disney, we must also recall their adaptation of *The Sorcerer's Apprentice* in *Fantasia*, in 1940 too: the enchanted broomsticks were given a humanoid form with arms and hands to carry the buckets for Mickey (see figure 3.3). The story in this movie is ancient, since it was adapted from a 1797 poem by Johann Wolfgang von Goethe, with the corresponding 1897 symphonic music by Paul Dukas. Goethe's poem is itself strongly inspired by a passage in a story by the Assyrian novelist Lucian of Samosata, written around the year 150, *Philopseudes* (*The Liar*, or *The Friend of Lies*) [4]. In the original version, an aging man tells that he was in his youth the apprentice of an Egyptian priest, and eavesdropped on him while he was turning a pestle into a servant; he could not resist to try the spell by himself, with the disastrous consequence of flooding the house. Apart from the moral of not meddling with things one doesn't understand, *The Sorcerer's Apprentice* also illustrates our long-caressed dream of freedom from chores thanks to knowledge, something robotics should eventually achieve. These

3. The word *karakuri* means mechanism or trick, and has a connotation of mystery; the word *ningyo* means puppet or doll.

4. For reference: Goethe (1797), Lucian of Samosata (c. 150/1905).

themes are also found in Jewish folk tales about golems, anthropomorphic beings made of clay and animated by rabbis inscribing Hebrew letters on their forehead. Similar to present-day humanoid robots, golems are not intelligent creatures, but rather clumsy and slow, and they will perform their instructions literally. In many legends, they are inherently perfectly obedient, but it is not uncommon that they become uncooperative and increasingly violent, eventually killing people or turning against their creator [5].

Figure 3.2 – Pinocchio as illustrated in the first Italian edition (1883). Note the humanoid hands! According to the tale, the wicked Pinocchio used them to play tricks on his old creator even before they were finished: "As he was about to put the last touches on the finger tips, Geppetto felt his wig being pulled off. He glanced up and what did he see? His yellow wig was in the Marionette's hand." (Collodi 1883/1926, chapter 3)

In this last respect, golems are early examples of today's most pervasive trope of robots: them becoming self-aware, escaping our control and rebelling against us. This concern, which really developed from the early twentieth century on, is strikingly the subject of the very work that coined the word "robot": Karel Čapek's 1920 science fiction play *R.U.R. (Rossum's Universal Robots)*, premiered in 1921 in Prague (see figure 3.4) [6]. From that moment on, humanoid robots were going to be recurring characters in an exponentially developing science fiction, which had eventually dealt with them in almost every aspect before they even actually existed. Listing all those

5. The most famous golem was created by Judah Loew ben Bezalel, the late sixteenth century chief rabbi of Prague, out of clay from the banks of the Vltava river. The rabbi constructed the golem to protect the Prague ghetto from pogroms. The golem grew and became violent, spreading fear and death in Prague, so that the rabbi was eventually begged to stop it in exchange of the end of the persecution of the jews. The deactivated golem was stored in the attic of the Old New Synagogue in Prague, and according to legend, it still lies there, waiting to be restored to life if needed.

6. The word "robot" was proposed by Josef Čapek to his brother Karel, who was unsatisfied with his own idea of "laboři" (from Latin "labor", work). "Robot" comes from the word "robota", meaning serf labor, drudgery, hard work, in Czech and Slovak. It was exported into English by the first translation of the play, and through English to all languages around the world.

Figure 3.3 – Mickey Mouse commanding to a broom in the *Sorcerer's Apprentice* (1940). The brooms were drawn with classical Disney four-fingered hands.

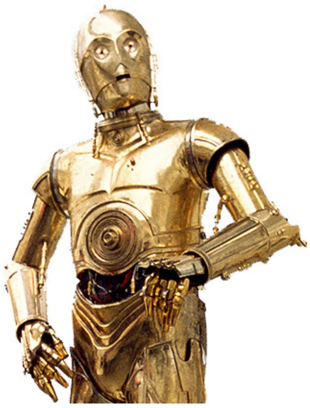
robots would be pointless, but of particular note are probably the Maschinenmensch in Fritz Lang's *Metropolis* (1927), the robots in many of Isaac Asimov's novels, the droid C-3PO in *Star Wars* (1977–2005), the Replicants in *Blade Runner* (1982), and the various cyborgs in the *Terminator* series (1984–2003) (see figure 3.5).

Figure 3.4 – A scene from *R.U.R.*, showing the robot rebellion leading to the extinction of humankind. The robots of the play are actually closer to clones than to the current idea of robots. They are not mechanical but biological machines, assembled like appliances, from bones, organs and skin produced by the company R.U.R.

So finally, in view of all those envisioned humanoid robots, we could conclude that our waiting for humanoid robots explains by itself research on anthropomorphic robots, including anthropomorphic end effectors. But beyond the evident anthropocentrism, there are also valid, steady and rational reasons for humanoid robot hands. They are explained in the rest of this section.

### 3.1.2 Humanoid hands and industrial robotics

In the 2010 version of its annual publication, *World Robotics*, the International Federation of Robotics estimated that “the total worldwide stock of operational industrial robots at the end of 2009 was in the range of 1 021 000 and 1 300 000 units” (International Federation of Robotics 2010). So many robots, so many end effectors:



(a) The protocol droid C-3PO in *Star Wars*.

(b) The endoskeleton of a T-800 Terminator in *Terminator 2* (1991). It is supposed to be powered by hydaulic actuators.

Figure 3.5 – Fictional humanoid robots sporting humanoid hands

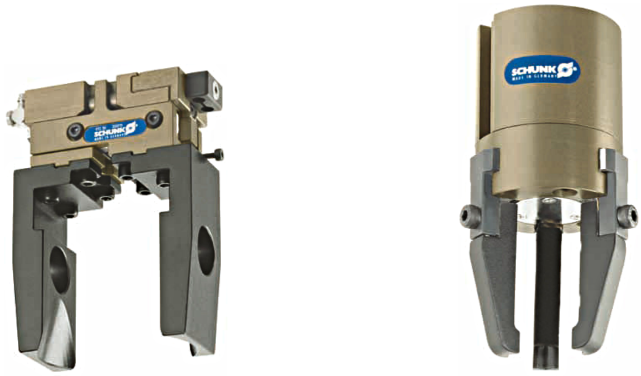
whatever the industry they work for, industrial robots are usually designed to handle some kind of workpiece, and for this reason they feature one or several end effectors to interact with the workpiece [7].

The iconic end effector of industrial robotics is probably the two-jaw gripper (figure 3.6). Designed for prehension, it grasps objects between its two mechanized jaws. Its variations are countless: three-jaw or four-jaw, parallel or angular opening and closing, electric, pneumatic or hydaulic actuation, designed to grasp small or large workpieces... Humanoid robot hands are end effectors that may be considered as high-tech evolutions of this kind of grippers; however, they are notably absent from the industrial scene. We start this section by providing a general overview of the wide and varied family of end effectors, so as to set humanoid robot hands back in context.

### A wealth of end effectors

Robot end effectors are extremely diverse. As a matter of fact, in just the half-century of its existence as a distinct engineering science, robotics has given birth to an exceptional variety of end effectors, the inventory of which is now the matter of dedicated works on the subject (e.g. Wolf, Steinmann, and H. Schunk 2005; Monkman, Hesse, Steinmann, and H. Schunk 2004/2007). The reason for such a variety is simply the needs of our industrial society, whose abundance of mass-manufactured goods requires fast and efficient robotized assembly lines for about everything from cars

7. In addition to this already important number of industrial robots, the International Federation of Robotics estimates the worldwide stock of service robots to 76 600 units sold for professional use and about 8 700 000 units sold for personal and private use, up to the end of 2009. Robots for professional use are those meant for defense applications (30%), milking robots (25%), cleaning robots (8%), medical robots (8%), underwater systems (7%), construction and demolition robots (6%), and so on. Robots for personal and private use are mainly household robots (vacuum cleaners and lawn mowers: one million vacuum cleaning robots were sold in 2009) and entertainment robots (toy robots and hobby systems). All those robots amount to a grand total of about ten millions robots worldwide... It must be noted however that personal service robots are "produced for a mass market with completely different pricing and marketing channels" from industrial robots and professional service robots, hence the huge number of the former in comparison to the later (International Federation of Robotics 2010).




(a) KTG, two-jaw parallel gripper (b) MPZ, three-jaw concentric gripper

Figure 3.6 – Two pneumatic grippers sold by the German firm Schunk, one of the world leaders in automation and end effector technology for industrial robots

to computers to children toys to baked goods... Nowadays, basically anything at the local supermarket passed between the end effectors of some robot at some point of its pre-shelf existence. The diversity of these goods and of their manufacturing or handling processes is the reason for the diversity of robot end effectors, that are specialized and customized by their creators for a specific application (figures 3.7 and 3.8).

Not all end effectors are designed for prehensive tasks. For instance on the assembly lines of automotive industry, the most common end effectors are spot welding heads (see figure 3.7(a)) and spray guns for painting; cutting tools, power drills, screwdrivers and sanders are other examples. On a surgical robot, the end effector could be a scalpel; in eye surgery, it would be a laser. In dairy industry, cow milking robots have sprays and cups for automatic cleaning of teats and cups for milking (positioned on the teats by a robot arm detecting the udder with optical sensors). On a personal vacuum cleaning robot, the end effector is a set of brushes and/or a suction device. And the list goes on.

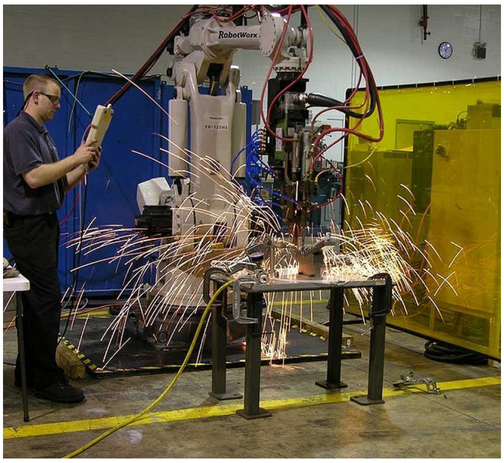
The end effectors designed for prehension are called grippers and may be loosely divided into four classes (Monkman, Hesse, Steinmann, and H. Schunk 2004/2007):

**Impactive grippers** Prehension is achieved by forces impacting against the surface of the object. Examples are jaws, claws, snares, pincers and other similar devices that grasp by direct impact (figures 3.6, 3.7(d) and 3.8).

**Ingressive grippers** The end-effector physically penetrates the surface of the workpiece. Examples are pins, needles, hooks and velcro. Such grippers are often found in textile, carbon fiber and glass fiber handling.

**Astrictive grippers** A binding force is applied by the gripper to the surface of the object. Examples are vacuum suction, magnetic forces (if the workpiece is made of magnetic material) and electrostatic forces (if the workpiece is light enough). Direct initial contact is usually not necessary for the object to be lifted (figure 3.7(b)).

**Contigutive grippers** Prehension takes place through some kind of adhesion. Examples are chemical adhesion (by glue or some other adhesive) and thermal



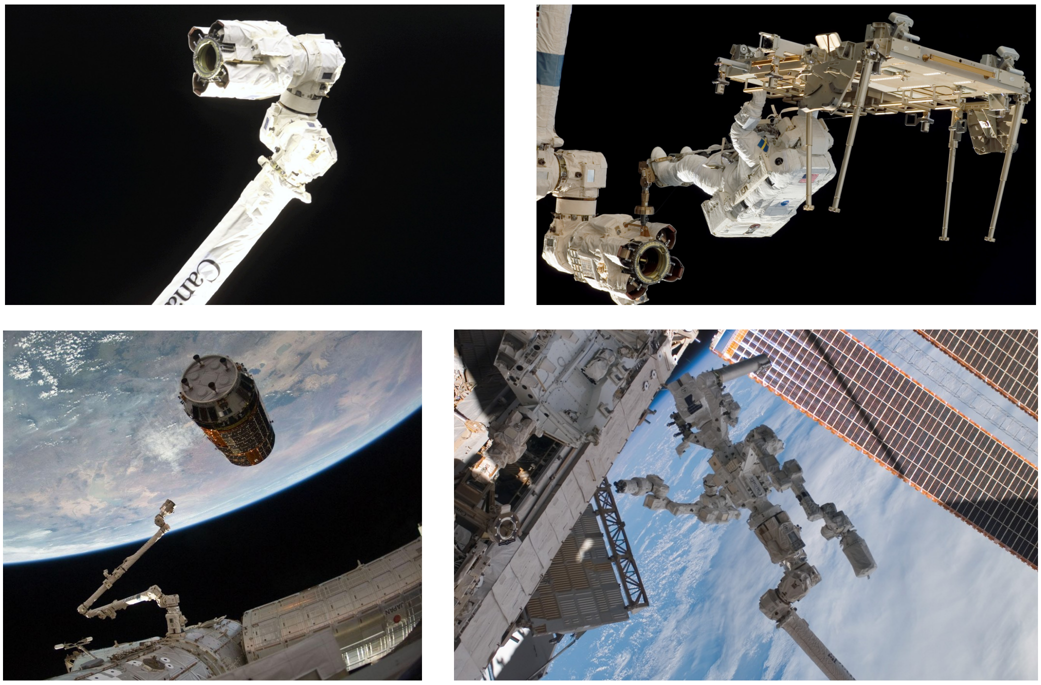

(a) A spot welding end effector, common in assembly lines. This one is human-operated.


(b) Fast parallel manipulator with a four-at-a-time vacuum-based end effector. The white hose is the vacuum line.

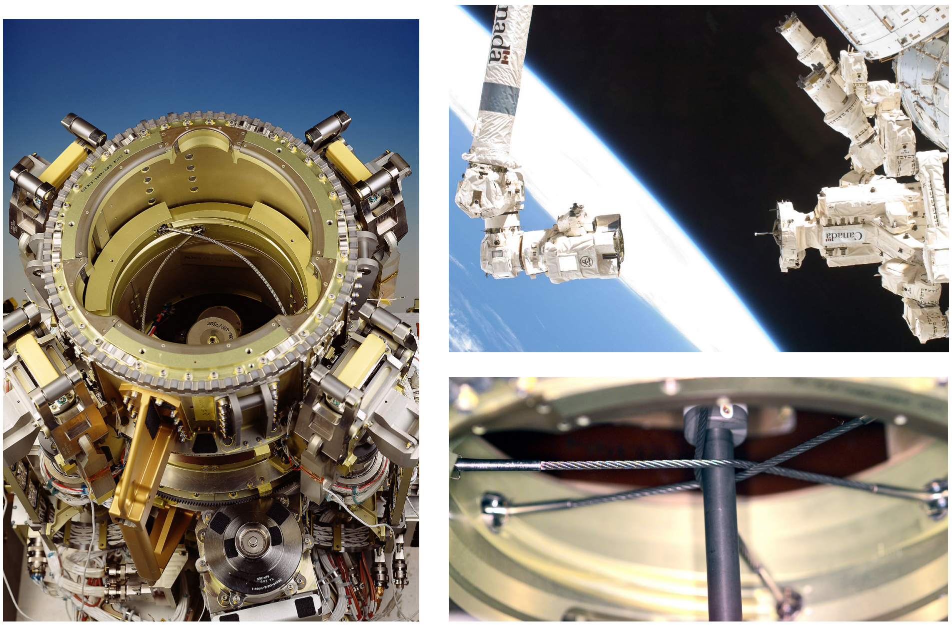
(c) Candied cherry gripper for the confectionery processing industry. Sticky workpieces cannot be accurately placed by conventional two-jaw grippers since they may remain stuck to their jaws. This gripper is made of two motionless jaws wrapped in a strip of moveable plastic tape.


(d) Baggage gripper at the end of a serial manipulator, for use in airports. A machine braces both the baggage and the gripper with two plastic ties. The robot places the baggage in the air-cargo container, cuts the ties with an inbuilt knife, and throws them out for disposal or recycling. This design copes with any size, shape or weight, and places the baggage in nearly any position.

Figure 3.7 – Examples of industrial robot end effectors ((c) and (d) from Wolf, Steinmann, and H. Schunk 2005)



(a) The previous version of this arm, the smaller and lighter Canadarm, is used on space shuttles since 1981, chiefly for deployment of payloads from the cargo bay and inspection of the shuttle's surface. The new version was launched in 2001 and used to build the station. Its missions now include station maintenance, replacement of plug-in equipment, assistance in docking and unloading the shuttle, moving of payloads and astronauts (top right), and many more. Its end effector is able to capture free-flying unmanned spacecrafts (bottom left). A set of two smaller robotic arms, called Dextre, complements the arm when the task needs other end effectors (bottom right).



(b) The end effector attaches to special fixtures by four mechanical latches and a three-wire snare mechanism. Power and data are provided to the arm through these fixtures, placed on payloads and on the outside of the station. The end effector features a video camera for operation from the inside of the station. Force and moment sensors ensure automatic smooth and safe motion of the payload. Unlike its shuttle version, Canadarm-2 is not fixed: it has end effectors at both ends and moves itself from fixture to fixture, reattaching either end effector to the station as its new base.

Figure 3.8 – The end effector of Canadarm-2, a robotic arm contributed by Canada to the International Space Station

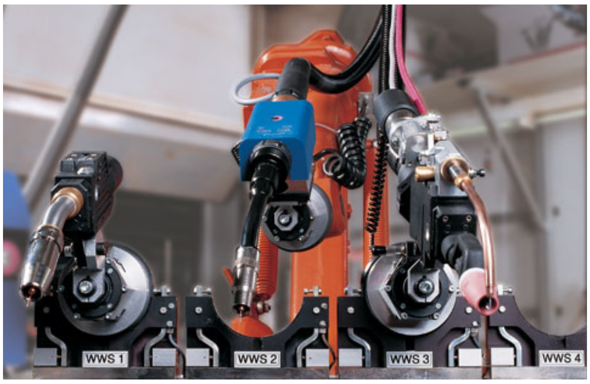
adhesion (usually by freezing or melting). Contrary to astrictive grippers, initial contact is necessary for a contigutive gripper to stick to the workpiece (figure 3.7(c)).

### Comparison between humanoid hands and industrial grippers

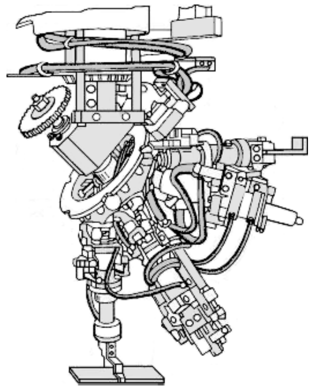
Humanoid hands are grippers of the impactive type, but they are also more than just grippers: besides prehension, they are supposed to serve manipulation (see section 2.2 for more on this distinction). This later ability is virtually absent in conventional grippers, whatever their type: the workpiece is kept fixed with respect to the gripper for the time of its handling. The motion of the workpiece is therefore realized by the whole robot. In contrast, human and robot hands are able to move the workpiece not only by moving the whole arm but also locally at the end effector level, by moving only the fingers. Therefore they are able to realize fine and precise manipulations in addition to large displacements of the object. Conventional grippers are just too basic for such manipulations. However, other end effectors could do the job. For instance, assembly tasks often require robots to mate nuts with bolts so as to fasten parts together: in such a situation, a first end effector could grip the nut to keep it from turning (prehension, by some kind of gripper) while a second end effector would drive the bolt into the nut (manipulation, by some kind of screwdriver).

This leads to the second main difference between grippers and hands: the versatility of hands, as opposed to the specialization of grippers. As we said previously, robot end effectors are extremely varied and customized for one specific application. The short overview we have provided illustrates this point. Even the Canadarm-2 end effector (figure 3.8), which looks versatile from the number of different payloads it can handle, actually is specifically adapted to grasping a special fixture attached to the payload (or the feet of an astronaut through a special foot restraint). This specialization of end effectors is somewhat inconsistent with the fact that robots themselves are supposed to be flexible machines. It would therefore make sense to endow them with more versatile end effectors, such as hands. Whereas conventional end effectors only perform a single task, hands have a wide range of grip and manipulative abilities (see section 2.2 in chapter 2), and may even turn into any specific tool by simply grasping it. However, simpler solutions than hands exist to overcome the limitation of end effector specialization: tool changing systems. The most basic is a simple tool rack, where the robot can put down its current end effector and attach another one to its last link (figure 3.9(a)). Another one is a tool turret, which gathers several end effectors on a common rotary mounting (figure 3.9(b)). Despite evident drawbacks not found in a humanoid robot hand, such as the time to disconnect and reattach an end effector or the cumbersomeness of a turret, these tool changing systems are preferred to robot hands in the industry because of their mechanical and control simplicity.

Table 3.1 summarizes the differences between humanoid robot hands and other end effectors, as exposed so far. From this table, it appears that, in a factory setting at least, humanoid robot hands do not seem to have obvious superior advantages over specialized end effectors. Both seem actually pretty equivalent, the specialization of the latter being compensated by tool changing systems and also by the use of multiple robots, while versatile hands may be specialized by grasping a tool. For instance, on an assembly line, a spot welding robot and a subsequent spray painting robot could be replaced by two robots with humanoid robot hands, one holding a spot welder




(a) A rack-based tool changing system sold by the German firm Abicor-Binzel. The tools are different welding torches.



(b) A turret with six separate end effectors, four of which are visible (Monkman, Hesse, Steinmann, and H. Schunk 2004/2007)

Figure 3.9 – Tool changing systems

| Conventional end effectors | Human and robot hands |
|---|---|
| Prehension or manipulation<br>and many other uses, depending on the end effector (e.g. a cutting tool) | Prehension and manipulation<br>and many other uses, thanks to tools (e.g. a knife) |
| Specialization<br>some degree of versatility may be achieved with tool changing systems | Versatility<br>any degree of specialization may be achieved with tools |

Table 3.1 – Comparison of hands versus other end effectors

and the other holding a spray gun. But what is the point of such a substitution? One of the first robot hands in history, the Belgrade/USC Hand (figure 2.43(a)), was in the words of one of its conceptors, George Bekey, "suitable for use in an industrial environment". However, it was not adopted by the industry "since it could not compete with a magazine of simple grippers in overall reliability" (Bekey 2005). The famed Utah/MIT Hand too, although it was intended for research purposes only, had eventually industrial applications in focus: according to its conceptors Jacobsen, Iversen, Knutti, T. Johnson, and Biggers (1986), "it is intended that, subsequent to a period of research, simplified versions of the Utah/MIT Dextrous Hand will be produced for industrial application using less expensive modules evolved from the original system". Similarly, the first robot hand developed at the University of Bologna, Italy, UB Hand I (figure 3.10), was presented as a "dextrous hand for industrial robots" (Bonivento, Caselli, Faldella, Melchiorri, and Tonielli 1988). The absence of humanoid robot hands in present-day factories speaks for itself and tones down that 1980s optimism. The truth is that "using five-fingered hands for industrial assembly tasks" creates "more problems than advantages, due to increased complexity" (Fermoso 2008, citing George Bekey). Operation speed, better reliability, easier control and lower cost are factors that favor specialized end effectors. And even if all these issues were resolved in robot hands, there is at the moment no evidence that hands would provide advantages in terms of productivity over a well-selected set of specialized end effectors.

The overall conclusion is that the practical reasons that justify research on humanoid robot hands do not stand on the industrial side of robotics. Even though they are

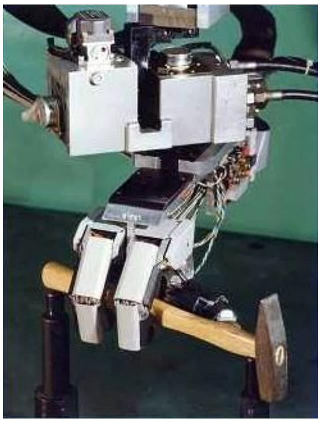


Figure 3.10 – UB Hand I, a three-fingered hand developed in the late 1980s at the University of Bologna, Italy

grippers, robot hands are probably not going to change the face of the world of industrial grippers. Therefore the reasons for humanoid robot hands are more likely to be searched on the other side of robotics: service robots. The rest of this section investigates this side.

### 3.1.3 Humanoid hands and service robotics

Whereas the purpose of industrial robots is manufacturing in factories, service robots are supposed to help humans in their daily lifes at work or at home. More likely to be mobile than industrial robots, they are paradoxically more numerous and less advanced than them, due to an enormous amount of cheap and basic service robots being sold each year for housework and entertainment (vacuum cleaning robots, lawn mowing robots, toy robots) (International Federation of Robotics 2010). The purpose of service robotics, helping humans in their daily lifes, points the fundamental difference between industrial and service robots: their respective environments.

#### How the environment influences the choice of an end effector

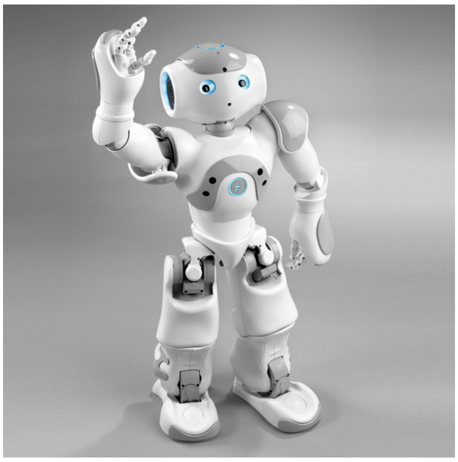
Robotized factories are highly structured environments. The assembly lines are adapted to their robots: the workpieces are always the same, and the automated conveyor belts may even bring them to the robot always at the same place and in the same orientation. This greatly simplifies the task of the robot, as well as the work of the roboticists who have to design its control, because it keeps the unexpected at a minimum. On the contrary, human environments are highly unstructured. They are extremely diverse and may change at any moment because of the presence and actions of humans; consequently they are not well-suited to brainless machines. Yet, unlike an industrial robot fixed in its unique, unchanging setting, service robots are supposed to adapt to a variety of places (homes, offices, gardens, stairs, streets. . . ) and to take into account the presence, the movements and the actions of humans (or pets, or other robots. . . ), let alone interact with them. The challenges to overcome are much superior to those of industrial robotics, which explains why current service robots in operation are quite primitive. The few sophisticated, expensive ones are mostly limited to robotics research laboratories (figure 3.11 presents some of them).

The complexity of human environments results in many hurdles for prehension and manipulation. Objects are various and dissimilar. There is no limit on their

(a) HRP-4 pretending to serve coke. This humanoid robot by Japan's National Institute of Advanced Industrial Science and Technology (AIST) and Japanese firm Kawada Industries is the latest installment in their HRP series (AIST 2010; Kawada Industries 2010). Design was simplified and optimized, so that the robot is lighter and less expensive (151 cm, 39 kg, around $ 300 000). Despite having five fingers, the hands are limited to simple movements, since each hand has two degrees of freedom and a maximal payload of 0.5 kg.

(b) Wheeled robot Armar III in the mock-up kitchen of the University of Karlsruhe, Germany (Asfour, Regenstein, Azad, Schröder, Bierbaum, Vahrenkamp, and Dillmann 2006). Its hands have five fingers and eight independent degrees of freedom each. The Armar robots are capable of artificial learning by interaction with the environment, meaning that they learn about objects by using them.

(c) Wheeled robot TPR-Robina, made by Japanese firm Toyota and used since 2007 as a tour guide at the Toyota Kaikan Exhibition Hall in Toyota, Japan (Toyota 2007). The robot is 120 cm tall and weights 60 kg. Its hands are three-fingered articulated grippers, designed to grasp pens to sign its name.



(d) The latest version of the entertainment robot Nao, by French company Aldebaran Robotics (58 cm, 5 kg, about 12 000 euros). Its three-fingered hands are articulated open/close grippers (Aldebaran Robotics 2011). They can seize and lift small objects, with a maximal payload of 0.3 kg using both hands.

Figure 3.11 – Some modern humanoid robots and their hands. The common point is that these hands are capable of grasping, but not manipulation.

shape, their mass, their size, their color, their material, their rigidity. They may change places because they have been moved by someone, or they may look different because of a different viewpoint or a different lighting. So the robot faces problems of recognizing objects, finding a suitable grasp and manipulation strategy, and realizing it with success, whatever the object is (Kemp, Edsinger, and Torres-Jara 2007). In such a situation, a simple, specialized gripper is a hindrance, and the diversity of the objects makes the versatility of a robot hand appear convenient. In other words: in factories, it is easier and cheaper to adapt the environment to the robot than to adapt the robot to the environment. But of course, it is out of question to do likewise in human-centered environments: they are made for us, with objects made for our hands. Robots have to adapt, and a sensible manner for them to do so is to adopt our hands since they are the favored end effector of these environments.

### Human-operated robots are better off with humanoid hands

Besides the environment, another advantage of anthropomorphic end effectors is that they are better suited to human operation (Bicchi 2000). That is to say, it is easier for a human operator to map his hand with the robot hand. This point has little importance for autonomous robots, but may be relevant for non-autonomous and semi-autonomous robots. For instance, teleoperated robots are often clumsy to operate and require their users to train extensively in order to be able to operate them at their best, "albeit slowly and with significant effort" (Kemp, Edsinger, and Torres-Jara 2007). One of the reasons for this is their common use of non-anthropomorphic design for arms and end effectors. Teleoperating a human-like robot hand would be easier and should cut training time, thanks to a better, more natural match between the slave hand and the master hand. That would also improve the feeling of immersion of the operator in the remote environment. This idea is visible in NASA's Robonaut project (NASA 2011c). A semi-autonomous teleoperated humanoid robot with very anthropomorphic hands, Robonaut is supposed to eventually help or replace astronauts during extra-vehicular activities, and it has also been thought that it could be adapted on other robots, for instance rovers for planet exploration (see figure 3.12).

Another example of human operation is prosthetic replacements for people missing a hand or fingers. Indeed, the ideal hand prosthesis is a replacement that integrates so tightly with the body of the amputee that it smoothly replaces the missing hand or fingers. Such a ideal hand is completely thought-controlled by its user, who uses it as if it were their biological hand. Needless to say, this ideal prosthesis does not exist, and the current state of the art does not make it likely that it will come true in the foreseable future. Still, when it does, the thought-controlled hand prosthesis will sensibly be anthropomorphic, since it is what our brain is used to operate at perfection. In the meantime, as low-tech as it may seem, simple open/close grippers are the most successful upper-limb prostheses, even though they are used in human-centered environments (see section 3.2 for more on the state of the art in hand prosthetics). Even when prosthetic hands are anthropomorphic five-fingered constructions, they are really only grippers in disguise, incapable of fine manipulation. And battery-powered myoelectric hands (see figure 3.13) are no exception, even though they are considered to be what comes closest to thought-controlled prostheses: control signals from the amputee to their prosthesis are the electrical activity from muscles in the residual limb, recorded by electrodes placed on the skin. Still, these prostheses also hardly achieve more than open/close grip function: there is much room for improvement before the ideal anthropomorphic thought-controlled hand prosthesis is reached.


(a) Robonaut 2 tweeting "Hello World!" on July 26, 2010. It was launched to the International Space Station on space shuttle Discovery as part of the STS-133 mission, on February 24, 2011, becoming the first humanoid robot in space.

(b) A mobile exploration/manipulation robot made of a Centaur 1 four-wheeled rover and a Robonaut 1. It is shown here during a field test in the Arizona desert in 2006, near Meteor Crater.

Figure 3.12 – NASA Robonauts. The second generation is a collaboration between NASA and the American company General Motors.

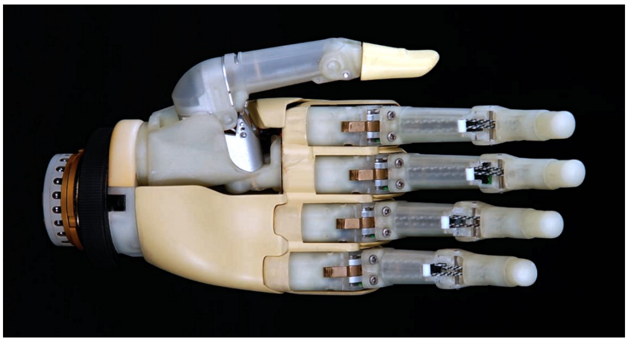


Figure 3.13 – An example of (advanced) myoelectric hand prosthesis: i-Limb Hand, by British company Touch Bionics (2009) of Edinburgh, Scotland. It is pictured here without its artificial skin covering.

### Conclusion

We can complete the table 3.1 about the differences between humanoid robot hands and other end effectors, by adding the nature of the environment and the possible human operability. We get table 3.2. It summarizes in which cases a humanoid robot hand is appropriate and in which other cases it is not. Indeed, although hands might seem on first thought an appealing multi-purpose replacement of all grippers, they are not an unconditional solution. The overall conclusion is that the application and the environment determine the end effector, or the end effectors. There is in this respect an interesting and unexpected analogy about human hand evolution: it is also usage and the environment that have determined and differentiated the various hands of the primates (see section 2.3 in chapter 2). A parallel may thus be drawn between all these hands: conventional grippers and non-human primate hands are both specialized whereas robot hands and human hands are both primitive, that is to say generic and non-specialized. In the words of Napier (1956): "In many respects the human hand is a remarkably primitive structure, the pitfalls of extreme specialization shown, for example, by the gibbon, the potto and the baboon having been avoided in its history. In its pentadactyl form, the relative length of its digits, the arrangement of its musculature and in the generalised nature of its movements, man's hand shows an ancient simplicity of structure and function."

| Conventional end effectors | Human and robot hands |
|---|---|
| Prehension or manipulation<br>and many other uses, depending on the end effector (e.g. a cutting tool) | Prehension and manipulation<br>and many other uses, thanks to tools (e.g. a knife) |
| Specialization<br>some degree of versatility may be achieved with tool changing systems | Versatility<br>any degree of specialization may be achieved with tools |
| Structured environments<br>mainly: factories<br>a consequence of specialization | Unstructured environments<br>in particular: human environments<br>a consequence of versatility |
| Autonomous robots<br>industrial robots, some service robots for professional use (for instance milking robots) | Autonomous and human-operated<br>humanoid robots, prostheses, teleoperation (army, exploration, space, hazardous environments. . . ) |

Table 3.2 – Comparison of hands versus other end effectors

## 3.2 A review of humanoid prosthetic hands

The first artificial hands in history were undoubtly for prosthetic use. Amputations were and are still the result of trauma and surgery, happening in wars and in accidents, or in the treatment of certain diseases (gangrene, cancer, diabetes). For many centuries, the loss of a limb often led to death: hemorrhage would kill the unfortunate victims, or infection spreading from the wound would claim their life the following days. But advances in medecine and surgery have occured. People facing a limb amputation today are very likely to survive it if medical care is provided.

Besides, prosthetics made advances too. Actually, the second half of the twentieth century saw a new type of prosthesis come true: powered by batteries and motors, myoelectric prostheses are somehow "thought-controlled" by the amputee, thanks to electrodes recording the electrical activity of the muscles of the residual limb – however futuristic this sounds, this technology still underachieves and presents many drawbacks. Nevertheless, starting with the first myoelectric hands, prosthetics slowly became involved with emerging robotics. And nowadays, research on humanoid hands in robotics and research on hand prosthetics converge on many technological points and issues.

This section is an overview of the highlights in the history of prosthetic hands, up to the current research and the perspectives for the future. Pointers to the relevant and often exciting literature on the subject are provided. The next section (3.3) will provide the equivalent state of the art about robot hands, but it must be kept in mind that the line between robot hands and prosthetic hands is thin nowadays, and keeps getting thinner. The historical distinction is kept for simplicity and clarity of the presentation.

### 3.2.1 Ancient prostheses

The first prosthetic hands in history were passive prostheses, that is to say, unarticulated prostheses. The most iconic one is the hook, which fits a certain pirate stereotype since James Barrie's *Peter Pan*. The passive hook offers some limited practical function, but this is not necessarily the case of all passive hands: other passive prostheses may be aesthetic replacements only, without practical function, meant to hide injuries sustained in battle or in manual work and perhaps provide the wearer with a certain sense of wholeness, to a limited extent. Usually, ancient passive prostheses were made of wood, iron or copper, with leather parts for attachment to the residual limb. Some prostheses could be made in a particular shape, for instance knights in the Middle Ages and Renaissance would have passive hands made for them that could hold a shield, so that they could return to battle. Ironically, the craftsmen who made them such hands were the same armorers who provided weapons and armors for the battles (B. Wilson J. 1963, 1992; Norton 2007).

One of the first accounts of an active prosthetic hand, that is to say a mechanical, articulated prosthesis, is the iron hand of German mercenary Götz von Berlichingen, in the early sixteenth century (Norton 2007; Monkman, Hesse, Steinmann, and H. Schunk 2004/2007, page 14; Karpa 2004, pages 18–19). A famous and colorful character, Berlichingen lost his right hand to a cannon ball during the siege of Landshut, Bayern, in 1504, around the age of 24. Having survived the injury, he had a mechanical iron hand made for him by his armorer in Jagsthausen, Württemberg, or perhaps by a craftsman in Nürnberg, Bayern (Putti 2005). The hand was ahead of its time, complete with five articulated fingers which could be bent by the other hand, then fixed and released at the push of a button through a system of levers and springs. It weighted about 1.5 kg, not a particularly heavy load for a warrior in those times. Fitted with it, Berlichingen could return to an active and long life of battles, feuds, raids and rebellions. Much later, in 1773, the young Johann Wolfgang von Goethe would base a successful play on his life, *Götz von Berlichingen mit der eisernen Hand* (Götz von Berlichingen with the Iron Hand) [8]. The hand itself is today on display in Berlichingen's castle in Jagsthausen. It is illustrated in figure 3.14.

With respect to amputation surgery, the ancient Greek physician Hippocrates of Cos described the use of blood vessel ligatures to prevent or stop bleeding. But this technique was lost during the Middle Ages, and hemorrhage from amputation was in those times stopped by cauterizing with hot irons or boiling oil. This painful ordeal resulted in extensive tissue damage, and therefore necrosis and infection. French military surgeon Ambroise Paré reintroduced the use of ligatures in 1529, and latter designed several ingenious prostheses for upper and lower limb amputees (Paré 1585; Karpa 2004, page 20). One of them is pictured in figure 3.15; like Berlichingen's prosthesis, it is an open/close gripper in the shape of a hand, actuated, locked and unlocked by the other hand. Paré opened a new era for surgery: although ligatures

8. In this play, Goethe made Berlichingen utter an expression that gained fame fast. In the third act, Berlichingen and his people are sieged in his castle in Jagsthausen by the army of Maximilian I of Habsburg, Holy Roman Emperor of the German Nation. Asked to surrender, he thunders back from a window: "Mich ergeben! Auf Gnad und Ungnad! Mit wem redet Ihr! Bin ich ein Räuber! Sag deinem Hauptmann: Vor Ihro Kaiserliche Majestät hab ich, wie immer, schuldigen Respekt. Er aber, sag's ihm, er kann mich im Arsche lecken!" Which can be translated as: "Me, surrender! At mercy! Whom do you speak with? Am I a robber! Tell your captain that for His Imperial Majesty, I have, as always, due respect. But he, tell him that, he can lick me in the arse!" The colorful expression, still used in German, evolved in English into the expression "kiss my ass", nowadays shouted all over the English-speaking world.

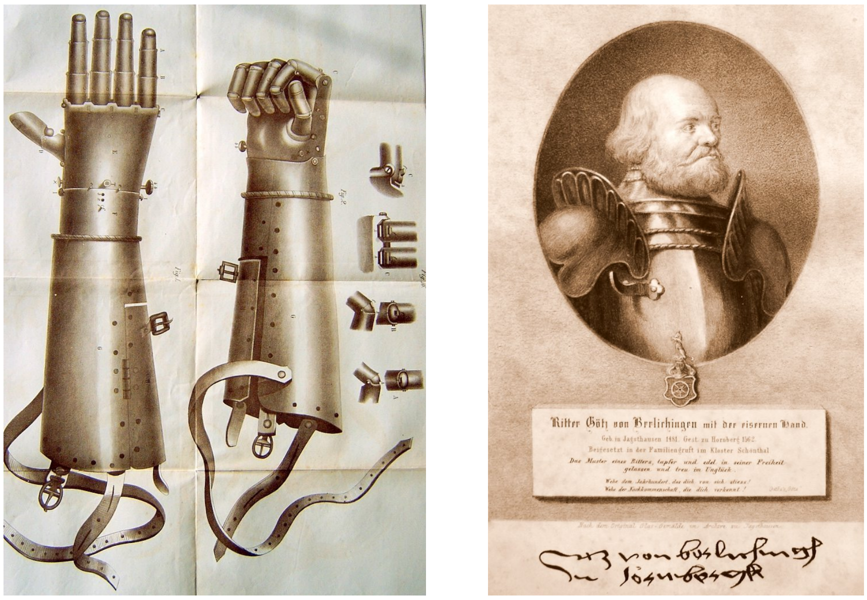



Figure 3.14 – Engraving of the iron hand of Götz von Berlichingen (left) and its owner's portait and signature (right)

at that time often spread infection, they still improved the outcome of amputations, which became therefore more life-saving (B. Wilson J. 1963, 1992; Norton 2007).

### 3.2.2 Mechanical body-powered prosthetic hands

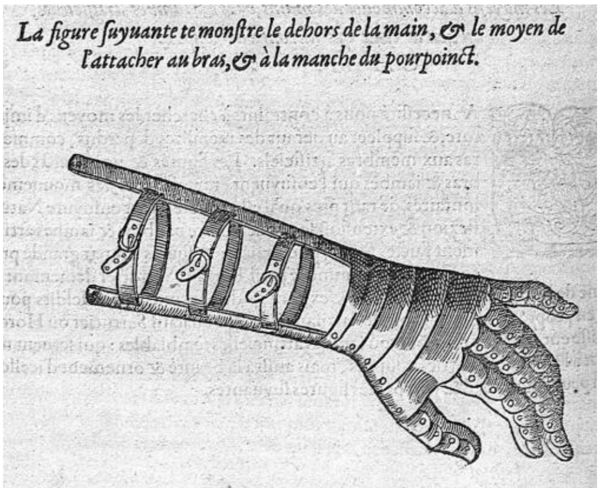
After the advances in medicine and prosthetics made by Ambroise Paré, the next innovations were to happen mainly during the nineteenth century (B. Wilson J. 1963, 1992; Norton 2007; University of Iowa Medical Museum 2006).

#### Cable-driven operation

In 1812, Pierre Ballif, a German dentist and surgical technician in Berlin, invented a mechanical hand prosthesis which could be controlled using straps connected to a chest harness (Karpa 2004, page 22). As illustrated on figure 3.16, the hand looked a bit like that of Götz von Berlichingen, but it was three times lighter (about one pound), made of brass, and most importantly it could be actuated without the help of the other hand thanks to the straps. It was made public in 1812 by Ferdinand Gräfe, the Prussian army surgeon general, and then described in 1818 by Ballif. In its repose posture, the hand was held closed in a fist by springs. Stretching the arm pulled on the cables, which opened the fingers. A drawback of this system is that the device grip force is low since it comes from the springs only, so heavy objects could not be grasped securely (plus, the repose posture is slightly threatening). Still, it was a ground-breaking advance in hand prostheses. Actually, this was the world's first cable-driven prosthesis, to the best of our knowledge, and the principle of actuation by cables and harness is still the basis of most of today's prosthetic grippers.

Ballif's invention was subsequently improved upon (Karpa 2004, pages 23–25). In 1836, Berlin engineer Margarethe Karoline Eichler inverted the motion of the prosthetic hand, making extension of the fingers by springs its repose posture and flexion in a fist its active motion. This achieves stronger grasp force. Her hand was made of nickel brass and was very light, about a quarter of a pound; besides, it was reportedly


(a) The workings of a mechanical iron hand designed by Ambroise Paré (1585), and its descriptive text in Middle French. Because his education had been exclusively practical, Paré, who never attended medical school, knew neither Latin nor Greek, and was not accepted by his colleagues. He deliberately published his writtings in French, against the opposition of the medical profession, but supported by the king and the intellectuals of his time. This was indeed an era of affirmation of French, and Paré clearly expressed in his works his desire "not to make the Arts cabbalistic".




(b) The outside of the iron hand and how to attach it to the amputee's arm. Paré (1585) also describes a mechanical iron arm, a lightweight hand prosthesis made of leather and paper, and a hand orthosis.

(c) Posthumous portrait by William Holl the Younger, from the original picture in the École de Médecine in Paris (XIXth century).

Figure 3.15 – Ambroise Paré and an example of his prosthetic work

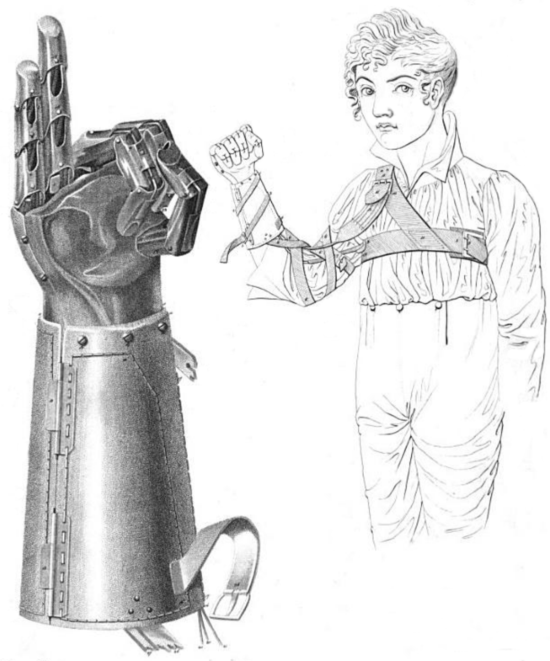


Figure 3.16 – The mechanical brass hand of Pierre Ballif (Gräfe 1812)

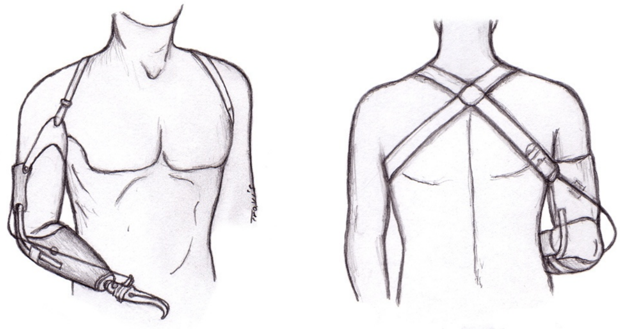
sleek-looking. In 1844, the Dutch sculptor van Peetersen made improvements to artificial arms for above-elbow amputees, and came up with the shoulder harness, less uncomfortable than the chest harness (see figure 3.17). During the 1850s and 1860s, the count Amédée de Beaufort, who had been appointed "deputy inspector general of charitable institutions" in France in 1847, invented a number of articulated devices for upper and lower limb amputees, especially for the less fortunate in society. Building on van Peetersen's ideas, he designed simple, practical, lightweight, inexpensive prostheses for below-elbow and above-elbow amputees, that could be manufactured in large quantities and would be robust enough to make it possible for their users to return to work (Beaufort 1867). The need for replacement limbs in France was growing, since a series of wars in which France was involved had left a lot of amputees (the Crimean War, the Second Opium War, the Second Italian War of Independence, the French intervention in Mexico; and the Franco-Prussian War was to come). Beaufort rightly called his inventions "prothèses du pauvre" (prostheses for the poor): in comparison, all previous articulated upper-limb prostheses were sophisticated, delicate, realistic five-fingered constructions that only the rich could afford and that were not designed for manual work.

### Amputation surgery

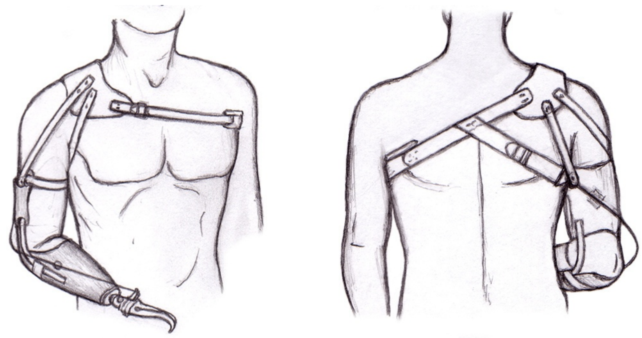
In the 1840s, the anesthetic action of ether and chloroform was discovered [9]. These early anesthetics made possible painless, and therefore longer, surgery. As far as amputation is concerned, this meant that surgeons could take the time to shape better and more functional amputation stumps, designed to improve the fit of the prostheses [10]. The newly discovered anesthetics were to be used at a large scale

9. Diethyl ether to be precise, $(C_2H_5)_2O$, and trichloromethane, $CHCl_3$. The word "anesthesia" was coined by this occasion, from the Greek words for "without" and "sensation".

10. Even though an amputation does not require a lot of time, careful shaping of the stump is difficult to consider without anesthesia, the procedure running for about ten to fifteen minutes,



(a) Figure-eight harness



(b) Shoulder saddle with chest-strap suspension

Figure 3.17 – Modern shoulder harnesses (B. Kelly, Pangilinan, Rodriguez, Mipro, and Bodeau 2009). From the top to the bottom of the fitting: the harness, a triceps pad, the control cable, the prosthesis socket, and the terminal gripper (hook or hand). Cable actuation has the advantage of giving the amputee some force feedback, to some extent.

during the American Civil War, which saw the number of amputations rise at an unprecedented level. It has been estimated that about 30 000 amputations were performed by the military surgeons on the Union side alone, out of the approximately 175 000 wounds to the extremities received among the Federal troops; roughly the same proportion of amputations is supposed to have occured in the Confederacy (Civil War Society 1997).

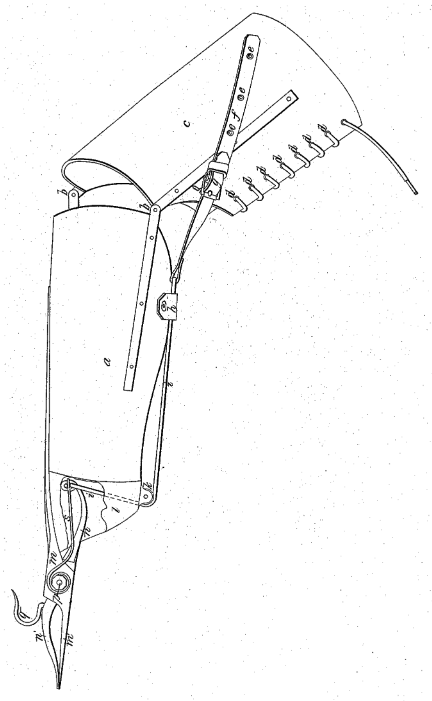
Unfortunately for the injuried soldiers, the war was fought “at the end of the medical Middle Ages”, according to the Union army surgeon general. At this time, French microbiologist Louis Pasteur was conducting his experiments on fermentation, proving that it is caused by the growth of micro-organisms, and supporting the idea that micro-organisms infecting humans cause disease (the so-called “germ theory of disease”). His work made British surgeon Joseph Lister try to keep the germs away from the patients at his hospital by cleaning the surgery instruments and the surgical incisions with phenol. This was a resounding success and the start of antiseptic surgery [11] (Lister 1867), but shortly after the end of the American Civil War. In comparison with these advances in Europe, surgeons operating on battlefields during

an eternity for a non anesthetized patient. In contrast, a simple cut-and-cauterize may be kept under a minute, already too long a suffering for the patient of course (R. Elliott 1998, chapter 1 and appendix A).

11. The 1879 antiseptic mouthwash Listerine was named after Joseph Lister, as well as the bacterial genus *Listeria* in 1940.

the Civil War had not even enough water to rinse their amputation saws before turning to the next soldier. The hygiene conditions were appalling and post-surgery infections were the rule, leading to further amputations because of gangrene. Despite these fearful odds, it is recorded that nearly 75% of the amputees survived (Civil War Society 1997; National Museum of Health and Medicine 2010). They provided a substantial market for post-war prosthetic companies, which flourished all the more that the government funded prostheses for war veterans (University of Iowa Medical Museum 2006). Figure 3.18 shows prosthetic grippers of that time.

(a) American Civil War veteran with bilateral below-elbow transradial amputation, fitted with gripper prostheses not unlike the one presented on the right



(b) A simple hook-and-pinchers prosthesis for below-elbow amputees: extension of the elbow opens the gripper jaws, which are held closed by a spring when the elbow is flexed (Reichenbach 1865)

Figure 3.18 – Artificial upper limbs of the second half of the nineteenth century

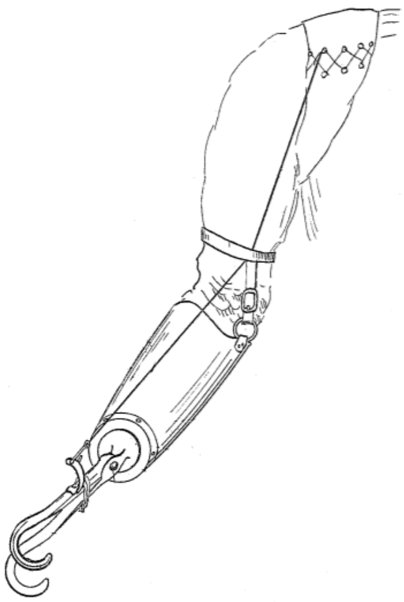
### Prosthetics at the turn of the twentieth century

During the last decades of the nineteenth century and at the start of the twentieth, prosthesis technology advanced at a faster and faster pace, particularly in America. Many developments were brought out at this time, mostly by newcomers in the field. Some of these developments, if not a significant number, were copies or attempts of further developments, that did not really introduce ground breaking innovations. Numerous patents were registered by all those ingenious inventors, culminating in number at the end of World War I, in what looks like an attempt to secure a piece of what was probably felt a significant business opportunity [12]. For instance, Allward (1889), Minzey (1893), Dorrance (1912), Bosch (1913, 1919), Jeffery (1918), and Baehr (1919) patented various cable-driven grippers, and Rowley (1915, 1916), Caron (1917, 1918a,b,c, 1920), and E. Robinson (1919) patented cable-driven hands

12. In fact, many of these early patents should clearly never have been granted by modern standards, as there is often obvious applicable prior art.

actuated through a shoulder harness. S. Lucas (1890), Patton (1903) and Z. Taylor (1905) patented simple designs of "Götz-like" grippers or hands, that is to say they had to be operated by the other hand. Nelson (1909), Shackelford and Alexander (1911), Carnes (1904, 1911, 1912a,b, 1913), Cronemiller (1917), and Rohrmann (1919) patented complex to very complex hand constructions, with numerous parts, gears, cables, springs, and so on.

It is doubtful that all these artificial hands made it further than prototype stage, and we may also wonder about their actual usability. One of them however was a milestone in prosthetics history: the Dorrance hook, patented in 1912 by its inventor David Dorrance, himself a right hand amputee and the founder of a prosthetics company, now the Hosmer Dorrance Corporation in San Jose, California [13]. The Dorrance hook, also known as the split hook or the Hosmer hook, is a simple, robust, inexpensive, durable and easy-to-operate two-jaw gripper; it is held closed by powerful rubber bands and opened by a shoulder-operated cord (see figure 3.19). This body-powered hook, and variations of it (e.g. Trautman 1919; Kosek and Trautman 1928; Dorrance 1930, 1935, 1936; David 1940, 1942), has remained a prosthesis of choice for amputees ever since, and is now the most common terminal device for upper-limb amputees. It continues to be manufactured by the Hosmer Dorrance Corporation, and it also forms the line basis of two other large prosthetics companies, the German Otto Bock Healthcare and the British RSL Steeper (Hosmer Dorrance Corporation 2010; Otto Bock 2010; RSL Steeper 2010).



(a) The original split hook, as patented by Dorrance (1912)

(b) A Dorrance hook sold by the Hosmer Dorrance Corporation (2010), with the rubber band in place. Adult size, stainless stell with nitrile rubber tine surfaces for gripping irregular shapes. For moderate duty environment.

(c) A Trautman hook recreated by the Open Prosthetics Project (2006), with the rubber band in place. The company that made this hook is now out of business.

Figure 3.19 – Split hooks: old but not outdated

13. Rowley also founded a prosthetics firm, the J.F. Rowley Company, probably at the beginning of the twentieth century. The company still exists and is located since 1910 in Cincinnati, Ohio, with offices in nearby Indiana and Kentucky (J.F. Rowley Prosthetic & Orthotic Laboratory 2007). They provide artificial limbs to amputees and services to people with disabilities, but do not manufacture prostheses themselves any more (including Rowley's original designs).

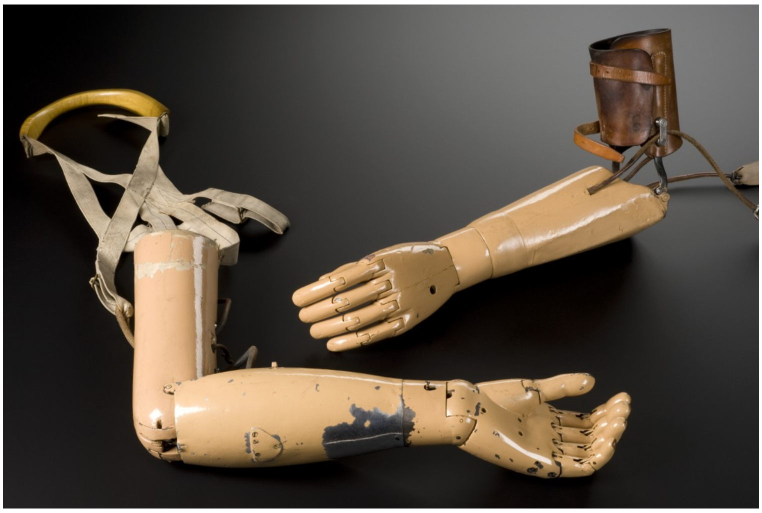


Figure 3.20 – Carnes arms for above-elbow and below-elbow amputations (1915). Each finger has two degrees of freedom in flexion-extension. The thumb has only one degree of freedom which makes it approximated to the index finger in a precision grip. The wrist has flexion-extension and prono-supination.

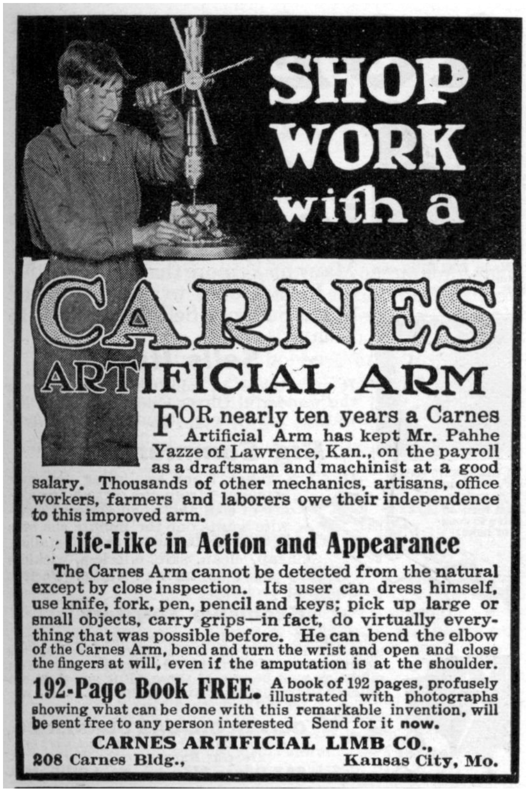



Figure 3.21 – Advertisement of the Carnes Artificial Limb Company (1924)

Another famous prosthesis of that time is the anthropomorphic Carnes arm (see figures 3.20 and 3.21), but for very different reasons. William Carnes, an American mechanic, had lost his right arm above the elbow in 1902 in a machine shop accident. Dissatisfied with the prostheses he tried, he went on to make one of his own (Carnes 1904), then sell similar arms to other amputees. This led him to the creation of the Carnes Artificial Limb Company in Kansas City, Missouri, with former clients as associates (Carnes Artificial Limb Company 1912). Their product, and subsequent revisions of it (Carnes 1911, 1912a,b, 1913, 1922), was allegedly very dextrous and life-like, and crafted relatively well. Its outer parts were made of vulcanized fiber and enclosed a complex mechanism of over two hundreds steel parts, operated by three cords controlled by movements of the amputee's shoulders and stump (Carnes Artificial Limb Company 1912). The prosthesis enabled its wearer to perform "detail-oriented movements that were beyond the scope of tool-like work prostheses" (Schweitzer 2010b).

The Carnes arm sold well in the United States and Canada, and was exported to Europe through demonstrations at medical and engineering conferences. In 1916, it attracted the interest of the German Prüfstelle für Ersatzglieder (Inspection Office for Prostheses), a governmental agency in charge of testing and recommending products and strategies for prosthetic limbs (Schweitzer 2010b). World War I was indeed sending back an unprecedented number of wounded soldiers from the front: at the end of the war, the total number of disabled ex-servicemen would reach approximately eight million, all countries included (Audoin-Rouzeau and A. Becker 2006, page 120). In Germany, as in the other European countries for that matter, prosthetics were not keeping pace with the actual requirements of such a growing number of users. Innovations were therefore sought from the United States and their experience in limb making following the Civil War: Germany purchased the patent licenses of the Carnes arm in 1916 for an enormous amount of money, and proceeded to manufacture the arm in large quantities.

It was however a bad decision, since in the long run the drawbacks of the Carnes arm outweighted its advantages. Because it was an impressively complex construction, it was also breakable, unsuited to heavy labor, long and costly to repair. Its operation was reportedly a physical exercice, that would cause soreness and pain on the stump if prolonged (Schweitzer 2010b). It was expensive to produce: in the United Kingdom, where the limb was imported from the United States, it became known as the "officer's arm", as it tended to be officers who bought them (Science Museum London 1999a). According to a German surgeon, the hands "show only several particular achievements (such as dressing and undressing, eating and drinking, writing, and so on), that when presented in clever succession create the appearance of a versatile functional replacement. In reality, in summary, the many expensive and very fragile parts of the prosthesis do not achieve a lot more than simpler prostheses" (translated from Karpa 2004, page 26, citing Witzel 1915).

So the evaluation of the Prüfstelle was wrong, and although the Carnes arm may have been a suitable prosthesis for some amputees, it was not worth mass-manufacturing it for everybody. Actually, it became rather unpopular relatively quickly, in the early 1920s, and was entirely dropped by the start of World War II. As for the Carnes Artificial Limb Company, it folded during the Great Depression [14]. The Prüfstelle's

14. The United States patent files have one last patent by Carnes (1942), but it appears to be the design he sold more than twenty years before to the German (Schweitzer 2010a).

decision was all the more unfortunate that it was made at the expense of a promising innovation: cineplasty, promoted by German surgeon Ferdinand Sauerbruch, consisted in isolating a muscle of the stump in a loop outside the body, covering it with skin, and using this loop to drive an adapted prosthetic hand (see figure 3.22). Much more information on this subject may be found in Karpa's thesis (2004), which provides a thorough historical account on arm prosthetics in Germany in the first half of the twentieth century, with extensive information on the contributions of Sauerbruch and his conflict with the Prüfstelle. Schweitzer (2010a,b) summarized some of this information in English.

Figure 3.22 – Sauerbruch's cineplasty on a boy with right above-elbow amputation and left shoulder disarticulation (1949). The muscles and the skin are shaped into tunnels whose contractions operate the control cables. The procedure has the significant advantage of enabling a fine force control of the prostheses, as well as a much better force feedback than actuation through a shoulder harness. It has the drawbacks of additional surgery, difficult hygiene, losing the function of a muscle and having to learn its new one. Cineplasty went out of fashion in the 1960s, but is not totally forgotten (Brückner 1992; Weir, Heckathorne, and Childress 2001; Kuiken 2003).

Between World War I and World War II, the development of prosthetic hands slowed down a little bit. In the early 1920s, some complex mechanical hands in the style of the Carmes arm were patented, perhaps inspired by the immediate post-war commercial success of this arm (J. Smith 1921; D. Anderson 1921; Dilworth 1921a,b; Nicola 1922; Pecorella, Patricolo, and Apel 1921, 1924a,b,c). Then, new designs and new mechanisms continued to be patented, mainly for simpler five-fingered cable-operated open/close hands (e.g. Ingold 1922; Dedic 1923; Burney 1924; Dorrance 1928; Trautman 1933; Carmack 1939; Mollenhour 1946; Hibbard 1947), but also for variations of the original Dorrance split hook (e.g. Trautman 1919; Kosek and Trautman 1928; Dorrance 1930, 1935, 1936; David 1940, 1942). New materials, including stainless steel, aluminium and light aluminium alloys, were increasingly used. A cable-actuated hand with coiled springs for fingers was developed by Laherty and D. Becker (1933), and then improved and marketed during several decades by D. Becker (1942a,b, 1953a,b, 1958a,b, 1968). The resulting designs, nowadays known as the "Becker Lockgrip Hand" and "Becker Imperial Hand" (see figure 3.23), are still manufactured by the inventor's family business in Saint Paul, Minnesota (Becker Mechanical Hand Company 2010). They have been remarked for their performance, reliability and durability, and were demonstrated to complete a maximum of "activities of daily living" (Schweitzer 2009–2010), which explains their good reputation.

(a) The fingers have jointed phalanges, covered by oval-shaped spring wire and ending in a semi-soft plastic tip. The hand is automatically locked when closed (hence the name).

(b) The inner mechanism is simple and sturdy, therefore reliable and durable. Pulling the control cable opens the fingers, releasing it makes the spring close the fingers. The grip force may be adjusted by turning a screw.

Figure 3.23 – A modern mechanical hand prosthesis: the Becker Lockgrip Hand.

### Modern prosthetics: the aftermath of World War II

At the end of World War II, in response to the mobilization of war veterans and at the request of the army surgeon general [15], the United States government increased funding for prosthetics research and development, and launched an ambitious research program through the National Academy of Sciences: the Artificial Limb Program (B. Wilson J. 1963, 1992). The National Academy of Sciences, and later the Veterans Administration, promoted and coordinated scientific research in several universities and industrial laboratories. The Army and the Navy also contributed to this program with their prosthetics research laboratories. Physicians, surgeons, physical therapists and engineers worked together on many of the program projects, and much emphasis was placed on investigating normal limb movement and function in order to base prosthetic devices on biomechanical fundations. Indeed, it had quickly become apparent that advances in biomechanical understanding were necessary to formulate adequate design criteria on which good engineering could be based to produce devices that could solve many of the problems faced by the amputees (B. Wilson J. 1992).

The Artificial Limb Program resulted in biomechanics changing the practice of prosthetics during the 1950s, with new "devices and techniques based on fundamental data" (B. Wilson J. 1963). Substitutions of materials for new ones, such as plastics, and later titanium and titanium alloys, also helped prosthetics progress, although "more significant advances were in the areas of socket design and alignment of the various types of prostheses" (B. Wilson J. 1992). Another result of the program was the establishment of a national certification board to ensure that prosthetists and

15. Norman Kirk, himself an orthopedic surgeon.

orthotists met certain standards of excellence; this authority still exists and certifies those qualified to practice. Also, the program introduced standardized prosthetics training (instead of the previous apprenticeships) for physicians, therapists, and prosthetists (students as well as working professionals). Indeed, “prior to 1957 medical schools offered little in the way of training in prosthetics to doctors and therapists” (B. Wilson J. 1963). The inclusion into medical and paramedical curricula of “courses in prosthetics at both undergraduate and graduate levels” was an important achievement of the Artificial Limb Program.

And so, the aftermath of World War II and the 1950s marked the birth of modern prosthetics and orthotics, as well as the beginning of the involvement of the United States government in prosthetics research. This involvement continues today, for instance through the Defense Advanced Research Projects Agency funding and coordinating the recent “Revolutionizing Prosthetics” program (DARPA 2006–2010b). For more on the Artificial Limb Program, the above cited references by B. Wilson J. (1963, 1992) have a wealth of information. The first one also provides a lot of information on amputation surgery, prosthetics and rehabilitation, and the second one reviews the post-war amputee programs in other countries than the United States. From a more surgical viewpoint, Dougherty, Carter, Seligson, Benson, and Purvis (2004) explain the advances in orthopedic surgery that resulted from World War II, and Manring, Hawk, Calhoun, and Andersen (2009) review the history of amputation, and more generally the history of war wound treatment by the United States military, up to the modern conflicts of the twentieth century (Korea, Vietnam, Iraq, Afghanistan).

### 3.2.3 Externally-powered prosthetic hands

The middle of the twentieth century also marked the start of research on externally-powered prosthetic limbs and on the use of electromyography to control them. This research would lead to the advent of a totally new type of prostheses.

In contrast to mechanical cable-driven hooks and hands, which get their power and control from the amputee’s body, externally-powered prostheses get their power from another source: electric batteries for those that use electric motors, and gas canisters, usually of liquid carbon dioxide, for those that use pneumatic actuators. Control of the former prostheses occur most often with muscle contractions which are detected by surface electrodes for electromyography, and control of the later ones occur usually with muscle movements which operate valves. The following paragraphs explain how they work and summarize their recent history.

#### Pneumatic prosthetic hands

The first gas-powered prostheses were developed right after World War II in university clinics in Heidelberg, Germany and Vaduz, Lichtenstein, respectively by Otto Häfner and Sigmund Weil and by Edmund Wilms (Marquardt 1965; Neff 1978; Childress 1985). The Vaduz construction was a voluntary-closing hand activated by muscle bulge: an air-filled pad was placed between the stump and the prosthesis socket and connected to some kind of switch by a flexible tube, so that when the amputee contracted the muscles in their stump, pressure change in the pad operated the switch, hence the control input of the prosthesis (Wilms 1951; Childress 1985). Development work on gas-powered prostheses continued during the 1950s, mainly in Germany, but it really accelerated at the turn of the 1960s and spread to other countries, because of the many children who were born without limbs because of the drug thalidomide. Various prosthetic arms and hands were made for these children, who would control them by operating switches or valves with their vestigial hands and fingers, if they had, or by opening and closing valves with movements of their shoulders (Marquardt 1965; Simpson and Lamb 1965; Neff 1978).

**Thalidomide-related research efforts** Thalidomide was a drug introduced in Germany in 1957 as a sedative and an antiemetic, and thousands of pregnant women used it to relieve morning sickness. It turned out to be a powerful teratogen, and by the time it was withdrawn in 1961, thousands of children had been born with congenital anomalies in the forty-six countries where the drug was sold (Marquardt and Fisk 1992). The anomalies were numerous and varied, but as far as the musculoskeletal system is concerned, they were most notably the absence of limbs (amelia) and the malformation and shortening of limbs, with deformed hands and/or feet somehow placed directly on the trunk (phocomelia).

The thalidomide tragedy pushed research forward in externally-powered prostheses, especially in Germany, United Kingdom, Sweden, and Canada (B. Wilson J. 1992). Indeed, body-powered prostheses are difficult to fit and use on high-level amputations, as the more limb is missing, the less muscle power and joint movement is available for power and control of the prosthesis. Consequently, children with upper amelia or phocomelia were especially disadvantaged, all the more if it was bilateral. This made the case for external power, and pneumatic power was on the whole preferred over electric power because its advantage-to-drawbacks ratio was at that time globally superior: pneumatic actuators were light in weight in comparison to electric motors and their gear mechanisms (an important aspect for child prostheses), they were less noisy and more easily controlled, they don't lost power through continuous loading, and they have "natural compliance [16] properties that keep them from being rigid", making them easier to use and better at withstanding shocks (Childress 1985).

Most notable among the thalidomide-related development efforts were those conducted by Ernst Marquardt at the orthopedic clinic of the University of Heidelberg, Germany, and by David Simpson at the Princess Margaret Rose orthopedic hospital in Edinburgh, Scotland (Marquardt 1962, 1965; Simpson and Sunderland 1964, 1965; Simpson and Lamb 1965; Simpson 1968). Both were major prosthetic centers for the limb disabilities due to thalidomide, and many children were fitted there.

Figure 3.24 illustrates one of the arm prosthesis made in Edinburgh. This arm had five degrees of freedom and was controlled by valves operated by movements of the two shoulders. It worked in spherical coordinates from its shoulder joint as follows (Childress 1985, page 7): elevation-depression of the right shoulder moves the hand up or down by rotating the arm around the shoulder joint; protraction-retraction of the right shoulder moves the hand away or closer to the shoulder; protraction-retraction of the left shoulder moves the hand right or left by rotating the arm about the shoulder joint; elevation-depression of the left shoulder pronates or supinates the hand. The shoulder, elbow and wrist joints were also coupled so that the hand would maintain its orientation during motion, in order to make moving objects safer. As for the hand, it was a simple open/close terminal device "controlled by a switch through some other motion of the body" (Childress 1985).

16. Compliance is the inverse of stiffness.

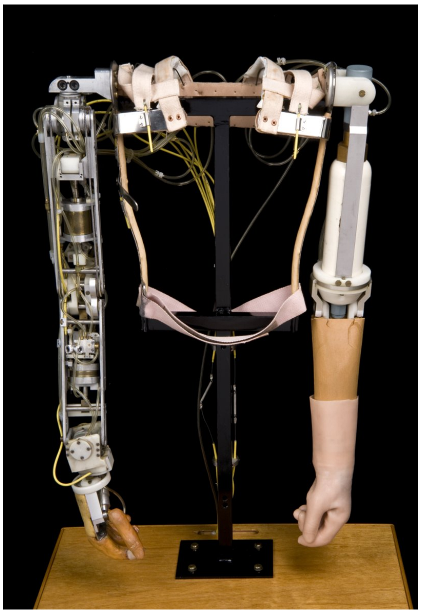


Figure 3.24 – A gas-powered prosthetic system for thalidomide children with upper bilateral amelia, made in the 1960s at the orthopedic hospital in Edinburgh, United Kingdom (Science Museum London 1979). The active arm may be hidden by clothes or a cosmesis. The compressed carbon dioxide is stored in canisters in the passive arm.

**Results of thalidomide-related research efforts** The results of these new prostheses were overall good (B. Wilson J. 1992). Childress (1985) notes that the Edinburgh arm prosthesis described above was operated "naturally" by children, "without much training, and seemingly without too much mental load". The remarkable control of this arm played without doubt a role in this ease of use. However, the arm was also "complex and difficult to keep functional on active children", and more generally all those new prostheses, albeit ingenious, were uncomfortable, wearying, heavy, needed regular re-fittings and adjustments as the children grew, and were too delicate to be really suited to the activities children typically get into. Besides, their function was once again limited to simple grasping: despite their display of high-end technology, they did not expand functionality further than traditional prostheses. In addition to their physical and functional shortcomings, they could also be at times psychologically overwhelming: children with upper and lower limb deficiencies would be almost entirely encased within complex limb systems. Last but not least, externally-powered prostheses cut totally all feedback to their user, they do not even give the kind of force feedback that cable-driven hooks and hands may offer (to a very limited extent though).

All these factors make it debatable whether fitted children gained any more independence than they would otherwise have done with their own short upper limbs or their feet. In fact, pneumatic prostheses were in the end "virtually all discarded by the time the children reached their teens" (Science Museum London 1999b; Schmidl 1977). Thirty years after the thalidomide tragedy, Marquardt and Fisk (1992) note that "very few individuals continue to use prostheses today. Some would use them in public, but behind their bedroom door they are independent with their feet."

The conclusion that we can draw from the desertion of gas-powered prostheses is that, in the long run, their advantage-to-drawbacks ratio was felt by their users to be inferior to the one of using "what they had" instead. It is true that the technology of powered prostheses was still primitive: they had hardly existed for a decade, and their control was in its infancy. It is also true that the lack of tactile and force feedback is a serious hindrance to usability (see sections 2.1.5 and 2.4.1, in chapter 2, for more on the importance of sensory feedback in human and robot hands). In cases of phocomelia, since vestigial hands are present, it is very sensible to make use of them as much as possible because of their sensitive capabilities, rather than using them to operate an insensitive prosthesis. In cases of amelia, feet are an option because of their sensitive capabilities too; high-level bilateral traumatic amputees also have been reported to learn how to use their feet in unsuspectedly skillfull ways (Marquardt 1965).

The story of gas-powered prostheses is very reminiscent of what happened to the Carnes arm, abandoned in favor of split hooks and simpler cable-actuated hands: in both cases, the achievements of the new devices were not worth their drawbacks, in comparison to already extant solutions. This ultimate criterion is what must be kept in mind when designing hands for prosthetic applications. It also reminds us that progress is not continuous but made of trials and errors. As for externally-powered prostheses, gas actuation was eventually dropped in favor of electric actuation and myoelectric control, because technological advances, especially in electronics, meant that the advantage-to-drawbacks ratio of myoelectric prosthetic hands had become superior to the one of pneumatic prosthetic hands.

**A modern pneumatic prosthesis** Gas-powered prostheses are not entirely forgotten though, and they may return in some cases where they could be more adapted than electric hands. A modern example of pneumatic prosthesis is reported by Fite, Withrow, Shen, Wait, Mitchell, and Goldfarb from Vanderbilt University in Nashville, Tennessee, United States. The researchers have recently "designed, fabricated, and demonstrated a twenty-one degrees of freedom anthropomorphic transhumeral prosthesis with nine independent actuators" (Fite, Withrow, Wait, and Goldfarb 2007; Withrow, Shen, Mitchell, and Goldfarb 2008; Fite, Withrow, Shen, Wait, Mitchell, and Goldfarb 2007, 2008). They used liquid hydrogen peroxide instead of carbon dioxide as the energy source, which results in much smaller and lighter canisters [17], and they also made appropriate miniature servo-valves. The resulting prototype, illustrated in figure 3.25, shows promise for potential use with the recent developments of orthopedic surgery, such as direct integration of the prosthesis into the user's skeleton (osseointegration) and extended neural interfacing of the prosthesis with the user's nervous system (neural signal control and targeted muscle reinnervation, see end of section 3.2.4).

### Myoelectric prosthetic hands

Electromyography means recording the electrical activity of a muscle, either by surface electrodes placed on the skin above the muscle (surface electromyography) or by needle electrodes inserted through the skin into the muscle tissue (intramuscular electromyography). It has been known since the nineteenth century that contraction of muscle fibers is associated with electrical activity (see, for instance, R. Elliott 1998,

17. Hydrogen peroxide decomposes into dioxygen and water when in contact with a catalyst: this is a chemical reaction that breaks molecular bonds, and therefore releases more energy than the phase change from liquid carbon dioxide to gaseous carbon dioxide. As a consequence the energy density of hydrogen peroxide canisters is greater than the one of carbon dioxide canisters.

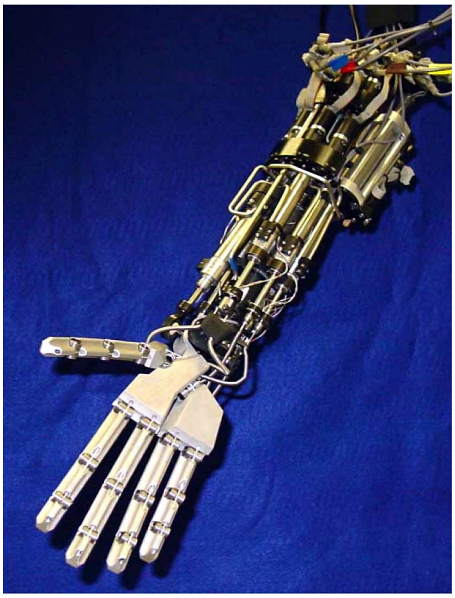


Figure 3.25 – The prosthetic Vanderbilt Arm. The pneumatic actuators are located in the forearm, similarly to our muscles (see section 2.1.2 on muscle anatomy, in chapter 2).

chapter 2 or Lovely 2004 for an explanation of this phenomenon at the molecular level), but the capability of accurately detecting these electrical signals has been dependent on advances in electronics made during the first half of the twentieth century, especially from the 1930s to the 1950s (progress relative to electrodes, amplifiers, oscilloscopes, signal processing).

It is important to stress that the action potentials recorded during electromyography come from the muscle cells, not from the nerve fibers, although both are related of course. Muscle fibers are innervated in small groups called "single motor units", the smallest voluntary contractible group. A single action potential in a single motor unit is associated with a twitch; sustained contractions require repeated firings of the single motor unit, resulting in a string of action potentials; and as more force is needed, more single motor units are fired, or "recruited" by the motor nervous system (Farry, I. Walker, and Baraniuk 1996). Intramuscular electromyography records the electrical activity of a few single motor units, whereas surface electromyography gives a more general picture. Both have many applications, for instance in hospitals to diagnose certain neuromuscular conditions, or in research laboratories involved in biomechanics or neuromuscular physiology, or in prosthetics.

**What is a myoelectric hand and how to use it** A myoelectric prosthetic hand is a battery-powered, motor-driven artificial hand that uses surface electromyography to get its control inputs from the amputee's muscles. Surface electrodes accommodated in the prosthesis socket make contact with the skin and detect action potentials emitted by the muscles when the user voluntarily contracts certain muscles in the residual limb. These signals are amplified, filtered, smoothed, averaged, and otherwise appropriately processed by the embedded electronics. The resulting control signals are sent to the motors that actuate the functional elements of the prosthesis (Trost and Rowe 1992; Sobotka 2010).

These functional elements are actually quite simple in general: an open/close terminal device, a rotating artificial wrist, sometimes an artificial elbow if needed. Figures 3.26 and 3.27 give examples of such standard myoelectric hands. Unfortunately, it is difficult to control more degrees of freedom myoelectrically, at least with the current commercially-available myoelectric techniques. Indeed, the general rule is that one electrode picks up the control signals for one movement, so two electrodes code for the open/close operation of the terminal device: this is called a myoelectric "channel", made of two electrodes placed on two "sites". Adding more electrodes to control additional degrees of freedom doesn't work well, because there are simply not enough suitable sites for surface electromyography on a residual limb. Indeed, in comparison with the full limb, only a few extrinsic muscles remain in a stump, and some of them might not give sufficient electric response to be used in myoelectric control. Besides, even if it were possible to fit out each remaining muscle with a surface electrode, it would be impossible for the amputee to throw one particular of those muscles into action to actuate one corresponding degree of freedom, because the muscular system is represented as movements in the central nervous system, not as individual muscles, and these movements are the product of several muscles acting at the same time (see section 2.1.2, in chapter 2, for more on muscle interactions and synergies).

Therefore, myoelectric prosthetic hands seldom feature more than two electrodes, and these electrodes have to be used sequentially in order to control the different powered components (B. Kelly, Pangilinan, Rodriguez, Mipro, and Bodeau 2009). For instance, with a single two-electrode channel, contraction of one set of muscles may trigger wrist pronation or hand closure, contraction of the antagonist set of muscles would realize wrist supination or hand opening, and co-contraction of both sets of muscles would switch between wrist rotation and terminal device operation. Additional degrees of freedom mean additional control modes to cycle through, so the more degrees of freedom in a myoelectric hand, the less practical its utilization.

Figure 3.26 – A typical myoelectric hand: Otto Bock's System Electric Hand, size 7, for teenagers and adults with small hands (Otto Bock 2010). It is an open/close three-jaw gripper in a PVC cosmesis.

Below-elbow amputees are more likely to benefit from myoelectric hands than above-elbow or shoulder amputees, because their stumps have remnants of extrinsic muscles associated with hand opening and closure (Sobotka 2010). They can therefore control the action of the prosthetic hand with the finger flexor and extensor muscles, or with the wrist flexor and extensor muscles. The result is that a rather natural relationship is maintained between the muscles used and the prosthetic motion. This means that the amputee is likely to learn usage of their prosthesis quickly and easily. This is also the reason why myoelectric prostheses are very often described, with high exaggeration, as “thought-controlled” or “bionic” by ill-informed media and boastful prosthetics manufacturers. Thought control would occur if control signals were recorded directly in the central nervous system, or at least in the nerves with high detail, but not from the muscles, through the skin, by only two electrodes. It is all the more wrong for above-elbow amputations and shoulder disarticulations: in those cases, the muscles that may be used for myoelectric control have nothing to do with normal hand operation (Sobotka 2010). Moreover, in some of those high-level amputation cases, the remaining muscles may not be able to present more than one exploitable myoelectric site. A single-electrode channel is therefore used, with a two-threshold strategy: if the myoelectric activity is below the first threshold, the hand is not actuated; if it is above the first threshold but below the second, the hand opens; and if it is above the second threshold, the hand closes (Lisi 2010, page 66). As a consequence of all these difficulties in electrode fitting, high-level amputees need significant training and therapy to master their myoelectrically controlled prosthesis, in a manner that is very remote from thought control.

Figure 3.27 – A bilateral amputee playing table football at Walter Reed Army Medical Center in Washington, District of Columbia. His right hand is a split hook, his left one is a myoelectric hand in a cosmetic PVC glove.

**Control aspects of myoelectric prostheses** The embedded electronic control systems of myoelectric prosthetic hands may be relatively sophisticated, compensating for the fact that the small number of electrodes limits the dexterity of the hand. First of all, most if not all contemporary myoelectric control systems allow for some kind of proportional control from the amputee to the prosthesis, that is to say that the degree of opening or closing of the hand, or the velocity of the joints, or the force of the grasp, are proportional to the intensity of muscle contraction (B. Kelly, Pangilinan, Rodriguez, Mipro, and Bodeau 2009). There is therefore feedback from some sensors to the prosthesis, for closed-loop control of prehensile force, joint position and joint velocity (see figure 3.28). For more on this subject, Scott (1990) provides a comprehensive view of the need for feedback in myoelectric prostheses. Also, compliant grasping may be allowed: in that case, the terminal device is made slightly compliant by means of motor control, that is to say that its fingers are not completely stiff when grasping an object, they tend to exhibit a spring-like behavior. This results in a grasp that is more gentle to fragile, breakable objects.

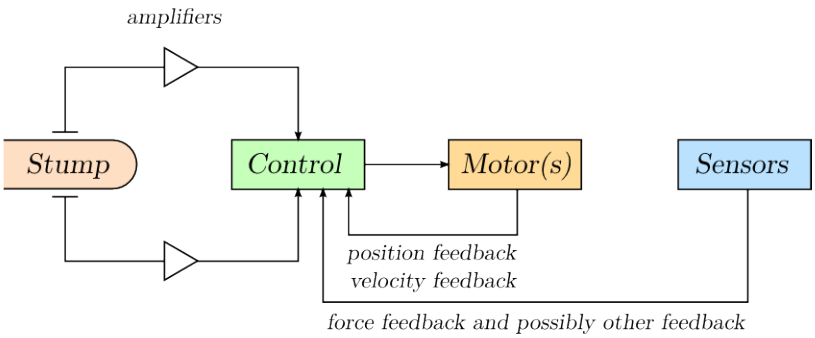



Figure 3.28 – Simplified block diagram of a myoelectric prosthetic hand

In newest prosthetic hands, advanced closed-loop control is provided by the embedded microprocessors, in an attempt to make the hand somewhat intelligent and semi-autonomous (Lisi 2010, chapter 2; Chappell 2011). The idea behind this goal is to provide the user with an artificial hand that cares for certain aspects of prehension by itself, in the same manner that the biological hand seems to care for those aspects on its own because its control by the nervous system is almost automatic and subconscious. For instance, Otto Bock's one degree of freedom SensorHand has sensors that enable its control algorithms to "recognize when an object starts to slip from the hand" and "automatically increase the grip force" to keep the object in grasp (Lisi 2010, pages 45–46). Touch Bionics' i-Limb has individually-actuated fingers with "a built-in stall detection feature, which tells each finger when it has sufficient grip on an object": at this moment, the finger is locked into position until the user "triggers an open signal through the muscles" (Lisi 2010, pages 46–47; Touch Bionics 2010). This trend towards semi-autonomous prostheses clearly brings prosthetics closer to robotics on a number of shared issues regarding sensors and control: two areas of research that are recognized as both difficult and critical to a potential future proper emulating of human hands by humanoid hands, be it for robotic or prosthetic applications (see section 2.4 in chapter 2).

**Benefits and downsides** Myoelectric hands have advantages and disadvantages (Trost and Rowe 1992; Sobotka 2010). On the bright side, they combine cosmesis and function, contrary to conventional body-powered hooks (see figure 3.27). And it seems nowadays a reasonable demand that amputees have access to prostheses which are not only functional but also look like hands. Also, myoelectric prostheses have sockets that provide self-suspension and embed the control electrodes, eliminating the need for a harness and its control cable. The result is twofold. First, more comfort, since the harness of a body-powered prosthetic hand must be tight to capture correctly the control motions of the shoulders and residual arm. Second, more operational space, that is to say that the prosthesis may be operated in any position, since it is not restricted by the tension of a cable. A greater range of motion is possible, "particularly when overhead motions are involved" (Sobotka 2010). Additional benefits of myoelectric hands are "superior grip strength, especially when compared with voluntary-opening devices", and possible operation by high-level amputees, who frequently "lack the body excursion or strength to operate and control a body-powered prosthesis, but can activate an electrode" (Trost and Rowe 1992).

On the other side, the drawbacks of myoelectric hands cannot be minimized. Their complexity obviously makes them more vulnerable and less durable than simple and robust split hooks. Mechanical and electrical breakdowns happen once in a while, and wear means that components need to be changed over the course of years. Repairs are usually costly because they demand some expertise and expensive spare parts. Batteries, too, need periodic replacement, in addition to frequent recharging. Since myoelectric prostheses are not so robust, their usage “demands certain restrictions of an amputee’s activities, a feature that is particularly cogent when considering very young children” (Trost and Rowe 1992). For instance, the prostheses “cannot be used to hammer, to pry objects, or to play in water without some risk of damage to the device”. Activity restrictions also affects adults: Sobotka (2010) notes that the myoelectric systems are “well suited for amputees such as salespersons, students, business people and professionals who are engaged in light work”, but “not usually recommended for patients involved in heavy work such as farming or construction”, at least not as a primary prosthesis. Weight of the prosthesis is a common complain, and discomfort from the socket may also happen (sweat issues, soreness, blisters), triggering phantom pain in extreme cases (Schweitzer 2008–2011). Because of the electrodes and embedded electronics, optimal operation is dependant on the absence of electromagnetic interferences and on a particular range of temperature and humidity conditions. The cosmetic glove is also a weak link. According to Trost and Rowe (1992), “it tears quite easily and becomes soiled. Certain stains such as ball point pen ink and newsprint are virtually impossible to remove. The cost of replacing cosmetic gloves is significant”, and has to be paid every six to twelve months: a few hundred dollars for the everyday one-color PVC glove and above a thousand dollars to several thousand dollars for a complex, custom-made, high-definition silicone cosmesis (W. Hanson 2001; Bowers 2002; Schweitzer 2008–2011). Price, actually, is finally the biggest single drawback of myoelectric hands: not only the cosmesis is expensive, but most of all the device itself. Trost and Rowe (1992) wrote that “the minimum cost for these devices is several thousand dollars”, and nowadays, current state-of-the-art myoelectric hands such as Touch Bionics’ i-Limb or RSL Steeper’s Bebionic are in the ten thousand dollars to twenty thousand dollars range, an expense not necessarily entirely covered by insurance companies. So high a price tag has actually been questioned by some users, for instance Schweitzer (2008–2011) repeatedly accuses prosthetic companies of overpricing cheap electronics [18] and 1960s myoelectric technology. Similarly, under the motto that “prosthetics shouldn’t cost an arm and a leg”, a nascent but growing community of users and engineers are trying to apply the successful model of open-source software to prosthetics, sharing designs, ideas and improvements for free with permission to distribute and modify (Open Prosthetics Project 2006–2010; Kuniholm 2009).

**History of myoelectric hands** The history of myoelectric hand prostheses is presented in great detail by Scott (1967), B. Wilson J. (1978), Childress (1985), and McLean and Scott (2004). In short, research on myoelectric control and electrically-powered prostheses started in the 1940s and 1950s independently in different parts of the world. It developed particularly during the late 1950s, the 1960s and the early 1970s. Myoelectric prostheses left research laboratories to hit commercial market in the late 1960s and early 1970s, and starting in the late 1970s, they “began to take

18. The reported case of an Otto Bock rechargeable battery for a myoelectric hand, sold around 700 dollars and found to contain only five Varta 1.2 V 260 mA h nickel-cadmium batteries, is striking.

on real clinical significance" (Childress 1985), that is to say that larger numbers of people were fitted with them. By the end of the 1980s, their commercial availability was widespread, and they are ever since a standard product of prosthetics companies, large (Otto Bock 2010; RSL Steeper 2010) and small (Hosmer Dorrance Corporation 2010; Motion Control 2010; Touch Bionics 2010).

According to Childress (1985), the first myoelectric prosthesis "was developed during the early 1940s by Reinhold Reiter, a physicist working with the Bavarian Red Cross". Reiter published his work in Germany after the war (Reiter 1948), but it was not widely known and myoelectric control was going to be "rediscovered" in several countries during the 1950s, apparently independently: in particular, in the United States (Berger and Huppert 1952), in the United Kingdom (Battye, A. Nightingale, and Whillis 1955), and in the Soviet Union (Kobrinski, Bolkhovitin, Voskoboinikova, Ioffe, Polyan, Popov, Slavutski, Sysin, and Yakobson 1961). The so-called Russian Hand, illustrated in figure 3.29, was an electric hand controlled by myoelectric signals from the residual wrist flexors and extensors of a transradial amputee. It was apparently the first to use transistors [19] instead of vacuum tubes for signal amplification, and consequently it was portable (previous systems were prototypes intended for concept testing rather than prosthetic use).

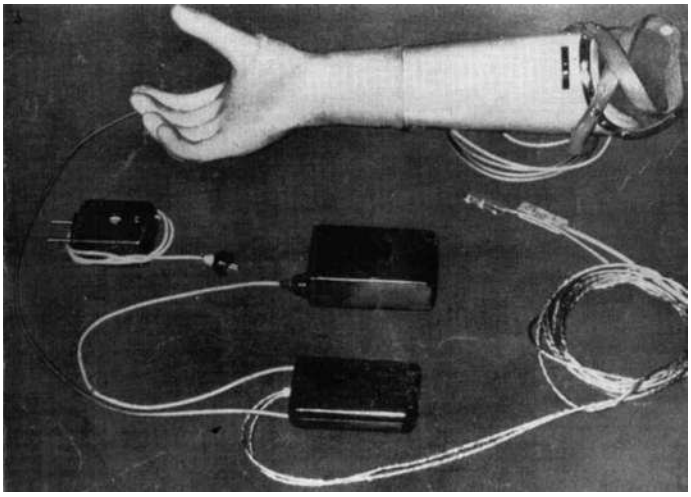


Figure 3.29 – The Russian Hand (mid-1950s). From Childress (1985): "The external battery pack is shown in the center of the photograph. The electronic package is beneath the battery. The battery charger is at left. Note the long electrode wires and the prosthesis suspension straps."

During the 1960s and 1970s, research on electric hands and myoelectric control spread to laboratories in other countries around the world: most notably Canada (McLaurin 1965; Dorkas and Scott 1966), Italy (Schmidl 1965, 1977), Sweden (Kadefors 1969; Herberts and Petersén 1970; Herberts, Almström, Kadefors, and P. Lawrence 1973), Yugoslavia (Tomović and Boni 1962; Rakić 1968; Tomović 1970), and Japan (Kato, S. Yamakawa, Ichikawa, and Sano 1970). Collaboration and communication between research centers increased, at both national and international levels. In particular, major international conferences happened during the 1960s in the United States,

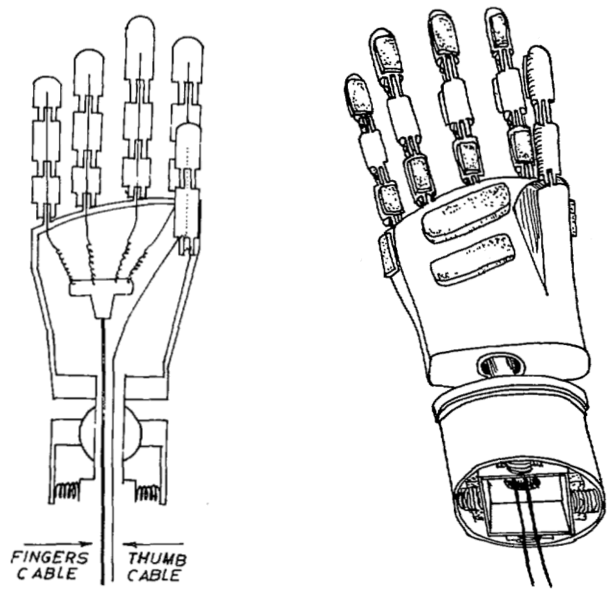
19. A recent invention, the transistor was revolutionizing electronics engineering. All subsequent myoelectric hands made use of them (actually, all electronic devices in general made use of them).

Yugoslavia, and the United Kingdom; they became milestones in the history of prosthetics research (Childress 1985; McLean and Scott 2004).

In Canada and Italy, research was primarily motivated by the birth of thalidomide children, and was accordingly government-funded (McLean and Scott 2004). In Canada, it took place essentially at the University of New Brunswick in Fredericton, New Brunswick, where Robert Scott headed one of North America's most active group on myoelectric control, and also at Ontario Crippled Children's Center in Toronto, Ontario. In Italy, an Austrian researcher, Hannes Schmidl, fitted "externally-powered artificial arms on a relatively large scale" during the 1960s and 1970s (B. Wilson J. 1978; Schmidl 1977). He worked closely with Otto Bock in Germany, which had become involved in myoelectric prostheses in the mid-1960s, and supplied him with electric hands and other prosthetics components.

In the United Kingdom, Bottomley (1965), of West Hendon Hospital in London, designed a hand with two important novel features for that time (actually, it was an electric split hook, but the idea could very well be applied to an open/close hand). First, it had proportional closed-loop control, with both force and velocity feedback: the velocity of the terminal device (when it moved freely) and the force it exerted (when it grasped an object) were proportional to the strength of the myoelectric signal, that is to say to the muscle contraction. In contrast, previous myoelectric hands such as the Russian Hand used a simple on/off open-loop control, that is to say that when myoelectric activity rises above a certain level, a switch is turned on and a motor activated, and stopping the motor requires the myoelectric activity to fall back below the threshold. Second, Bottomley's hand featured a unique myoelectric signal smoothing circuit, which allowed for the fluctuations in the myoelectric signal amplitude to occur without disrupting the smooth control of the motor. Proportional control and signal smoothing were integrated in the designs of most of the research groups involved in subsequent myoelectric devices.

In Yugoslavia, two of the key researchers in externally-powered prosthetics were Rajko Tomović and Miodrag Rakić. Tomović was in fact working at the University of California in Los Angeles at the turn of the 1960s, "when myoelectric control was becoming a broad area of research across the United States" (McLean and Scott 2004). He instigated there the first adaptive, multi-articulated electric hand (Tomović and Boni 1962; Rakić 1962). "Adaptive" means that the hand can alter the shape of its grasp to conform to the shape of the object. To achieve this effect, the four fingers are linked to a common cable that closes the hand when pulled by a motor, and a spring is inserted between each finger and the common cable (figure 3.30(a)). This system realizes a simple elastic coupling between the joints of the fingers, allowing individual adjustment of the fingers to the shape of the object. Pressure-sensitive pads are placed on the surface of the palm and phalanges (figure 3.30(b)). They provide feedback for the control: the motor is stopped when pressure is approximately equal among the pressure pads, indicating that the hand has succesfully adapted to the shape of the object. This elegant development was continued and improved upon the return of Tomović to Yugoslavia, with a number of prototypes being designed and fabricated in the University of Belgrade (Rakić 1964, 1967, 1968; Tomović 1970; Jaksic 1970; Rakić, Jaksic, and Ivancevic 1970). The adaptive artificial system became known as the Belgrade Hand. It wasn't that much of a clinical success (Kay, Kajganic, and Ivancevic 1970), and is now remembered as "not sufficiently reliable to be used" because "the control and sensor technologies of the day were not adequate for the task" (Bekey 2005). However, Childress (1985) notes that "it was used extensively in research laboratories and has had influence on robotic hand developments". Indeed, even though work on the Belgrade Hand was abandoned during the 1970s, the prosthesis was reborn as a famous multifingered hand for robots in the late 1980s, when research on multifingered robotic manipulation really took off. This new version, called the Belgrade/USC Hand, was a joint project between Rajko Tomović of the University of Belgrade and George Bekey of the University of Southern California in Los Angeles (see figure 2.43(a) in section 2.4, chapter 2). It kept the underactuation and adaptive capability that was the distinctive feature of its prosthetic predecessor (Bekey 2005; Fermoso 2008).




(a) Underactuation system (b) Pressure sensors

Figure 3.30 – The adaptive hand described by Tomović and Boni (1962). The pressure sensors are visible on the palm, proximal phalanges and distal phalanges.

In the United States, research on electric prostheses, myoelectric signal and myoelectric control was conducted in military-related laboratories such as the Army Medical and Biomechanical Research Laboratory and the Veterans Administration Prosthetics Center (Childress 1985), and in several universities across the country, especially the University of California at Los Angeles, the Massachusetts Institute of Technology in Cambridge, Case Western Reserve University in Cleveland, Ohio, and later in the 1960s Northwestern University in Chicago, Illinois and the University of Utah in Salt Lake City. The Northwestern group was headed by Dudley Childress and was a major advocate of self-containment and self-suspension for below-elbow myoelectric prostheses. In the early days of myoelectric control, indeed, the battery and the control electronics "had to be worn outside the prosthesis, usually in a chest pouch, on a clip at the waist, or on a band around the humeral section of the arm. The wires and connections required by this kind of configuration led to failures due to wire breakage. [...] In addition, the components outside the prosthesis were a nuisance to fit and to wear" (Childress 1985). Eliminating these components and wiring required refined hand and socket designs, which the researchers achieved in 1968 (Childress and Billock 1970). Nowadays, self-containment and self-suspension are standard for all below-elbow myoelectric hands (figure 3.27). At the Massachusetts

Institute of Technology, research was primarily focused on the development of a high-performance electric elbow with myoelectric control, for above-elbow amputees. The result of their research, the so-called Boston Arm, was marketed internationally; development and marketing of the device is continued by Massachusetts prosthetics company Liberating Technologies (2010). At the time of the original development, Stephen Jacobsen was a graduate student working at the Massachusetts Institute of Technology; he became well known in the fields of prosthetics and robotics after leaving for the University of Utah in the late 1960s, where he developed the Utah Arm in the 1970s, another electric elbow (Jacobsen and Jerard 1974; Jacobsen, Jerard, and Knutti 1974, 1975; Jacobsen, Knutti, T. Johnson, and Sears 1982; Jacobsen, Knutti, and T. Johnson 1985). The design was sold to Salt Lake City prosthetics company Motion Control (2010), which still produces it (in its third revision). The research teams at the Massachusetts Institute of Technology and at the University of Utah eventually began to collaborate through Jacobsen, and their joint research lead in the 1980s to the famous Utah/MIT Dextrous Hand, one of the first really anthropomorphic robot hands, and a milestone in the history of robotic dextrous manipulation (Jacobsen, Iversen, Knutti, T. Johnson, and Biggers 1986).

**Current state of the myoelectric hand market** Nowadays, commercially-available myoelectric hands are mostly the same in principle as they were in the 1970s and 1980s: open/close grippers in cosmetic gloves, as illustrated in figures 3.26 and 3.27, making use of usually no more than one myoelectric input channel. They aim more at the reliability of a simple grasp than at the complexity of the grasping patterns, let alone any real manipulation abilities. Commercial myoelectric hands are prehension systems only, just like all other hand prostheses. Manipulation is out of their league, for mechanical reasons (you can't manipulate anything with an open/close gripper) and control reasons (you can't manipulate anything with one myoelectric channel).

The perceived stagnation in commercial prostheses does not mean that research has stopped, though. Actually, the end of the twentieth century and the first decade of the twenty-first century are rich in advances (Lisi 2010, pages 50–72; Belter and Dollar 2011). Starting in the mid-1970s, myoelectric signal analysis progressed a lot: with proper electrode fitting and proper signal processing, it has become progressively possible to recognize the type of grasp that the user wants to perform; say, a cylindrical power grasp or a two-finger precision grasp. Consequently, hands able to perform several types of grasps have started to attract attention. Contrary to the classical one degree of freedom design, such "multifunction hand prostheses", as they are called, must be able to arrange their fingers in different configurations. Therefore, many advances made in robotics were transferred to prosthetics, especially from the 1990s on: multifingered prosthetic hands with several degrees of freedom and human-like kinematics were developed, on the model of multifingered humanoid robot hands. These prototypes integrated sensor technology and automatic control strategies developed initially for robot hands, but adapted for prosthetic applications, with a human in the control loop. Last but not least, research on sensory feedback from the prosthesis to the amputee has begun, mainly in the form of tactile stimulation of the amputee's skin, which gives information about the interaction force between the prosthesis and the object.

However, up to now, most of these improvements remain in prosthetics laboratories, and the multifingered, biomimetic, multifunction, highly sensorized prosthetic hands remain work-in-progress prototypes for experimental use, whose transformation into commercial devices has yet to be made. Nevertheless, a market trend towards multifunction devices is already noticeable. Indeed, the state-of-the-art commercially-available myoelectric hands are now five-fingered articulated devices with several degrees of freedom and some ability to arrange their fingers into four or five grip patterns. In addition to their increased utility, they appear more human and move in a more life-like manner than the conventional one degree of freedom myoelectric hands. Those state-of-the-art prostheses are Touch Bionics' i-Limb hand (as well as its follow-ups the i-Limb Pulse hand and ProDigits fingers), RSL Steeper's Bebionic hand and Otto Bock's Michelangelo hand. All those prostheses are very recent, and Otto Bock's Michelangelo is not even released yet.

Touch Bionics' i-Limb was the first one to hit the market, in July 2007. Unfortunately for us, there isn't any official technical documentation available on this hand; but it is at least fairly well described online and in the user and prosthetist manuals (Touch Bionics 2010). The i-Limb hand has five individually powered digits. Each one has two phalanges, one less than the biological model. The phalanges are actuated in flexion by a tendon connected to a small direct current motor. The thumb has one additional degree of freedom for abduction-adduction, but this degree of freedom is not active, instead, it may be positioned by the user with their other hand, according to the grip pattern they want to realize. Lateral power grip, cylindrical power grip, fingertip precision grip, spherical power grip and hook grip are possible (figure 3.31; see section 2.2.2 on grasp types, in chapter 2), as well as a few non-prehensile hand postures. At the time of the i-Limb introduction, this capability for various grasping patterns was new to the market, as well as the human-like, adaptive wrapping of the prosthesis around objects, which offers a tightier, more secure grasp. Both these features are made possible by the multifingered design and the multiple actuation. The myoelectric control is traditional: proportional control via one myoelectric channel of two surface electrodes, with all the motors activated together by the myoelectric signal. According to Touch Bionics (2010), a "built-in stall detection feature tells each finger when it has sufficient grip on an object, thus when to stop powering. Individual fingers lock into position until the patient triggers an open signal through the muscle." The hand is manufactured in three adult sizes and two wrist configurations, one for transradial amputations and the other for wrist disarticulations.

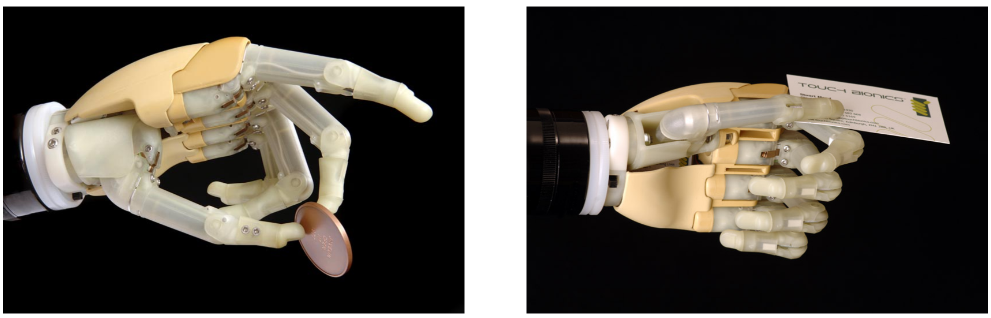


Figure 3.31 – Touch Bionics' i-Limb hand without its cosmetic skin

The i-Limb Pulse hand was introduced in June 2010. It is a robust evolution of the original i-Limb, with an aluminium frame instead of plastic, and additional grip force. It comes with a configuration software for the amputee to customize its operation, by selecting single-electrode or dual-electrode control strategies and activating or deactivating pre-selected grip patterns and other features to their own preference.

The fact that the i-Limb's fingers are individually powered makes them standalone units which may be possibly arranged into customized prostheses for patients with partial hand amputations, such as missing fingers or transmetacarpal amputations (figure 3.32). To date, Touch Bionics's ProDigits are the only myoelectric solution for partial hand amputations.

Figure 3.32 – Four ProDigits arranged into a myoelectric prosthesis for a transmetacarpal amputee

RSL Steeper joined the market of multifunction hand prostheses in May 2010, with the Bebionic hand (figure 3.33) (RSL Steeper 2010). The influence of i-Limb is blatant, with five individually powered two-phalanx fingers, a manually adjustable thumb, five grip patterns and a few non-prehensile hand configurations (lateral power grip, fingertip tripod precision grip, cylindrical and spherical power grip, hook grip, index point and a neutral posture). As in the case of the i-Limb hands, alternating between those grip patterns is done by predefined myoelectric signals such as co-contraction (sending simultaneously an open and a close signal) or open-open (sending successively two open signals): there is no identification of the grip pattern intent from the user myoelectric signal. On the contrary, myoelectric control is once again classical open/close/switch two-electrode single-channel proportional control. An innovative feature however is that the hand electronics are supposed to sense if a gripped item is slipping and automatically tighten the grip to prevent dropping of the object. Also, the fingers are fixed on the palm in such a way that they move together as they close towards the palm, reproducing a natural adduction behavior (see the paragraph on metacarpophalangeal joints in section 2.1.1 on skeletal anatomy, in chapter 2), and enabling lateral grasps between fingers. In contrast, the finger axes of i-Limb are parallel.

Very little information is available about Otto Bock's Michelangelo hand (figure 3.34), which has been premiered in the fall of 2008 but is still not commercially available. From what is known (Otto Bock 2010), i-Limb influence seems very present in this device too. According to Lisi (2010, page 48), the prosthesis is "endowed with two electrodes and five independent fingers, therefore it is guessable that only the opening and the closing movements are available, and this means that it doesn't bring any new grasping abilities". Schweitzer (2008–2011) points out that once again, Otto Bock


Figure 3.33 – RSL Steeper's Bebionic hand, its batteries and its surface myoelectrodes. The protective cosmetic glove is absent.

and the other myoelectric prostheses manufacturers offer fashionable but under-performing devices, at a prohibitive cost, without adressing known, easier-to-adress but non-media-friendly problems such as socket comfort, interference-free operation or delays and time lags.

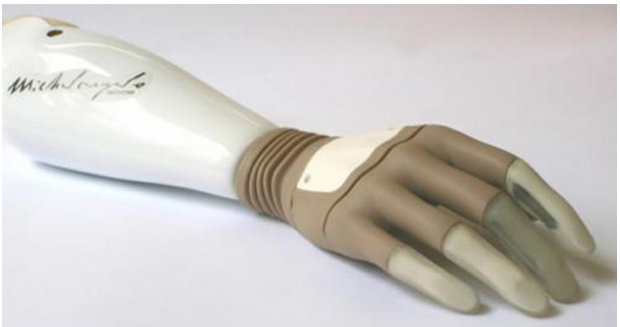


Figure 3.34 – Otto Bock's Michelangelo hand, as it is supposed to look

### 3.2.4 Prosthetics research: recent advances and perspectives

As we wrote previously, the end of the twentieth century and the first decade of the twenty-first century have been a period of intense research in upper prosthetics, especially as far as myoelectric hands are concerned. Three main research areas emerge: the prosthetic hands themselves, the analysis of the myoelectric signal, and the attempts to give sensory feedback to the user. All three of them are of equal importance to the future of prosthetics.

Indeed, the prosthetic hands that are currently investigated in research laboratories are increasingly human-like, with several degrees of freedom, in contrast to most commercially-available myoelectric hands. Using these anthropomorphic devices with primitive myoelectric control, such as the classical one-channel two-electrode open/close approach, would be a waste of technology. Myoelectric control has to be sufficiently advanced to make profit of the improved articulation, and turn the multifingered mechanics into a multifunction hand prosthesis. Research in myoelectric signal analysis aims therefore at extracting as much information as possible from muscle action potentials, and ultimately guessing the intent of the user with respect to the grip type, joint configuration, finger motion, contact forces, grasp stiffness, and so on. This research must be understood as an attempt to blur the line between the prosthesis and its user by improving their interfacing, in the “efferent” or “motor” direction (from the user to the prosthesis). The ultimate, long-term goal is of course to integrate the prosthesis with the user in a sufficiently tight manner to get enough motor information to achieve not only prehension but also true dextrous manipulation. The “afferent” or “sensory” direction (from the prosthesis to the user) is the dual side of the same interfacing issue, and is equally important: as we have stressed several times now, tactile and proprioceptive feedback is essential to human dexterity (see sections 2.1.5 and 2.4.1 in chapter 2), hence the need for research on sensory feedback to the user too.

The following paragraphs present the state of the art and the current perspectives in these three areas of prosthetics research, with pointers to the relevant litterature and to some of the most remarkable humanoid hands designed to date. It also mentions some of the latest developments of prosthetics surgery, which open very exciting perspectives for the future of the integration of the robotic replacement into its human user.

#### Knowledge transfer from robotics: design, actuation, sensing, control

Research prosthetic hands are now made with many degrees of freedom, and tend to emulate closely the kinematics of the human hand. In this respect, prosthetics research has clearly benefited from robotics research on a number of technical aspects, such as the mechanical design of the hand, the actuation and transmission issues, the sensory equipment, and the control strategies. There is nowadays little difference, from a mechatronics point of view, between electric prosthetic hands and humanoid robot hands. The artificial hands presented by Zollo, Roccella, Guglielmelli, Carrozza, and Dario (2007) and Schulz, Pylatiuk, Kargov, Oberle, and Bretthauer (2004a), for instance, explicitly claim their possible usage for prosthetic and robotic applications.

**Hierarchical shared control** Knowledge transfer from robotics to prosthetics began essentially in the 1990s, after the outburst of humanoid robot hand research of the 1980s (the age of the Stanford/JPL Hand, the Utah/MIT Hand, and the Belgrade/USC Hand). In the early 1990s, the European Union funded a collaboration between research centers in the United Kingdom (Oxford and Southampton) and Italy (Bologna and Pisa), to develop an articulated and intelligent myoelectric hand and conduct its clinical evaluation in both countries (Kyberd, Tregidgo, Sacchetti, Schmidl, Snaith, Holland, Scattareggia Marchese, Bergamasco, Bagwell, and Chappell 1993). “Articulated” means that the aim was more than the conventional one degree of freedom prosthetic claw, and “intelligent” refers to the semi-autonomy we have mentioned previously (see figure 3.28), that is to say that the grasp control is shared between the user and the embedded electronics. The user has high-level myoelectric control of their prosthesis: they decide where and when to close and open the hand, and they also input an intensity value for the proportional control of position and force. The embedded microprocessors, on the other hand, have low-level control of the prosthesis: they can, for instance, monitor the contact forces exterted on the object and increase them automatically if they detect that the object slips between the fingers, or they can try to guess the general shape of the object from sensor data and automatically choose the best-suited arrangement of the articulated fingers from a repertoire of predefined grasps.

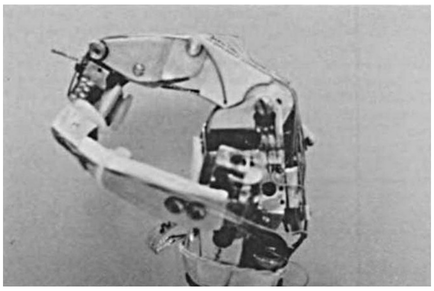
**Marcus Hand** That is precisely what does the Marcus Hand, the three-fingered prosthetic hand resulting from the British and Italian cooperation, illustrated in figure 3.35(a). During grasping, it detects the general shape of the object using sensors on the palmar surface of the hand, selects one of the two possible grip postures that the hand can perform (a precision grip and a power grip), and further makes small corrections to the posture to try and maximize the contact area. When the object is in hold, the hand detects if it starts to slide using acoustic slip sensors positioned at the fingertips (a very small microphone detects the vibrations produced by the object slip), and adjusts the force applied. The user controls the general operation of their prosthesis, and may override the automatic control at any moment, for instance to squeeze more than what is necessary to prevent slip. That way, a two-level hierarchical control of the hand is realized. Hence the name Marcus: Manipulative Automatic Reaction Control and User Supervision.

The hierarchical shared control scheme, called the Southampton Adaptive Manipulation Scheme, is explained in more detail by Kyberd and Chappell (1991, 1994), Kyberd, Holland, Chappell, S. Smith, Tregidgo, Bagwell, and Snaith (1995), or by Lisi (2010, pages 57–60). As for the mechanical design of the Marcus Hand, it is described by Bergamasco and Scattareggia Marchese (1995). The hand features three fingers with three phalanges each, but only two independant degrees of freedom because place and weight constraints made it difficult to accomodate more than two electric actuators. The fingers are roughly equivalent to a thumb, an index finger and a middle finger, and the degrees of freedom are the thumb flexion-extension and the finger flexion-extension. A tendon transmission mechanism couples the other degrees of freedom, while still providing a certain degree of adaptability thanks to a purposely conceived mechanical adjuster.

**Southampton Hand** The Southampton Adaptive Manipulation Scheme was also implemented at the same time in a new version of the Southampton Hand, a prosthetic hand made at the University of Southampton, whose first version dates back to 1969 (Kyberd and Chappell 1994). The Southampton Hand, illustrated in figure 3.35(b), is more anthropomorphic than the Marcus Hand, with five articulated fingers and four degrees of freedom: index finger flexion-extension, thumb flexion-extension and abduction-adduction, and flexion-extension of the other three digits as a coupled group. All four actuators fit within the palm of the hand.

Both the Marcus Hand and the Southampton Hand were the firsts of their kind: “intelligent”, sensorized myoelectric prostheses featuring hierarchical shared control of grasping between the user and the device. Because they achieve “good trade-off between good grasping capabilities and low attention required by the user to complete grasping tasks”, sensor-driven hierarchical shared control architectures such as the Southampton Adaptive Manipulation Scheme are still relevant research topics nowadays (e.g. Cipriani, Zaccone, Micera, and Carrozza 2008; Chappell 2011).

**Robot hands used as prosthetic hands** Also in the early 1990s, the Belgrade/USC robot hand, which was a descendant of 1960s prosthetic research (Tomović and Boni 1962), was investigated for myoelectric control and possible use as a prosthetic hand (Iberall, Sukhatme, Beattie, and Bekey 1993b,a, 1994; Beattie, Iberall, Sukhatme, and Bekey 1994). In fact, it was rather used as “a testbed for issues of control, sensing and actuation”, since robot hands in general “are not restricted in weight, actuator size and computing power to the same extent as prosthetic devices”,



(a) Marcus Hand

(b) Southampton Hand

Figure 3.35 – Two artificial hands implementing the Southampton Adaptive Manipulation Scheme for hierarchical control of grasping

which can make their implementation "not compatible with human rehabilitation requirements" (Beattie, Iberall, Sukhatme, and Bekey 1994). The Belgrade/USC Hand was therefore used to evaluate a control system of hand posturing ("pre-shaping") and object grasping based on the concepts of virtual fingers and opposition type, previously introduced by Iberall and her colleagues (Arbib, Iberall, and Lyons 1985; Iberall 1987; Iberall and MacKenzie 1988, 1990). These concepts are the basis of a grasp taxonomy based on opposition patterns, with three main groups of grasps: palm opposition, pad opposition and side opposition (see section 2.2.2 in chapter 2). Beattie, Iberall, Sukhatme, and Bekey (1994) explain that "at least twenty-one different combinations of these oppositions can be observed, creating a large repertoire of hand shapes for driving prosthetic hands, in contrast to the Southampton Hand which is fixed to use one of the seven postures defined by Schlesinger" (Schlesinger 1919, and also figure 2.36 in section 2.2, chapter 2).

Work on myoelectric control of a robot hand was also performed at the same time on the Utah/MIT robot hand (Farry and I. Walker 1993; Farry, I. Walker, and Baraniuk 1996), but for teleoperation of this hand rather than prosthetic applications, although prosthetics could still profit from this research since it focused on myoelectric grasp and thumb control and on myoelectric user interface.

**Myoelectric hands of the last decade** During the end of the 1990s and during the 2000s, several other attempts at anthropomorphic articulated myoelectric hands with advanced control and sensor equipment were made in various prosthetics research centers around the world. Most famous are the Southampton Remedi Hand (Southampton, United Kingdom), the Manus Hand (Madrid, Spain), the Hokkaido Hand (Sapporo, Japan), the RTR I/II/III Hands, CyberHand and SmartHand (Pisa and Pontedera, Italy, Lund and Malmö, Sweden, and partners in other European countries), as well as FluidHand (Karslruhe, Germany) and the Vanderbilt Hand (Nashville, Tennessee, United States, reviewed previously, see figure 3.25 in section 3.2.3). But this list is in no way complete.

**Southampton Remedi Hand** In the United Kingdom, funding from the Rehabilitation and Medical Research Trust (Remedi) has enabled the University of Southampton to develop a lightweight underactuated adaptive five-fingered prosthesis, called the Southampton Remedi Hand and illustrated on figure 3.36. The hand has a peculiar five-bar linkage mechanism for its finger transmission chain, instead of the more common tendon system. Each of the four fingers has therefore one (actuated) degree of freedom. The linkage mechanism is designed so that the fingers curl in a natural-looking trajectory when flexed. The thumb has two degrees of freedom, a circumduction [20] and a flexion-extension that realize good anthropomorphic motion of this digit (Light and Chappell 2000; Kyberd, Light, Chappell, J. Nightingale, Whatley, and Evans 2001).

On the control side, the hand implements the Southampton Adaptive Manipulation Scheme combined with a multiple-degree-of-freedom controller developed at the University of New Brunswick, Canada (Light, Chappell, Hudgins, and Englehart 2002; Cotton, Cranny, Chappell, White, and Beeby 2006). The first control scheme brings the semi-autonomous grasp behavior due to its hierarchical shared structure. The second one analyses the myoelectric signal with a classifier based on an artificial neural network, identifies four types of muscular contraction from a single myoelectric channel in the upper arm (one electrode on the biceps and one on the triceps), and deduces which one of the four corresponding grip patterns the user is wanting the fingers to perform.

In addition to this new, all-myoelectric user interface (the former Southampton Hand required the user to trigger certain external sensors on the prosthesis in order to initiate the desired grip pattern), the Southampton Remedi Hand is highly instrumented with sensors to improve the feedback loop of its autonomous control algorithms. Digital magnetic encoders and motor-current sensors provide respectively finger position and the force applied to the manipulated object, and each fingertip is endowed with extrinsic tactile sensors (see figure 2.45 in section 2.4.1, chapter 2): a piezoresistive sensor measures grip force (static force), a piezoelectric sensor detects the onset of object slip (dynamic force), and a thermistor measures the temperature of the object (Cranny, Chappell, Beeby, and White 2003; Cotton, Cranny, White, Chappell, and Beeby 2004, 2005; Cranny, Cotton, Chappell, Beeby, and White 2005a,b; Cotton, Chappell, Cranny, White, and Beeby 2007; Chappell, Cranny, Cotton, White, and Beeby 2007).

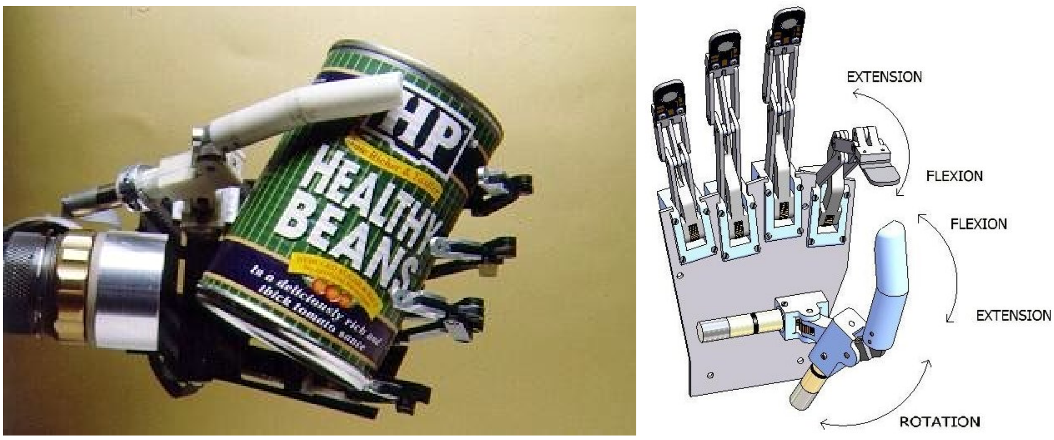



Figure 3.36 – The Southampton Remedi Hand and its six actuated degrees of freedom

20. A rotation in a kind of conical movement, typical in the human body of the hip and shoulder ball-and-socket joints, but also realized, to a certain extent, by a combination of flexion, extension, adduction and abduction at the thumb carpometacarpal joint.

**Manus Hand** The Manus Hand, illustrated on figure 3.37, is another example of intelligent hand prosthesis with shared human/device control. Its construction and control are fairly different to that of the Southampton Remedi Hand, though (Kyberd and Pons 2003). First, the Manus Hand is more underactuated, with nine joints but only two actuators (the Southampton prosthesis has fourteen joints and six actuators). The index and middle fingers have three tendon-coupled phalanges each and are actuated by the same motor. The thumb has the other three joints and the other motor. The ring and little fingers are not articulated but may be manually shaped for long-lasting grasps. A special construction of the thumb mechanism makes it possible to position the thumb both in flexion and opposition with only one actuated degree of freedom. As a consequence, four grasp types are available with just two actuators: cylindrical, fingertip precision, hook and lateral (see section 2.2.2 in chapter 2) (Pons, Rocon, Ceres, Reynaerts, Saro, Levin, and Moorleghem 2004). Also, since the Manus Hand embeds less actuators than the Southampton Remedi Hand, they can be larger, resulting in a more powerful grasp (these motors are clearly visible in the palm of the hand, on the photograph of figure 3.37).

The sensory system is simpler, too: Hall-effect position sensors in the actuated joints and intrinsic Hall-effect force sensors in the fingertips. Given these sensors, an impedance control approach has been chosen for the autonomous part of the shared control (Pons, Rocon, Ceres, Reynaerts, Saro, Levin, and Moorleghem 2004). That is to say that the fingers behave like virtual springs: the "thumb" spring opposes the "index and middle" spring, and the autonomous control keeps the grasp stable by adjusting these springs so that the finger and thumb forces match each other and the equilibrium is maintained. As for the human part of the shared control, it comes from a single myoelectric channel used by the amputee in sequences of three myoelectric bursts of three possible intensities: inexistent, low, high. That defines a "control language" of $3 \times 3 \times 3 = 27$ myoelectric words, for instance "low, high, low" is such a word, coding for a particular command sent by the user to their prosthesis. In clinical trials, users were successfully able to learn the command language and grasp objects with the Manus Hand, which means that this approach could be relevant to high-level amputees, who have few available sites for electromyography and therefore need an electrode-saving solution (this one requires only one electrode). However, the fact that the control is entirely non-intuitive makes it require too much mental effort, which is incompatible with everyday, prolonged use and is well-known to result in high rejection rates in practice (Pons, Rocon, Ceres, Reynaerts, Saro, Levin, and Moorleghem 2004; Pons, Ceres, Rocon, Reynaerts, Saro, Levin, and Moorleghem 2005).

**Hokkaido Hand** The Hokkaido Hand, developed originally at the University of Sapporo, Japan, is once again an underactuated adaptive articulated prosthetic hand. It has five fingers with ten (actuated) degrees of freedom, two per finger. The third degree of freedom of each finger is the distal interphalangeal joint, which is coupled to the proximal interphalangeal joint (both are actuated by the same tendon). The hand has a peculiar tendon transmission system: the course of the tendons is slightly adjustable by a spring and shifts proportionally to the load applied on the finger (Y. Ishikawa, Yu, Yokoi, and Kakazu 2000; Yokoi, Arieta, Katoh, Yu, I. Watanabe, and Maruishi 2004; Arieta, Katoh, Yokoi, and Yu 2006). These adjustable transmission mechanisms control the torque-velocity ratio of the joints and allow the fingers "to move faster under light loads and slower but with more torque under

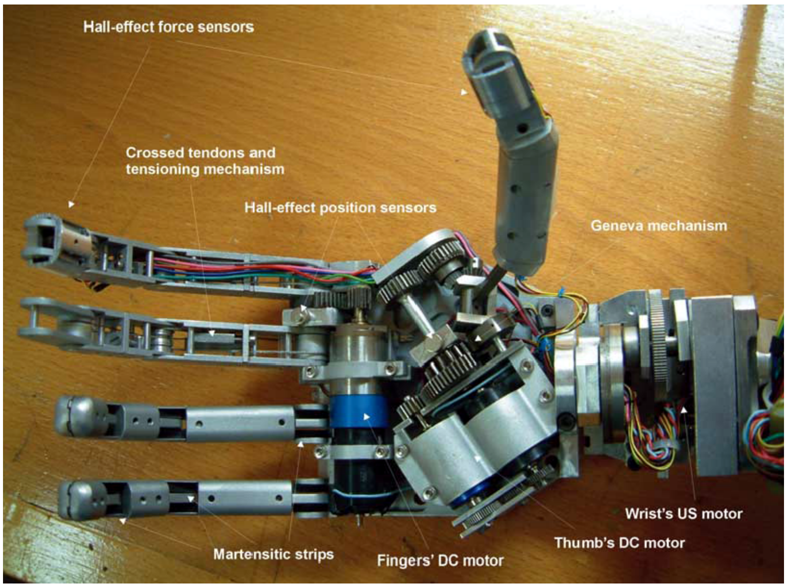



Figure 3.37 – The Manus Hand (Pons, Rocon, Ceres, Reynaerts, Saro, Levin, and Moorleghem 2004)

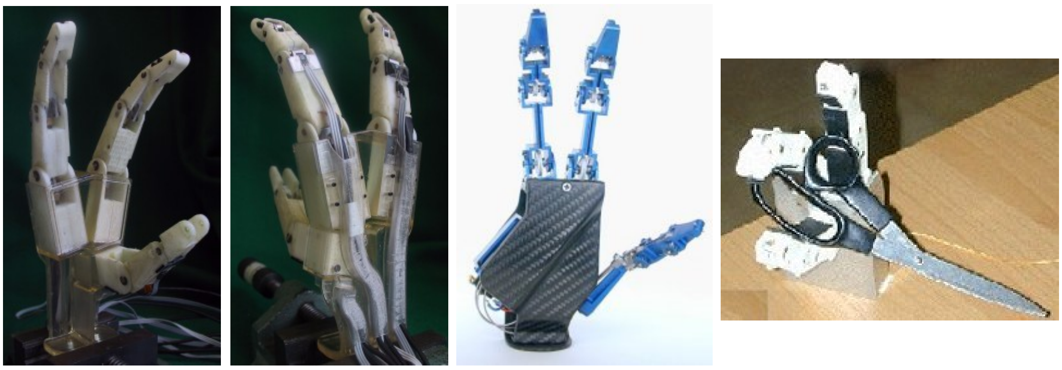
heavy loads". This design was proposed as a possible solution to the problem of the power-weight ratio of electric actuators, and on the belief of the authors that "for the purposes of normal activities, it is not necessary for a prosthetic hand to offer high speed and high power simultaneously". Keeping with the goal of light weight, the Hokkaido Hand also arranges the actuators very proximally, on the outside of the prosthesis socket, "because the greater part of the load of a current prosthetic hand is an actuator arranged into the hand". This design "reduces the load on the amputee by shifting the center of balance from the hand to the forearm", but since it also lenghtens the course of the tendons, it makes the system "complex, time-delayed, and non-linear".

**RTR Hands** In Pontedera near Pisa, Italy, artificial hands for robotics and prosthetics are studied since 1999 at ARTS Lab (Advanced Robotics Technology and Systems Laboratory, Scuola Superiore Sant'Anna), a major player in research on rehabilitation engineering and biomedical robotics. Several design solutions, components and technologies have been investigated, and a number of research prototypes have been built in national and international collaborations with private and public entities, with European and United States funding (Sebastiani, Roccella, Vecchi, Carrozza, and Dario 2003; Carrozza, Laschi, Micera, Dario, et al. 2007). Their most famous prosthetic hands are probably the RTR Hand series, CyberHand and SmartHand (see figures 3.38, 3.39 and 3.40). Except for the RTR I Hand, which is not so anthropomorphic and is based on intrinsic micro-actuation (Carrozza, Dario, Lazzarini, Massa, Zecca, Roccella, and Sacchetti 2000), their artificial hands are anthropomorphic, bioinspired, multifunctional, underactuated, adaptive, tendon-driven, and sensorized in proprioception and exteroception.

The RTR I Hand has three digits: index finger, middle finger, and a thumb in opposition, with six independent actuated degrees of freedom: the first two flexions of each finger and the two flexions of the thumb. The third flexion of each finger is function of the second one by a four-bar link, in the usual coupling between proximal and distal interphalangeal joints. This hand has been designed to offer two grasping patterns, the cylindrical grasp and the tripod grasp. It embeds its six small actuators very close to the joints, three in the palm and three in the proximal phalanges (Carrozza, Micera, Massa, Zecca, Lazzarini, Canelli, and Dario 2001; Carrozza, Massa, Micera, Lazzarini, Zecca, and Dario 2002).

The RTR II Hand also has three fingers only, but contrary to its predecessor, it was meant to be underactuated and adaptive, with only two actuators for nine joints (Massa, Roccella, Carrozza, and Dario 2002; Dario, Carrozza, Menciassi, Micera, Zecca, Cappiello, Sebastiani, and Freschi 2002). The index and middle fingers have three degrees of freedom in flexion-extension, the thumb has one degree of freedom in abduction-adduction and two in flexion-extension. The motors are located in the palm and their motion is transmitted to the underactuated mechanisms by tendons for flexion; extension is realized by antagonists torsion springs, as in most tendon-driven hands. The hand provides the same grasping patterns as its predecessor. The tendon tension is measured by strain gauges accommodated in pulleys, and this information is used by the low-level control algorithms of the grasping force, and also to avoid excessive load on the motors. The hand also embeds proprioceptive Hall-effect joint position sensors and an exteroceptive tactile pressure sensor at the thumb fingertip (Zecca, Cappiello, Sebastiani, Roccella, Vecchi, Carrozza, and Dario 2003; Carrozza, Vecchi, Sebastiani, Cappiello, Roccella, Zecca, Lazzarini, and Dario 2003).

The RTR III Hand, also known as the Spring Hand, takes the underactuation approach a step further with one motor only for three fingers and eight degrees of freedom (Carrozza, Suppo, Sebastiani, Massa, Vecchi, Lazzarini, Cutkosky, and Dario 2004). The finger mechanisms feature three tendons and two compression springs per finger. These springs make the phalanx joints passively compliant, which improves the adaptive behavior of the phalanges, results in a good and natural-looking adaptability to different object shapes, and also produces a good distribution of the contact forces among the phalanges in contact with the grasped object. However, one single actuator also means low dexterity: the different grasp patterns that the hand can perform come solely from the hand auto-adaptability when in contact with an object; they cannot be triggered voluntarily by the user as in, say, the Southampton Remedi Hand.



(a) RTR I

(b) RTR II

(c) RTR III demonstrating grasp adaptability

Figure 3.38 – The RTR Hand series

**CyberHand** An evolution of the RTR II Hand, CyberHand is a step towards the realization of a cybernetic hand prosthesis, that is to say a prosthesis that is intended to be connected to the user's nervous system directly thanks to implantable neural electrodes, rather than indirectly via the muscles thanks to surface electromyography. Originally a three-fingered hand like the RTR Hands (Carrozza, Dario, Vecchi, Roccella, Zecca, and Sebastiani 2003; Carrozza, Cappiello, Cavallaro, Micera, Vecchi, and Dario 2004; Carrozza, Cappiello, Beccai, Zaccone, Micera, and Dario 2004), it then turned into a five-fingered hand, more functional and more aesthetic (Carrozza, Cappiello, Micera, Edin, Beccai, and Cipriani 2006).

CyberHand has now sixteen degrees of freedom and six electric actuators. Each digit has three flexion-extension degrees of freedom underactuated by one actuator, and the thumb has in addition one abduction-adduction degree of freedom controlled by one actuator. This last actuactor is located in the hand palm, whereas the actuators for finger flexion are housed in the forearm, in compliance with the human extrinsic anatomical model. The transmission chain is tendon-based. The underactuation mechanism of the fingers is quite similar to that of the RTR II Hand, but the thumb mechanism and position have changed, and the phalanges have been re-designed in a cylindrical shape without sharp edges, to improve the grasp and the anthropomorphism. The size of the hand has beed reduced and is now comparable to that of a human hand. The palm has been re-designed too, and its volar surface may be covered by a soft padding made of silicon rubber in order to increase the compliance of the grasp. The sensorization is rich, with a total of fifty-three sensors: Hall-effect joint position sensors, magnetic encoders integrated with each motor, tendon tension strain gauges, distributed contact sensors on the phalanges, intrinsic strain-gauge-based triaxial force sensors in the fingertips, and an extrinsic compliant skin with embedded triaxial force micro-sensors to measure force distribution at the fingertips.

The CyberHand control system is classically organized into "a high-level controller with which the subject directly interacts and specifies grasp type and force requirements, and a low-level controller that executes the required kinematic patterns and ensures grasp stability" (Carrozza, Cappiello, Micera, Edin, Beccai, and Cipriani 2006). The higher-level unit recognizes the user's intent among a predefined set of grasping primitives from Cutkosky and Wright's grasp taxonomy (see figure 2.38 in section 2.2.2, chapter 2): cylindrical heavy-wrap power grasp, spherical power grasp, tripod precision grasp, fingertip thumb-index precision grasp, and lateral pinch power grasp. This accounts for more than 80% of the grasps used in the activities of daily living, and the hand adaptability resulting from underactuation further ensures that many different object shapes are grasped correctly. As for the grasping task in itself, it is composed of a pre-shaping phase performed under proportional-integral-derivative position control, followed by a closure phase under force control. During the second phase, the low-level controller closes the fingers until the desired force specified by the high-level controller is reached, and also balances finger actuation so that each finger grips the object with the same force, in order to increase grasp stability and reduce slip risk.

For further information, the CyberHand design, actuation, sensing and control are thoroughly described by Carrozza, Cappiello, Micera, Edin, Beccai, and Cipriani (2006).

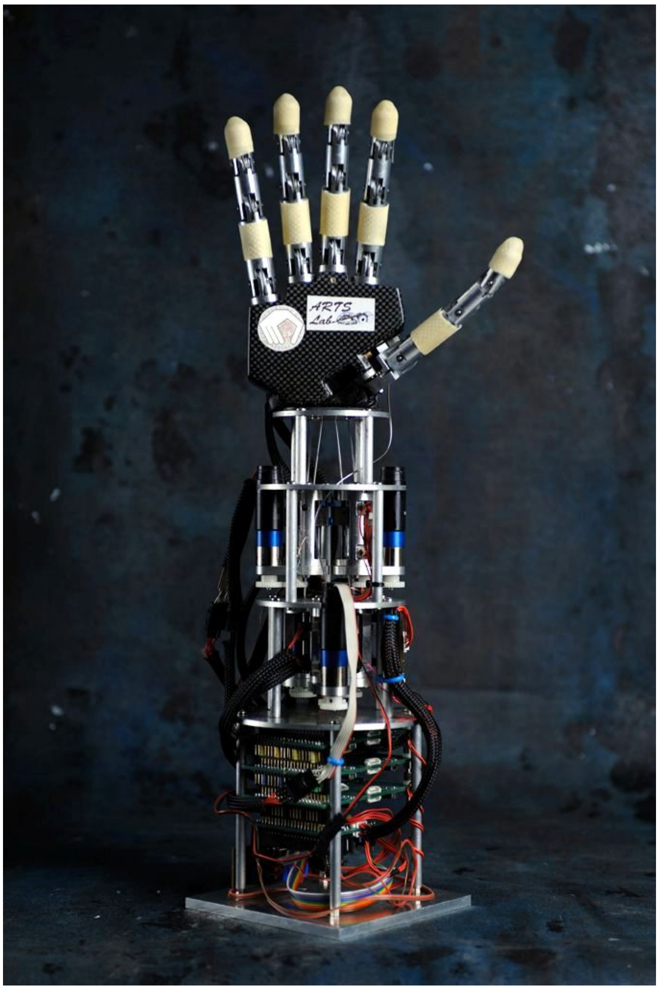


Figure 3.39 – Complete view of the CyberHand prototype prosthesis. The extrinsic electric actuators are visible below the hand, as well as the control printed circuit boards, below the motors.

**SmartHand** Because of the extrinsic design chosen for CyberHand, the resulting device is unfit for actual use by a below-elbow amputee, except perhaps if the amputation is very close to the elbow, but then that would cause socket design difficulties and electrode placement issues. Besides, there is no wrist rotator in CyberHand. In fact, CyberHand was designed "as a prototype for testing and evaluating neural interfaces, control algorithms, and sensory feedback protocols" (Carrozza, Cappiello, Micera, Edin, Beccai, and Cipriani 2006).

SmartHand however, developed in the line of CyberHand and illustrated on figure 3.40, is a self-contained hand for transradial amputees which can be actually used, at least for clinical evaluation (Controzzi, Cipriani, and Carrozza 2008; Cipriani, Controzzi, and Carrozza 2009, 2010). Compromises had to be made: no more than four actuation units could be housed inside the palm, so to keep the five-fingered appearance, the hand relies more on underactuation than CyberHand (see figure 3.41), the palm is more bulky, and sensors requiring complex wiring have been avoided. SmartHand has sixteen degrees of freedom, three for each finger, plus one for the thumb opposition axis. As in CyberHand, nylon-coated steel tendons flex the joints, and extension is achieved by torsion springs. The hand is provided with forty proprioceptive and exteroceptive sensors which feed position, tactile and force data back to the embedded control architecture.

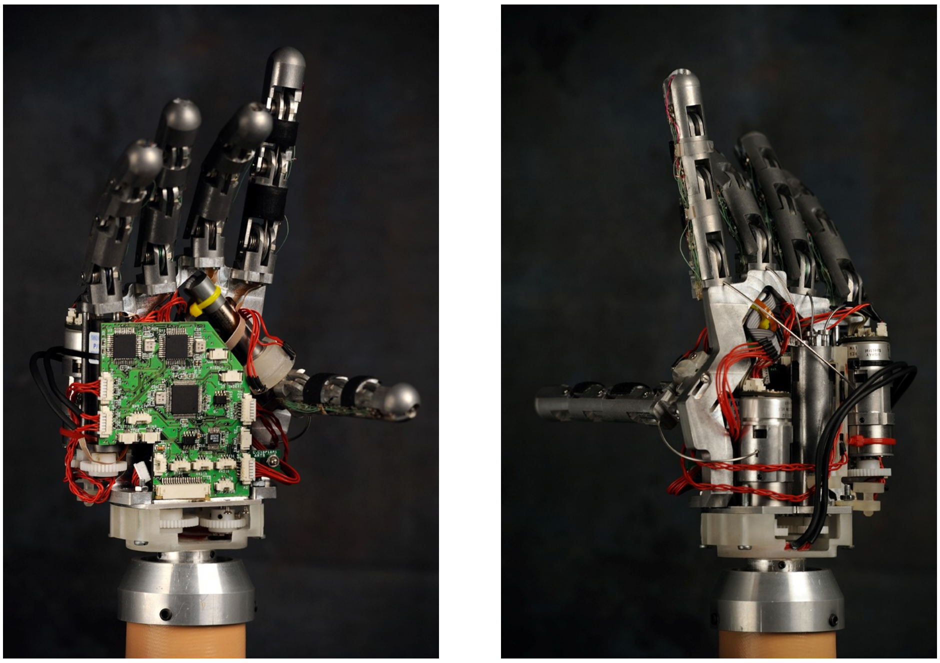


Figure 3.40 – SmartHand self-contained design: the electric actuation units and the control printed circuit board are in the palm of the hand. The dimensions are comparable to that of the human hand.

All those hands developed at ARTS Lab in Pontedera are well-known by academia around the world, and are used by researchers in many universities. Since 2009 they are manufactured, customized and sold by a spin-off of Scuola Superiore Sant'Anna, Prensilia. Research institutes use them as advanced prostheses for biomedical, rehabilitation and neurological research, as end-effectors for humanoid robots, and more generally "in all research fields where it is important to have an artificial hand that behaves as a natural one" (Prensilia 2010).

**The pivotal role of underactuation** The articulated hands we have mentioned up to now have underactuation in common. On the bright side, underactuation brings grasp adaptability, thanks to ingenious mechanisms that distribute motion and force from one actuator to several joints: when one of the joints is stopped in its motion by a contact with the object, the other joints can still move because the underactuation mechanism still distribute motion and force to them. But on the other hand, underactuation also limits the possible motions of the hand to those allowed by the mechanisms in question. This is not so much of a problem as long as prosthetic hands, even experimental ones, are still only grasping devices, not meant for manipulation tasks. However, manipulation *is* the next big step. Extended neural interfacing of the prosthesis with the user's nervous system, via implantable neural electrodes or targeted muscle reinnervation for instance (see further in this section), is for sure still highly experimental. But it hints at a future where, possibly, enough information might be extracted and deciphered from the user's nervous system to be able to reproduce complex hand motions and dextrous manipulations in addition to

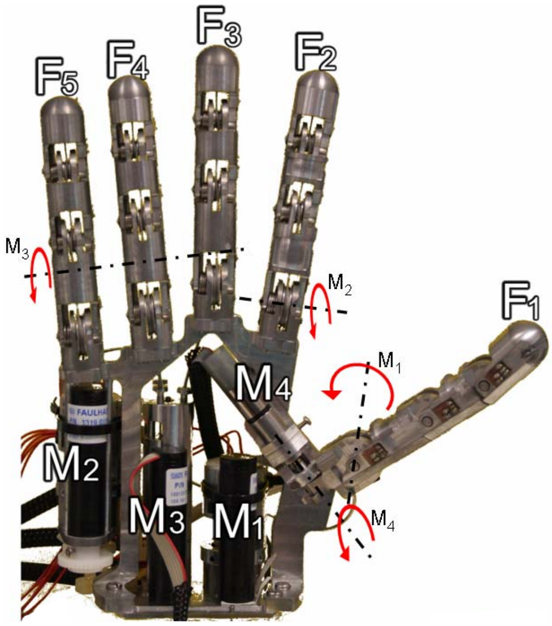



Figure 3.41 – SmartHand motors and degrees of actuation: M1 flexes the thumb, M2 the index finger, M3 the middle, ring and little fingers through a differential mechanism, and M4 rotates the thumb.

simple grasps. And underactuated hands are without doubt not dextrous enough for manipulation.

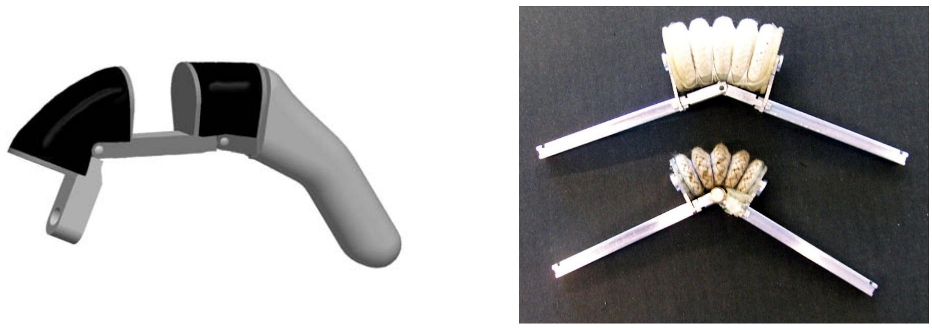
The main reason for underactuation is that all these new articulated prostheses have many degrees of freedom and at the same time use electric motors. However small and lightweight direct current motors can be, they still have a low power-to-weight ratio and take therefore more space than they should, not to forget the various gear mechanisms necessary to reduce their speed and increase their torque. Moreover, they are also disturbingly noisy. For these reasons, advances in actuator technology towards small, lightweight, and at the same time powerful actuators, are regarded as a means to free articulated hand prostheses from their current "compulsory underactuation" by actuating independently more degrees of freedom, thereby increasing the number of possible grasp patterns and hand motions, that is to say dexterity, while at the same time reducing total weight and achieving noiseless operation.

**The problem of actuator size** This actuator size issue is actually exactly the same for robot hands, as explained in section 2.4.1, chapter 2. In this section, we mentioned actuators based on shape memory alloys or electroactive polymers as possible solutions for miniaturization without loss of performance – although these solutions are not perfect of course, they would have their own drawbacks too (see e.g. Andrianesis, Koveos, Nikolakopoulos, and Tzes 2010, section 2.2). Shape memory alloy actuators, in particular, have been implemented in a few experimental prosthetic constructions at Rutgers University in New Jersey, United States (C. Pfeiffer, DeLaurentis, and Mavroidis 1999; DeLaurentis, Mavroidis, and C. Pfeiffer 2000; DeLaurentis and Mavroidis 2002), at the University of Victoria in British Columbia, Canada (Bundhoo, Haslam, Birch, and E. Park 2008; Bundhoo 2009), at the University of Patras in Greece (Andrianesis and Tzes 2008; Andrianesis, Koveos, Nikolakopoulos, and Tzes 2010) and at Dublin Institute of Technology in

Ireland (O'Toole, McGrath, and Hatchett 2007; O'Toole and McGrath 2007; O'Toole, McGrath, and Coyle 2009). None of these constructions are operational prostheses though, with sensorization and control. They are rather just fingers and simple hand structures meant as testbeds for finger actuation.

Another option for actuator size reduction is the flexible fluidic actuators developed at the Forschungszentrum Karlsruhe [21] in Germany (Schulz, Pylatiuk, and Bretthauer 1999). They consist of reinforced flexible bellows which expand in a bent motion during inflation with pressurized air or water. This operation makes them transform pressure directly into rotation or torque, hence their integration to the finger joints as illustrated on figure 3.42. They are very light and produce a force function of their cross-section and the operating pressure, with a cubic relation between their diameter and the joint torque. Thus, they present a very good power-to-weight ratio, combined with a natural, inherent compliance that enables grasp adaptability.

**FluidHand** FluidHand, illustrated on figure 3.43, is a prosthesis based on those flexible fluidic actuators. It evolved through successive updates from the first prototype (Pylatiuk, Mounier, Kargov, Schulz, and Bretthauer 2004; Pylatiuk, Schulz, Kargov, and Bretthauer 2004) to the hand that was used in clinical evaluations (Schulz, Pylatiuk, Reischl, J. Martin, Mikut, and Bretthauer 2005; Kargov, Pylatiuk, Oberle, Klosek, Werner, Rössler, and Schulz 2007) to its current status, known as FluidHand III (Gaiser, Pylatiuk, Schulz, Kargov, Oberle, and Werner 2009). It has eight actuated degrees of freedom and uses a small direct current motor to drive a hydraulic micropump located in the palm of the hand. Then, five custom, independent microvalves under electronic control distribute fluid pressure to certain actuators, depending on the prehension pattern chosen by the user, who is fitted with two myoelectric electrodes. The myoelectric signal analysis algorithms are able to recognize five different grasp types.



(a) This model shows an inflated actuator, an actuator at rest, and a flexible, elastic fingertip (Pylatiuk, Mounier, Kargov, Schulz, and Bretthauer 2004).

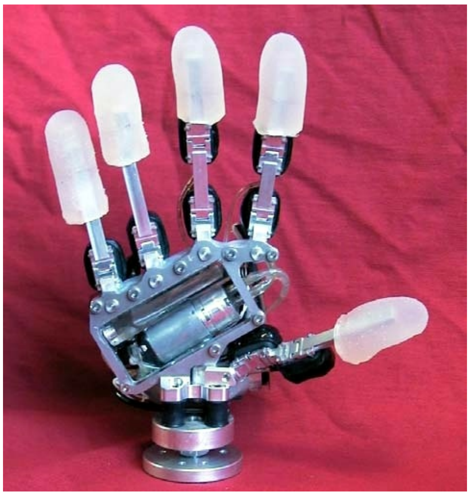
(b) The bellows that are inside the actuators (two sizes of actuators) (Gaiser, Pylatiuk, Schulz, Kargov, Oberle, and Werner 2009).

Figure 3.42 – Flexible fluidic actuators, generating the flexion movement of the digits. The extension movement may be performed by a spring element.

### Myoelectric signal analysis

As we explained previously, multifunction prostheses such as the ones reviewed in the previous section are not meant to be used with the classical threshold-based

21. Karlsruhe Research Center, now Karlsruhe Institute of Technology.



(a) FluidHand I (Schulz, Pylatiuk, Kargov, Oberle, and Bretthauer 2004a)

(b) FluidHand III (Gaiser, Pylatiuk, Schulz, Kargov, Oberle, and Werner 2009)

Figure 3.43 – FluidHand, first and current generation. The palm houses the hydraulic micropump, the microvalves and the controller unit. The water tank is on the back of the hand.

single-channel myoelectric control. To make profit of their multifingered articulation, control must be more than just open and close signals. User intent recognition from the myoelectric signal is desirable, beginning with the grip pattern the user wants to perform. Then, the aim is to extract as much information as possible from the myoelectric signal, using time-domain and frequency-domain methods: for example, the desired configuration of the fingers, their velocities, the contact forces, the stiffness of the grasp, and so on. Ultimately, enough information might be decoded from the muscle action potentials to enable dextrous manipulation in addition to grasping.

But it is actually doubtful that this goal could be reached by the analysis of the myoelectric signal of the residual muscles alone: this signal does not contain enough information, because the muscles in question are the extrinsic muscles of the hand, their role is mainly about power grasping (see section 2.1.2 in chapter 2). To achieve multifingered dextrous manipulation, the myoelectric signals of the intrinsic muscles of the hand should be picked up too, because they play an important role in dextrous manipulation. Except that after amputation, there is no hand to record signals from.

**Principle of myoelectric signal analysis** Here is how grip pattern recognition from myoelectric signal analysis works, in broad outline (from Lisi 2010, page 67):

1. First, a set of time-domain and/or frequency-domain features is extracted from the myoelectric signal, "for example time-domain statistics, short-time Fourier transform values, wavelet transforms, model parameters and others more". This form a feature vector. For instance, a simple five-element time-domain feature vector could be formed by "the mean absolute value [of the myoelectric signal], the mean absolute value slope, the zero crossing, the slope sign changes and the waveform length".

2. After that, "the next step is to train a classifier in order for it to be able to match each feature vector with a particular hand movement". This is done by having the amputee perform grasps with their phantom hand while their

> myoelectric activity is recorded and the classification algorithm is fed both the corresponding feature vector and which grasp is performed. Grasp after grasp, the classifier learns to discriminate between the different grasp patterns thanks to the feature vectors. Possible typical classifiers for such a task include "Bayes classifiers, linear discriminant analyzers, multilayer perceptron neural networks, and support vector machines".

Once the classifier achieves a sufficiently error-free classification performance by itself, it is considered trained enough and ready to be used in real life. However, in order to be useful, it must not introduce any significant delay in the operation of the prosthesis: the feature extraction and classification algorithms have to be real-time. Besides, it must be able to keep learning in order to adapt to the variances "caused by donning, fatigue, perspiration and other conditions that cause changes in the electrical characteristics of the signal" (Ohnishi, Weir, and Kuiken 2007), in other words it must be capable of online learning with an acceptable performance, not only of the initial offline learning.

**Multichannel signal analysis** Contrary to the classical threshold-based myoelectric control, which doesn't work well with more than one myoelectric channel (see previously in this section), myoelectric signal analysis may benefit from an increase in the number of channels. Indeed, more channels mean a more complete information about contractions of the residual muscles, and therefore feature vectors that better reflect the myoelectric activity.

The first approaches to myoelectric signal analysis were single-channel (Graupe and Cline 1975; Parker, Stuller, and Scott 1977), but more channels were quickly added. In 1982, Saridis and Gootee proposed a two-channel system able to recognize six limb movements with a classification performance of 85%, from just two time-domain features inputed into a linear discriminant classifier: the zero crossing (number of times the waveform crosses zero) and the variance of the myoelectric signal (modeled as an amplitude-modulated gaussian noise). In 1983, Doerschuk, Gustafson, and Willsky achieved a classification performance of 95% on the three degrees of freedom of the wrist, with a four-channel system, a feature vector of sixteen components (each channel provides a signal that is modeled by an autoregressive moving average model, and four parameters of this identified ARMA model are used in the feature vector), and a nearest neighbor classifier. Numerous other approaches followed, varying in the number of channels, the extracted features, and the chosen classifiers. For instance artificial neural networks began to be used as classifiers in the 1990s (M. Kelly, Parker, and Scott 1990; Hudgins, Parker, and Scott 1993; Christodoulou and Pattichis 1995), and support vector machines more recently (Bitzer and Smagt 2006; Maier and Smagt 2008; M.-F. Lucas, Gaufriau, Pascual, Doncarli, and Farina 2008; Oskoei and H. Hu 2008).

For more on this subject, Lisi (2010, pages 65–71) presents a summarized history of myoelectric signal analysis; Zecca, Micera, Carrozza, and Dario (2002) and Parker, Englehart, and Hudgins (2006) give more technical details.

**Use of signal analysis in actual myoelectric hands** Grip pattern recognition by myoelectric signal analysis has been implemented in the controllers of some of the experimental prosthetic hands reviewed previously, especially in the Southampton Remedi Hand, the Hokkaido Hand, CyberHand, and FluidHand. In the Hokkaido

Hand, the classification algorithms are able to discriminate ten forearm motions from two channels of myoelectric signals: four wrist motions and six hand motions. Moreover, the classifier learns fast, within four to twenty-five minutes. Unfortunately its classification performance is too low, with an average accuracy of 85% on five test subjects (Nishikawa, Yu, Yokoi, and Kakazu 1999a,b, 2001; Arieta, Katoh, Yokoi, and Yu 2006).

To conclude on myoelectric signal analysis, let us note that it is not restricted to grasp pattern classification anymore: Castellini, Smagt, Sandini, and Hirzinger (2008; 2009) recently proposed an approach to not only classify the finger movements, but also determine quantitatively the amount of grip force involved. They used ten electrodes placed on the wrist and forearm, and tested three different classifiers (artificial neural networks, support vector machines, and locally weighted projection regression). All three of them can discriminate between four different functions with an average accuracy of 90%: grasp by opposing the thumb and index finger, by opposing thumb and middle, by opposing thumb and ring, and last by opposing the thumb and all other fingers. In addition to this, “the applied force can be predicted with an average error of 10%, corresponding to about 5 N over a range of 50 N” (Castellini, Smagt, Sandini, and Hirzinger 2008). Their results are a first step towards meeting the goal of simultaneous, independent, and proportional control of multiple degrees of freedom with acceptable performance via surface electromyography.

#### Sensory feedback to the user

Sensory feedback is essential to human dexterity, and precise manipulation is in fact pretty impossible without adequate proprioceptive and tactile feedback from the fingers (see sections 2.1.5 and 2.4.1 in chapter 2). Simpler tasks like power grasping also require such feedback, force feedback especially. Yet there isn’t any commercial myoelectric hand that features feedback paths from the prosthesis to the amputee, who must rely on vision only to judge the quality of the grasp, and on secondary cues like motor noise and vibrations. Therefore, it is desirable to provide tactile and proprioceptive information to the user of a prosthetic hand, even though the richness of this feedback will not be even remotely close to that offered by the biological hand.

**Vibrotactile and electrotactile interfaces** Attempts at feedback delivery to the user focus mainly on vibrotactile and electrotactile interfaces, usually affixed to the skin of the forearm (Scott 1990; Kaczmarek, Webster, Bach-y-Rita, and Tompkins 1991; Kaczmarek 2000; Lundborg and Rosén 2001; Lisi 2010, pages 60–63). Vibrotactile interfaces induce mechanical vibrations of the skin, typically via piezoelectric transducers at frequencies of 10 Hz to 500 Hz. Electrotactile interfaces pass a local electric current through the skin via surface electrodes, producing various sensations such as a tingle, itch, pinch, pressure, vibration, and pain. The sensory information that must be fed back to the user can be coded in the amplitude, frequency and duration of the vibrotactile signal, and in the voltage, current, and waveform of the electrotactile signal. Besides, the user is not limited to only one of those devices, several tactile displays may be used to make the feedback richer.

Nearly any kind of sensory information may be delivered through those interfaces, as long as the hand is equipped with the proper sensors and that the amputee is informed about how the sensor data is translated into vibrotactile or electrotactile stimulations. For instance, a common choice of feedback is the grip force, but Antfolk, Balkenius, Rosén, Lundborg, and Sebelius (2010a,b) recently experimented with tactile feedback for "discrimination of site of stimuli and pressure levels at a single stimulation point", using SmartHand, and had pretty good accuracy results.

Vibrotactile and electrotactile interfaces aren't exactly new ideas. In fact, they have been used for decades now, with applications in many different fields, in particular as sensory substitution systems for vision-impaired and hearing-impaired people (e.g. Diespecker 1970; Strong and Troxel 1970; Saunders 1973, 1983; Kaczmarek 2000). They are also used as feedback systems for distant or virtual environments, for instance in virtual reality (e.g. T. Cheng, Kazman, and J. Robinson 1996; Okamura, Dennerlein, and Howe 1998), telemanipulation (e.g. Massimino and Sheridan 1992, 1993; Shimoga 1993; Dennerlein, Millman, and Howe 1997), and minimally invasive surgery (Schoonmaker and Cao 2006a,b). In prosthetics, they began to be investigated in the mid-1960s at the Massachussets Institute of Technology, by Alles (1966, 1968, 1970), Mann and Reimers (1968; 1970; 1971/1974), and McEntire (1971).

**Use of tactile interfaces in actual myoelectric hands** While completely absent from the current prosthetics market, vibrotactile and electrotactile interfaces have been integrated with some of the experimental prosthetic hands reviewed previously: the Manus Hand, SmartHand, and FluidHand have all been tested with vibrotactile feedback systems, and the Hokkaido Hand with electrotactile systems (respectively, Manus Hand: Pons, Rocon, Ceres, Reynaerts, Saro, Levin, and Moorleghem 2004; SmartHand: Cipriani, Antfolk, Balkenius, Rosén, Lundborg, Carrozza, and Sebelius 2009; Antfolk, Balkenius, Rosén, Lundborg, and Sebelius 2010a,b; FluidHand: Pylatiuk, Mounier, Kargov, Schulz, and Bretthauer 2004; Gaiser, Pylatiuk, Schulz, Kargov, Oberle, and Werner 2009; Hokkaido Hand: Yokoi, Arieta, Katoh, Yu, I. Watanabe, and Maruishi 2004). In the case of the Hokkaido Hand and the electrotactile feedback, surface electrodes are used for both the myoelectric control (efferent direction) and the sensory feedback (afferent direction): Arieta, Yokoi, Arai, and Yu (2005a,b) have found out that the myoelectric signal obtained from the user is contaminated by the electrical surface stimulation of the skin, but fortunately the performance of the pattern recognition process (for grip type classification) is not damaged.

#### Surgical perspectives for prosthetics

When we think about it, it stands to reason that the best way to deal with the loss of a limb would be to regrow it, rather than replacing it with a necessarily inferior prosthetic limb. After all, "regeneration of lost body parts is an ability shared to a varying degree by all living things" (R. Becker 1961), perhaps because the term "regeneration" actually encompasses a wide variety of renewal, restoration, and regrowth processes in cells, tissues and organs (Carlson 2007, page 3). Everyone knows that many lizards can shed part of their tail to escape a predator, and then regrow it over a period of weeks. Other examples in the vertebrate order are certain amphibians such as salamanders, newts, and axolotls, whose impressive regenerative abilities range from limbs and eyes to more vital structures such as the heart and some parts of the brain (figure 3.44). Mammals however have fewer regenerative capabilities. The best self-healers among them are some strains of mice, especially the Murphy Roths Large strain: they are capable of complete closure and scarless regeneration of through-and-through ear hole puncture wounds, regrowth of articular cartilage, and partial regeneration of amputated digits. Unfortunately for us humans, limb regrowth is not part of our regenerative abilities, limited mainly to the skin and hair (easily regrown), bones (fractures healed from the periosteum), muscle (in cases of minor wounds), nerves (slowly and incompletely), liver (from as little as 25% of its tissue), and the tip of the digits during childhood (regenerated within one to three months, provided the wound is not sealed up with flaps of skin; this was first reported by Douglas (1972) in Australia and Illingworth (1974) in the United Kingdom; Carlson (2007, page 97) notes that "the surgical community was slow to accept this new mode of treatment").

The key morphological events of amphibian limb regeneration are well identified, since it has been studied a lot: following amputation, the cut surface is rapidly covered by epithelial cells that migrate from the surface of the stump, and under this specialized wound healing, adult cells dedifferentiate into stem-like cells quite similar to embryonic stem cells, then proliferate and redifferentiate into the various tissues of the regenerated limb, more or less the same way that the original limb developed the first time. Recent advances in molecular biology and genomics indicate that there is hope to understand much more about amphibian limb regeneration, by finding out the cellular and molecular mechanisms at play (Whited and Tabin 2009). Then it might be possible to figure out how to use this knowledge in humans, and skew healing outcome from scar formation to regeneration of functional tissue. For instance, it has recently been found that "normal" mice genetically engineered to lack a certain gene [22] gain the ability to repair holes in their ears similarly to Murphy Roths Large mice, instead of healing with scar tissue (Bedelbaeva, Snyder, Gourevitch, Clark, X.-M. Zhang, Leferovich, Cheverud, Lieberman, and Heber-Katz 2010). According to the researchers who made this discovery, we may wonder whether temporarily inactivating the gene in question at the site of a wound through locally applied drugs could accelerate or improve healing in humans. Actually, even though human limb regeneration is a very long way off, research on human tissue have already started, with the Defense Advanced Research Projects Agency having obvious interest in it (DARPA 2006–2010a). Reportedly, mouse and human skin cells have been successfully dedifferentiated to act more like stem cells, able to form the early structures needed to begin the process of regrowing lost tissues other than skin.

For more on the topic of limb regeneration, short reviews by Whited and Tabin (2009, 2010) and more detailed reviews by Alvarado and Tsonis (2006) and Yokoyama (2008) constitute starting points in the scientific litterature. Books by Carlson (2007) and Atala, Lanza, Thomson, and Nerem (2010) are recent references on the matter.

While waiting for human limb regeneration to be commonplace, prosthetic replacements are our best option when the original limb is missing. Failing a new biological limb, there is much focus into interfacing at best the artificial robotic one with the human who uses it: a cybernetic dream of perfect human-robot integration. We have already reviewed most of the research efforts that concentrate on the robotic side of this integration: the actuation, sensorization and control of the current experimental hand prostheses, the state of the art in the analysis of the myoelectric signal, and the systems aimed at giving sensory feedback to the user. In the following paragraphs, we

22. The CDKN1A gene, short for cyclin-dependent kinase inhibitor 1A, located on chromosome 17 in mice and chromosome 6 in humans. It codes for a protein known as p21, or cyclin-dependent kinase inhibitor 1A protein. This protein functions as a regulator of the progression of the cell division cycle: it is involved in stopping this cycle in the growth phase of the cell, prior to DNA replication and mitosis, if it appears that the cell is somehow not ready for DNA synthesis. As such, it is related to tumor suppressor proteins.

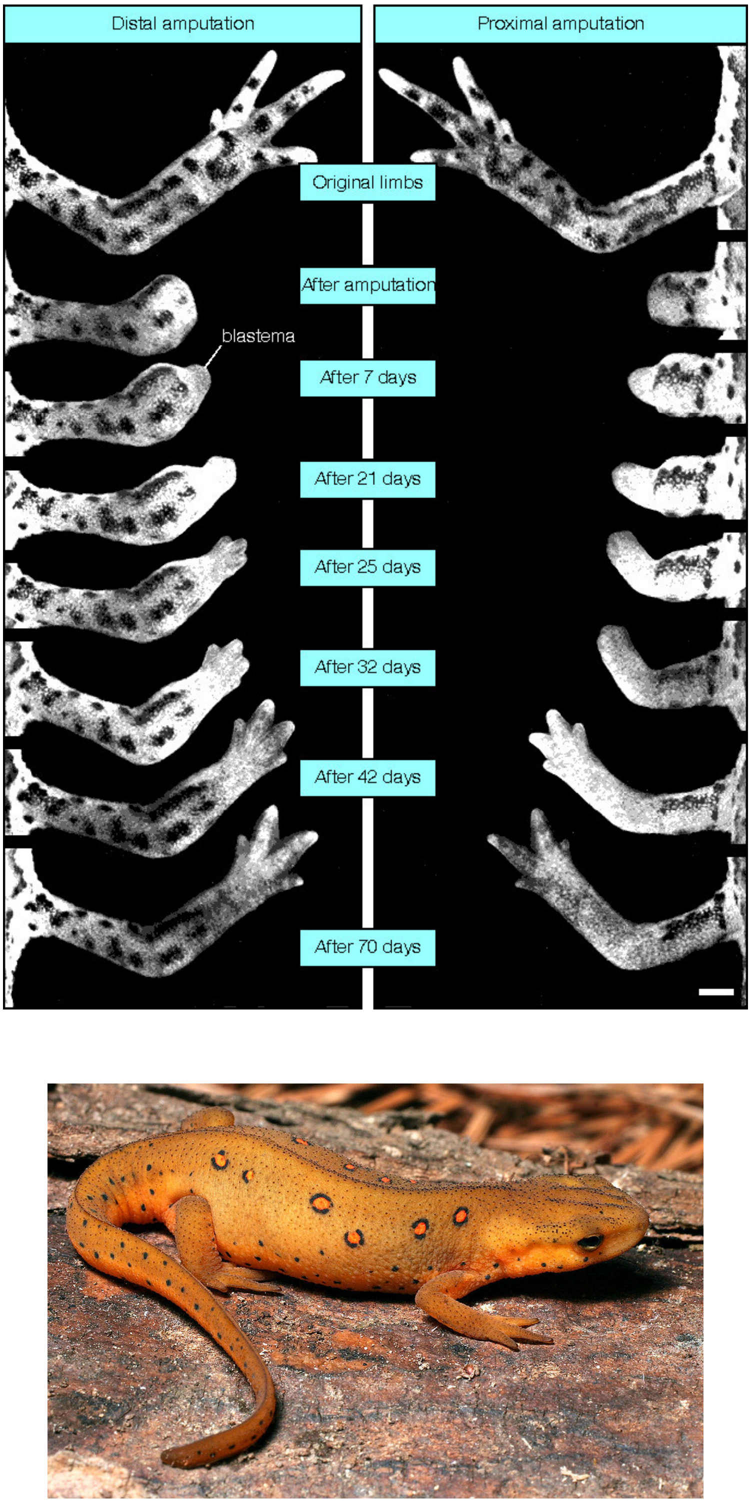
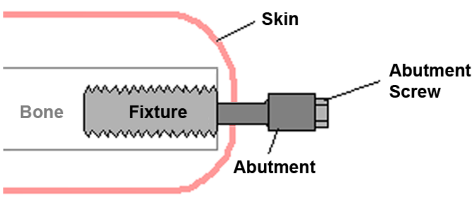



Figure 3.44 – Limb regeneration after amputation in a newt. Below, a juvenile red-spotted newt, a common newt of eastern North America. The adult form has olive green skin and lives underwater.

present the research efforts that concentrate on the human side of the integration: or, how to use surgery on the user to improve prosthesis utility and make the artificial limb more like the original one.

Four surgical procedures are worth of mention: one of them is the direct integration of the prosthesis into the user's skeleton (osseointegration) and the three others are about extending the neural interfacing of the prosthesis with the user's nervous system, at the muscle level (targeted muscle reinnervation and targeted sensory reinnervation), at the peripheral nerve level (neural signal control and neural sensory feedback), and at the brain level (cortical control and cortical stimulation).

**Osseointegration** The term "osseointegration" refers to the direct structural and functional connection that forms between bone tissue and an implant made of biocompatible material, for instance titanium or certain titanium alloys. The bone tissue grows right up to the surface of the implant, without intervening connective tissue. No scar tissue, cartilage or ligament fibers are present between the bone and implant surface (figure 3.45(b)). Osseointegration was incidentally discovered by Swedish surgeon Per-Ingvar Brånemark in 1952: he had implanted titanium chambers into the femurs of rabbits to study blood circulation in bone marrow, and at the end of the experiment several months later, it had become impossible to remove the implants from the bone without fracture (P.-I. Brånemark 1959). It occured to him that such strong bonding of the bone with the implant might be useful for supporting dental prostheses on a long-term basis, and nowadays dental implants are indeed by far the main application of osseointegration (R. Brånemark, P.-I. Brånemark, Rydevik, and Myers 2001). But osseointegration has also found use in facial reconstruction surgery and hearing aid devices, and since the 1990s it is used to keep in place artificial joints between bones in patients with joint damage (Lundborg, P.-I. Brånemark, and Carlsson 1993; R. Brånemark, P.-I. Brånemark, Rydevik, and Myers 2001), and attach upper and lower limb prostheses directly into the skeleton of patients who are contraindicated to classical socket fitting (Lundborg, P.-I. Brånemark, and Rosén 1996; R. Brånemark, P.-I. Brånemark, Rydevik, and Myers 2001; Manurangsee, Isariyawut, Chatuthong, and Mekraksawanit 2000; Palmquist, Jarmar, Emanuelsson, R. Brånemark, Engqvist, and Thomsen 2008).

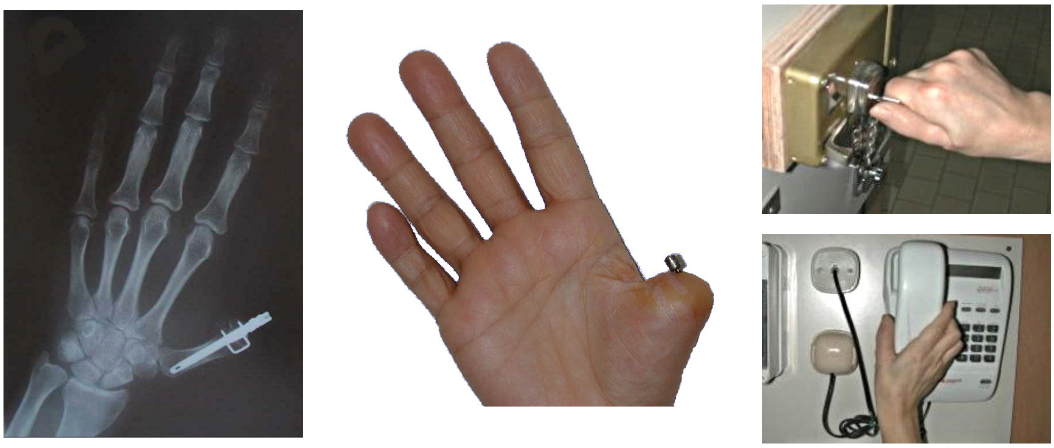



(a) Schematic view of the implant system

(b) Bone tissue (pink) has grown within the threads of the fixture (black). Histologic section under light microscopy.

Figure 3.45 – Prosthesis osseointegration

Implanting an osseointegrated prosthesis requires two surgical procedures (Fairley 2006; Hagberg and R. Brånemark 2009). At the first surgery, a titanium fixture is carefully threaded into the medullary cavity of the bone of the residual limb, and the wound is closed. A healing period of several months is allowed for osseointegration to take place; the bone has to grow into the threads of the fixture for optimal attachment. At the second surgery, the implanted fixture is exposed and a titanium bolt, called an abutment, is connected to the fixture, then the wound is closed with the abutment penetrating the skin and protruding from the residual limb (figure 3.45(a)). The patient is immobilized for a dozen days to achieve critical healing of the skin penetration area and soft tissues, then a recovery and rehabilitation period of several months follows, during which the implant is gradually loaded. Eventually, the final prosthesis can be attached to the abutment (figure 3.46).



(a) X-ray photograph of an osseointegrated fixture in the thumb metacarpal

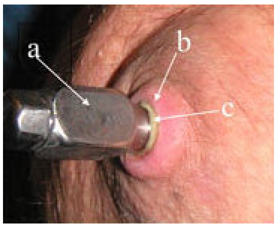
(b) An abutment locked in the implant and penetrating the skin

(c) Grasps performed with a passive silicone thumb prosthesis in place

Figure 3.46 – Thumb osseointegrations performed at the INAIL Prosthesis Center in Vigorso di Budrio (Bologna, Italy). Reported by Bicchierini, Sacchetti, Pilla, Grassi, Davalli, and Orlandini (2004).

Osseointegration has advantages and downsides (Fairley 2006). On the bright side, it suppresses all the problems associated with prosthesis sockets: discomfort, sweating, pain, soft-tissue problems such as skin irritation and muscle soreness, and the need to remake a socket every few years because of wear and changes in stump volume; it is therefore indicated in patients who suffer from these issues. Users also report that osseointegrated prostheses provide less feeling of weight, feel more like an extension of the body, offer better control, and present easier donning and doffing. Another significant advantage is the return of a certain extent of sensory capacity, hypothetically because tactile stimuli are transfered to nerves in the bone via the fixture (Lundborg, P.-I. Brånemark, and Rosén 1996); this phenomenon is known as "osseoperception" (R. Brånemark, P.-I. Brånemark, Rydevik, and Myers 2001).

On the other hand, osseointegration presents serious disadvantages. First, two surgeries are required, both with long recovery periods. Then, the pressure and stress coming from the prosthesis are focused at the distal end of the bone, rather than being distributed over a large area. This may lead to fatigue fracture of the implant, bone, or bone-implant interface in case of excessive loading, especially in torque since the fixture is threaded; recent research tries to avoid this outcome via overload protection systems and novel implant designs (Fairley 2006). But most importantly, there is a high risk of deep infection, as the implant permanently penetrates the skin and leads into the inside of the bone (figure 3.47). This risk is controlled through rigorous personal hygiene and the use of antibiotics when needed, because "if infection does occur, it can cause major problems: bone loss, loosening of the implant, and a possible need to re-amputate the limb at a higher, less functional level" (Fairley 2006). Current and possible future solutions to the infection issue are reviewed by Fairley (2007).




(a) Titanium abutment penetrating the skin.
(b) Surrounding skin.
(c) Layer of pus between skin and abutment.

Figure 3.47 – Serious infection at osseointegration site (Fairley 2007)

Any type of prosthesis can be used with osseointegration, since it is just the fixation technique: passive, body-powered and externally-powered. Most osseointegration procedures are conducted for lower-limb amputees, the majority of them transfemoral (over one hundred reported cases). Upper-limb amputees can be osseointegrated at both transhumeral and transradial levels (over thirty reported cases). Finger and thumb passive prostheses are also possible options (Lundborg, P.-I. Brånemark, and Rosén 1996; Manurangsee, Isariyawut, Chatuthong, and Mekraksawanit 2000).

**Neural signal control, neural sensory feedback** While osseointegrated implants are meant to bring the prosthesis closer to the user's skeleton, implantable electrodes and neural interfaces are meant to bring it closer to the user's nervous system. They represent a credible technology for the restoration of motor and sensory functions to unprecedented levels (Ohnishi, Weir, and Kuiken 2007; Micera, Carpaneto, and Raspopovic 2010). For instance, peripheral neural interfaces are implantable devices whose electrodes tap into the peripheral nervous system, that is to say the nerves. That way, control information for the prosthesis may be gathered that is superior in quality and detail to the myoelectric information; for that purpose, the electrodes must record the action potentials from the efferent fibers of the nerves (axons of motor neurons). Moreover, sensory information may be fed back from the sensors on the prosthesis directly into the nervous system; for that purpose, the electrodes must appropriately stimulate the afferent fibers of the nerves (axons of somatosensory neurons) (figure 3.48).

Research in electrode development has produced, and keeps producing, a wide variety of electrodes for interfacing with the peripheral nerves. Navarro, Krueger, Lago, Micera, Stieglitz, and Dario (2005) wrote a thorough review of them; figures 3.49 and 3.50 illustrate some of them. Depending on whether they are placed on the surface of the nerve or whether they penetrate it, they are called "extraneural" or "intraneural". Quite understandably, invasivity and selectivity are linked: extraneural electrodes provide simultaneous interface with many nerve fibers, while intraneural electrodes are able to contact smaller groups of nerve fibers. The rest of the implanted neural interface consists of a small electronics package, hermetically sealed in biocompatible plastic, and surgically placed beneath the skin, sutured to the underlying fascia to prevent migration. This package receives power transcutaneously, via a magnetic link, from an external exciter; it also transmits and receives data in the same way with an external telemetry system, usually combined with the exciter. For recent examples of such systems, see Donaldson, L. Zhou, Perkins, Munih, Haugland, and Sinkjaer

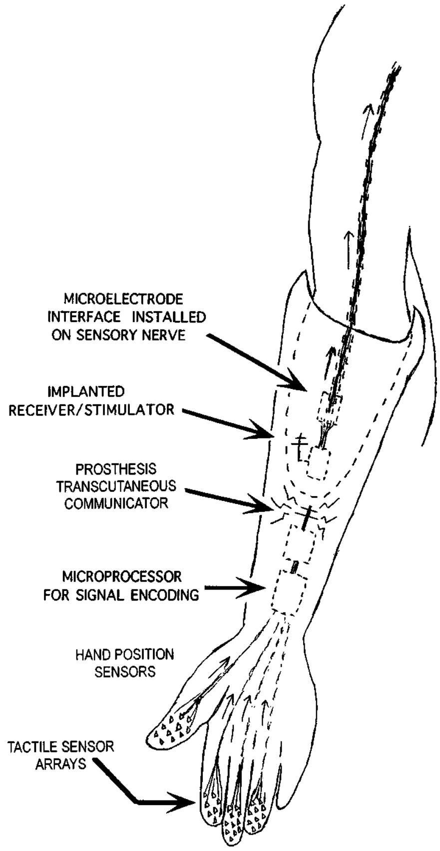



Figure 3.48 – Principle of neural sensory feedback (from Riso 1999). For neural signal control, the principle is similar, except that the efferent signal runs the other way and ends up in actuators instead of sensors.

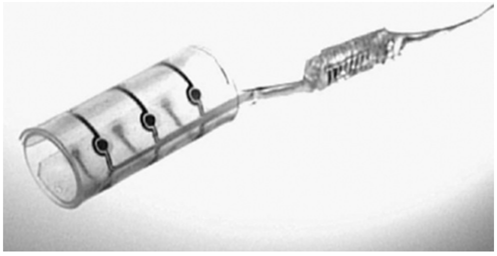
(2003), Liang, J.-J. Chen, C.-L. Chung, C.-L. Cheng, and C.-C. Wang (2005), or Sacristán-Riquelme, Segura-Quijano, and Osés (2006).

Prostheses making use of a peripheral neural interface may theoretically be thought-controlled by their user, who would merely desire a particular motion for it to be executed by the prosthesis (that is to say, volitional control). Indeed, the efferent signals originating in the central nervous system would be picked up by the electrodes in the peripheral nervous system, transmitted out of the body via the wireless link between the implant and the external transmitter-receiver, appropriately analyzed and processed by the prosthesis embedded control algorithms, and finaly turned into corresponding motor commands for the prosthesis actuators. Depending on the higher or lower ability of the electrodes and signal processing unit to extract correctly the efferent signals from the nerves, multiple degrees of freedom and distinct limb functions could be controlled. Indeed, although the muscles normally controlling the desired motions may no longer be present (depending on the level of amputation), the peripheral nerves containing the motor fibers for these muscles are still accessible in the remaining part of the limb, and they remain functional for several months to several years after amputation: Dhillon, S. Lawrence, Hutchinson, and Horch (2004), and later Jia, Koenig, X. Zhang, J. Zhang, T. Chen, and Z. Chen (2007), found out through clinical experiments that “both central and peripheral motor and somatosensory pathways” associated with a missing limb “retain significant residual connectivity and function for many years after limb amputation”, despite long-term neural amputation issues such as degeneration and atrophy of the unused neural pathways and reorganization of the associated brain areas through cortical plasticity (the reason for this persistence is unknown at the moment). Therefore, although an elbow amputee misses all the extrinsic muscles of their hand, the open/close degree of freedom of the hand may still be recovered from the median and radial nerves in their upper arm: the extrinsic volar muscles, which are flexors of the hand and fingers, are mostly under median innervation, and the extrinsic dorsal muscles, which are the antagonist extensors, are under radial innervation (see sections 2.1.2 and 2.1.3, in chapter 2, for muscle and nerve anatomy of the hand). In addition to this essential degree of freedom, other ones may be recovered; for instance the opposition of the thumb would necessitate electrodes in the median and ulnar nerves, since they serve the thenar muscles.

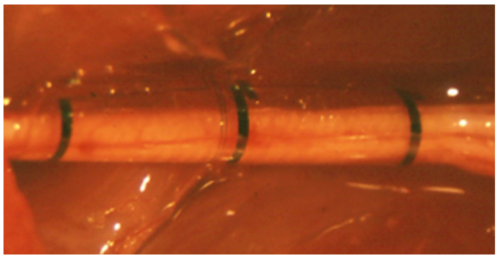
Compared to myoelectric control, neuroelectric control of a prosthesis is much more natural, as there is no need for activation of muscles unrelated to the desired movement. Another advantage is the high frequency of the neuroelectric signal, whose power density spectrum peaks at approximately 2 kHz, compared to 50 Hz for the myoelectric signal recorded with surface electrodes (De Luca 1978). Therefore, “the detected signal can be high-passed above 180 Hz, thereby removing the low-frequency electromagnetic interference associated with electric motors without losing a substantial amount of the signal” (De Luca 1978). As for the drawbacks, they are the same as those of all implants: surgery, invasiveness, and long-term stability. Also, neuroelectric signal analysis needs more research so that sufficient information from the recorded action potentials may be extracted to operate multiple degrees of freedom; most reseach efforts so far have concentrated on very few degrees of freedom.

Peripheral neural interfaces are not only useful for a more natural control of the prosthetic device, but also for providing somatosensory feedback to the user. In an interesting review on sensory neural interfaces, Riso (1999) remarked that the spatial expanse and the quality of the tactile sensation elicited by the electrical stimulation of the peripheral nerves were dependent on the selectivity of the utilized electrodes. For example, a typical extraneural electrode (figure 3.49) stimulates many sensory nerve fibers “all at once and with an unnatural synchronicity that is phase-locked to the stimulus pulse train”. These nerve fibers used to innervate different cutaneous areas of the amputated hand and to be connected to different cutaneous mechanoreceptors (see section 2.1.5 on skin anatomy, in chapter 2). As a consequence the perceived sensation seems to originate from a large area of skin, “encompassing an entire finger or much of the palm for example”, and it “remains a foreign feeling ressembling a vibration, taping or flutter on the skin” (Riso 1999). This result is very far from the original tactile sensitivity.

To restore a more spatially discrete tactition, it is necessary to use intraneural electrodes to activate specific sensory fibers in the nerve (figure 3.50). This difficult task is somewhat facilitated by the fact that the nerve fibers are not mixed up within the nerves, but segregated by a variety of membranes into fascicles, by function and area: consequently, “activation of a sensory fascicle in the median nerve (at the level of the forearm) that used to be connected, for example, to the thumb of the amputated hand evokes a sensory experience that seems to emanate from the thumb of the phantom hand” (Riso 1999). Using intrafascicular electrodes, it is therefore possible to elicit sensations that have a better spatial resolution. This is the kind of electrodes that Dhillon, S. Lawrence, Hutchinson, and Horch implanted in the nerves



(a) Tripolar cuff electrode and its connector (Navarro, Krueger, Lago, Micera, Stieglitz, and Dario 2005).



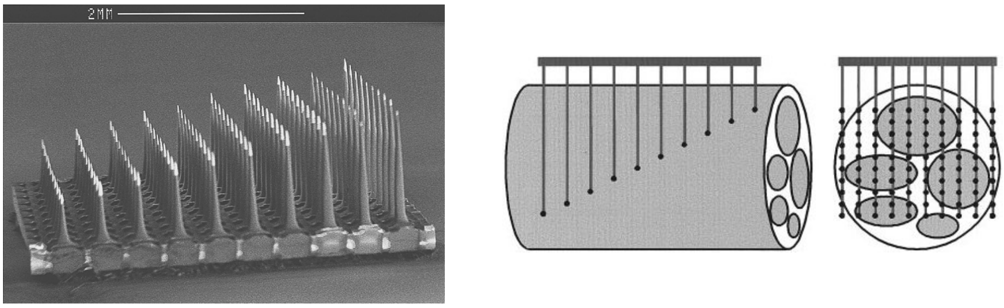
(b) Cuff electrode implanted around a nerve in a rat (Raspopovic, Carpaneto, Udina, Navarro, and Micera 2010).

Figure 3.49 – Extraneural cuff electrodes, so-called because they encircle the nerve. The insulating tubular sheath is usually made of silicone and/or polyimide, and the electrode contacts are typically in platinum, platinum-iridium or tantalum.

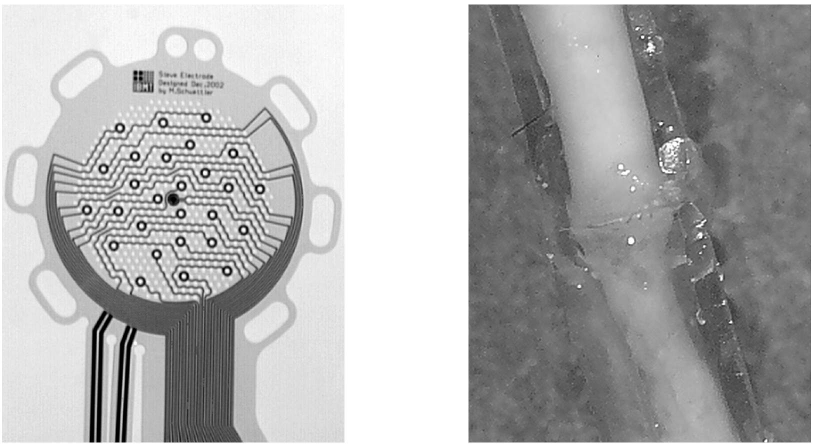
of several amputees for clinical experiments and evaluation at the University of Utah, Salt Lake City, United States; they found out that electrical stimulation through these electrodes could provide "discrete, unitary, graded sensations of touch, joint movement, and position, referring to the missing limb", and that these sensations could be used "to provide feedback information about grip strength and limb position" (Dhillon, S. Lawrence, Hutchinson, and Horch 2004; Dhillon and Horch 2005).

Restoring the variety of tactile sensations is even more difficult than restoring the spatial discreteness of tactition. Indeed, the four types of cutaneous mechanoreceptors have specific roles regarding skin indentation, skin stretch, and sensitivity to vibrations, and tactile perception is the sum of their different functions (see section 2.1.5 in chapter 2.1). Artificially reproducing complex tactile sensations such as contact with an object, movement of an object accross the skin, or surface texture and compliance, would therefore require independent and coordinated electrical stimulation of hundreds of individual cutaneous afferent fibers, with specific stimulation patterns for each type of tactile afferent fiber. Yet stimulation of isolated afferents is not an easy goal, and there are so many of them to coordinate: the median nerve, for instance, "is estimated to contain about 14 000 tactile afferents subserving the hand" (Riso 1999). This goal might perhaps be attainable in the future, but for the moment electrical stimulation of small bundles of afferents seems a more realistic goal. The major drawback is that "the evoked sensations will have an unnatural feeling since a mixture of afferents sub-serving different modalities may be co-activated indiscriminately". However, it seems at least possible to separate tactile feedback from proprioceptive feedback, because "cutaneous afferents seem to run in separate fascicles from muscle afferents within the nerves" (Riso 1999).

Despite their sounding state-of-the-art technology, implantable neural interfaces are actually not new concepts: they started to be investigated as soon as the miniaturization of electronics allowed the development of devices small enough to be implanted in the human body. Early examples of peripheral neural interfaces include the works of Clippinger, Avery, and Titus (1974) in the United States and Anani, Ikeda, and Körner (1977) in Sweden, for sensory feedback. Shortly thereafter, in the United States, De Luca (1978) and his coworkers introduced the opposite motor concept, for control of upper limb prostheses. Nowadays, neural signal control and neural sensory feedback are still being investigated in prosthetics and robotics laboratories,




(a) Scanning electron microscope image of a Utah Slanted Electrode Array, invented at the University of Utah (Branner, Stein, and Normann 2001). The electrode has ten rows of ten micro-electrodes of varying length between 0.5 mm and 1.5 mm, electrically insulated except for their exposed platinum-platted tips. They provide access to most fascicles within the nerve, as illustrated on the right.



(b) Sieve electrode are implanted by transecting the nerve stump and letting its fibers regenerate through the array of holes, encased in a guidance tube (Navarro, Krueger, Lago, Micera, Stieglitz, and Dario 2005). Some of the holes are platinum-deposited contact electrodes, in black on the picture on the left. The picture on the right shows a regenerated nerve through a polyimide sieve electrode.

Figure 3.50 – Two examples of intraneural electrodes

with researchers pursuing the aim of a cybernetic prosthesis, and it appears that in spite of promising initial results, these techniques are “not likely to be available for general use in the near future” (Cotton, Cranny, Chappell, White, and Beeby 2006).

Nevertheless, we have several recent reports of successful, albeit limited, trials of neuroelectric control of a robotic or prosthetic hand with neural sensory feedback, on amputated and non-amputated volunteers [23]. For instance in Japan, Shimojo, Suzuki, Namiki, Saito, Kunimoto, Makino, H. Ogawa, M. Ishikawa, and Mabuchi (2003) reported successful neural sensory feedback of the grasping force of a (classicaly) teleoperated robot hand equipped with tactile sensors. They wrote that the human operator sensed a force applied to the robot hand as a force applied to their own hand, which is a form of tactile perception in remote manipulation.

In England, at the University of Reading, Kevin Warwick and his team had an experimental intraneural electrode implanted into the median nerve of the left arm

23. These laboratory experiments usually do not need electrodes to be implanted on a long-term basis in the nerves (especially in the case of non-amputated subjects, obviously). Therefore they don’t implant transcutaneous wireless telemetry devices as afore-mentioned, they rather use percutaneous wire connections for the time of the study. This requires close monitoring of signs of infection at the site where the wires exit the body.

of a non-amputated volunteer [24]. After a threshold was applied to the output signals obtained from the electrode, the subject became able to control neuroelectrically the opening and closing of a multiple degree of freedom prosthetic hand operating under the Southampton Adaptive Manipulation Scheme (the Snave Hand, described by Kyberd, Evans, and Winkel 1998). The force applied by the hand to grip an object was recorded by sensors on the fingertips and fed back to the subject as a microcurrent via the neural electrode, closing the loop for force control. Successful grasping with the prosthetic hand without visual input, that is to say with only neural sensory feedback, was experimentally verified, as well as remote neural control and remote neural feedback over the Internet, with the subject in New York and the prosthetic hand and object in Reading (Gasson, Hutt, Goodhew, Kyberd, and Warwick 2002, 2005; Warwick, Gasson, Hutt, Goodhew, Kyberd, Andrews, Teddy, and Shad 2003; Warwick 2003).

In the United States, Dhillon and Horch (2005) of the University of Utah were able to have six upper limb amputees set the joint position of the elbow of an artificial arm and the grip strength of that same arm, through intrafascicular electrodes which also returned joint position and grip strength back to the user (one at a time, not both at the same time). Neuroelectric control of force and position without visual feedback was possible, that is to say control based on neural sensory feedback alone.

Last but not least, CyberHand, developed at ARTS Lab in Pontedera, Italy, is intended since its conception to be a cybernetic prosthetic testbed interfaced to the peripheral nervous system (Carrozza, Dario, Vecchi, Roccella, Zecca, and Sebastiani 2003; Carrozza, Cappiello, Micera, Edin, Beccai, and Cipriani 2006; Micera, Carrozza, Beccai, Vecchi, and Dario 2006). Its follow-up, SmartHand, also has neural interfacing in mind (Cipriani, Controzzi, and Carrozza 2009). In a recent trial (Rossini, Micera, Benvenuto, Carpaneto, et al. 2010), CyberHand was interfaced for one month to an amputee via four intrafascicular multi-electrodes implanted in the median and ulnar nerves. Artificial intelligence classifiers were trained off-line to analyze the signals recorded during three distinct voluntary movements of the phantom hand: thumb opposition, hand closing and movement of the little finger. After completion of classifier training, real-time neuroelectric control of the hand was achieved for these three actions, with 85% correct classification performance. Neural sensory feedback was tested too: "different types of current stimulation were determined to allow reproducible and localized hand/fingers sensations". Moreover, it was confirmed via transcranial magnetic stimulation that cortical reorganization reversed, presumably from the afferent fibers being stimulated again, and it was also confirmed that phantom pains were alleviated, which represents an attractive potential therapeutic benefit.

**Cortical control, cortical stimulation** An alternative to connecting the prosthesis and the user at the peripheral nerve level consists in fetching the control signal directly at its source and bringing the sensory feedback directly where it is processed: in the upper part of the central nervous system, the brain. Although implants in the brain are extremely invasive and involve major surgery, they are justified in certain cases. For instance, certain stimulation devices have proven successful in restoring some level of audition in the hearing impaired, and others at relieving the symptoms of otherwise treatment-resistant neurological movement disorders such as

24. Namely Warwick himself.

Parkinson disease and dystonia. As far as limb prosthetics are concerned, though, there is at the moment no central neural interface in actual use: they are found only in research and experimental settings. People who would most likely benefit from them are primarily those paralyzed or movement-impaired by spinal cord injury, stroke, cerebral palsy, multiple sclerosis, amyotrophic lateral sclerosis, and other severely-disabling conditions. In those patients for which peripheral neural implants are of no use, direct neural interfaces could help restore some degree of autonomy, mobility and/or communication (depending on the disability) by letting them control easily robotic arms and hands, electric wheelchairs, and speech synthesis systems, directly from their brains.

The origins of cortical control go back to neurophysiology studies on monkeys in the late 1960s in the United States, when researchers first tried to elucidate the correlations between neuronal activity in the primary motor cortex [25], recorded by implanted electrodes, and characteristics of the motion of the upper limbs. For instance, in an experiment about wrist movement, Evarts (1968) found that for the majority of the recorded neurons, "discharge frequency was related primarily to the force [generated by the joint] and rate of change of force and was only secondarily related to the direction of displacement". Humphrey, Schmidt, and Thompson (1970) demonstrated that the time course of a simple wrist movement could be predicted quite accurately with the use of "comparatively simple quantitative procedures" on the activity of small sets of simultaneously recorded neurons from the primary motor cortex. Especially significant among these neurophysiology studies on monkeys is the research done by Georgopoulos and his colleagues in the 1980s at Johns Hopkins University in Baltimore, Maryland (Georgopoulos, Kalaska, Caminiti, and Massey 1982; Georgopoulos, Kalaska, Crutcher, Caminiti, and Massey 1984; Georgopoulos, A. Schwartz, and Kettner 1986; Georgopoulos, Kettner, and A. Schwartz 1988). They showed that endpoint movement, that is to say the movement of the end of the arm, is represented rather directly in the activity of motor cortical neurons. In broad and simplified outline, the discharge rate of these neurons is "directionally tuned": each individual neuron discharges for all directions of movement of the hand, but at the highest rate for movements in a particular direction, and at progressively lower rates for movements in directions away from this particular direction, as if each neuron had a "prefered direction" of hand movement. A vector sum of these prefered directions weighted by the discharge rate of the corresponding neurons, on a population of 475 simultaneously recorded motor cortical neurons, results in a fairly good prediction of the actual direction of hand motion; in addition to direction, speed of the motion can also be inferred from neural activity. With these properties, the movement trajectory, i.e. the time-indexed succession of hand positions, could be extracted from the activity of neuronal ensembles for reaching-and-grasping movements, in subsequent studies during the 1990s.

All these studies were perhaps more motivated by scientific curiosity than by the desire to build direct neural interfaces and prosthetic systems, but they nonetheless advanced knowledge necessary to reach this goal. From the beginning of the 2000s, several research groups have worked on extracting information related to reaching movements, by recording signals primarily, but not exclusively, from the motor

25. The primary motor cortex is the main brain region involved in the planning and execution of movements. In humans, it is located in the posterior portion of the frontal lobe, see figure 2.42(a) in section 2.3.1 about the relation between the hands and the brains, in chapter 2.

cortex [26], in order to drive simple or complex robotic arms: one degree of freedom levers for rats (Chapin, Moxon, Markowitz, and Nicolelis 1999) and multiple degree of freedom arms with a gripper for monkeys (Wessberg, Stambaugh, Kralik, Beck, Laubach, Chapin, J. Kim, Biggs, Srinivasan, and Nicolelis 2000; Carmena, Lebedev, Crist, O'Doherty, Santucci, Dimitrov, Patil, Henriquez, and Nicolelis 2003; Velliste, Perel, Spalding, Whitford, and A. Schwartz 2008). Usually, the monkeys have visual feedback of the robotic arm, which means that they know that they control it, usually for self-feeding. Their own arms are restrained so that they are forced to use the robotic one through the neural interface. In that way, all four components of neural closed-loop control are in place: a neural interface extracting the activity of chosen neuronal ensembles, signal processing and control algorithms that decode these biological signals and translate them into motor commands for the robotic device, the robotic effector in question, and sensory feedback, usually in the form of vision, but it could potentially be other sensory modalities, brought directly to the brain by another neural interface if necessary. Indeed, it is possible to produce useful sensory perceptions from direct electrical microstimulation of the brain (Romo, Hernández, Zainos, Brody, and Lemus 2000; Fitzsimmons, Drake, T. Hanson, Lebedev, and Nicolelis 2007; O'Doherty, Lebedev, T. Hanson, Fitzsimmons, and Nicolelis 2009).

Promising results have been achieved with this approach of endpoint trajectory prediction from the motor cortex. For instance, Velliste, Perel, Spalding, Whitford, and A. Schwartz (2008) had monkeys control the spatial position of a robot gripper and its open/close operation for self-feeding, that is to say a total of four degrees of freedom, as fast and as effectively as their own hands would carry out the task. The first human trial happened in the United States from June 2004 to April 2005: a tetraplegic 25-year-old male patient had a 96 micro-electrode array [27] implanted in his primary motor cortex for recording of neuronal ensemble activity, three years after spinal cord injury. It was found that intended hand motion could still be retrieved from the discharge patterns, and the patient was able to use neural control "to open and close a prosthetic hand, and perform rudimentary actions with a multi-jointed robotic arm" (Hochberg, Serruya, Friehs, Mukand, Saleh, Caplan, Branner, D. Chen, Penn, and Donoghue 2006).

In all these results, the controllable prosthetic device is limited to very simple functions. This is because extracting reliable information on the trajectories of many different joints is very challenging, especially for such complex tasks as grasping or, worse, dextrous manipulation. Consequently, the recent possibility of extracting higher-level information, namely the goal of the reaching movement from the visual and motor cortices (Musallam, Corneil, Greger, Scherberger, and Andersen 2004) and the type of the grasp from the premotor cortex (Micera, Carpaneto, Umiltà, Rochat, Gallese, Carrozza, Krüger, Rizzolatti, and Dario 2005), is very attractive for the control of multiple degree of freedom hand prostheses. It might eventually be possible for the user of a direct neural interface to realize hierarchical shared control

26. The motor cortex consists of the primary motor cortex and the three secondary motor cortices: the premotor cortex, the posterior parietal cortex and the supplementary motor area. In the cited works, signals from neurons in the primary motor cortex were always recorded, since it is the main brain area for motion; in addition, Wessberg, Stambaugh, Kralik, Beck, Laubach, Chapin, J. Kim, Biggs, Srinivasan, and Nicolelis (2000) implanted electrodes in the premotor and posterior parietal areas, and Carmena, Lebedev, Crist, O'Doherty, Santucci, Dimitrov, Patil, Henriquez, and Nicolelis (2003) in all three secondary motor cortices, plus the primary somatosensory cortex.

27. A 100 micro-electrode array similar to the one in figure 3.50(a), but with all electrodes the same size; 96 electrodes are available for neural recording.

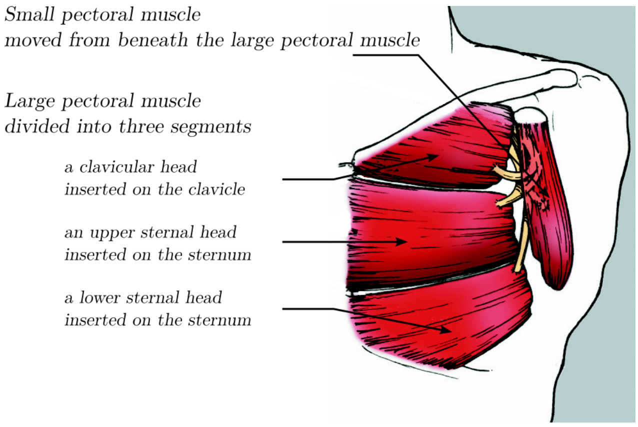
of their prosthesis: selection of the grasp pattern by the high-level controller, i.e. the user's brain, and autonomous management of the grasp by the low-level controller, i.e. the algorithms embedded in the prosthesis.

More information and references about direct neural interfaces and direct neural control may be found in the reviews written by Donoghue (2002), Friehs, Zerris, Ojakangas, Fellows, and Donoghue (2004), and Ohnishi, Weir, and Kuiken (2007). Longer, more thorough reviews, are also worth reading, for instance those by Wolpaw, Birbaumer, Heetderks, McFarland, Peckham, Schalk, Donchin, Quatrano, C. Robinson, and Vaughan (2000), Wolpaw, Birbaumer, McFarland, Pfurtscheller, and Vaughan (2002), Vaughan (2003), A. Schwartz (2004), Lebedev and Nicolelis (2006), and Hatsopoulos and Donoghue (2009). They present in detail the state of the art in neural control and the tremendous, but exciting difficulties to overcome for the future.

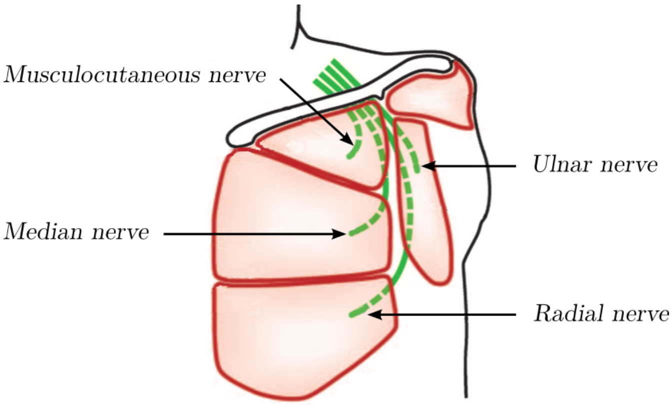
**Targeted muscle reinnervation, targeted sensory reinnervation** Targeted muscle reinnervation is a recent surgical technique that consists in transfering the nerves severed by the amputation to the muscles that are no longer biomechanically functional because they are no longer attached to the missing limb: the chest muscles in the case of a shoulder disarticulation, the upper arm muscles in the case of a transhumeral amputation or elbow disarticulation, and the forearm muscles in the case of a transradial amputation or wrist disarticulation. The nerves regenerate and innervate the target muscles, which then serve as biological amplifiers of the amputated nerve motor commands, facilitating myoelectric control of a multiple degree of freedom prosthesis.

This procedure was thought up by physiatrist Todd Kuiken from the Rehabilitation Institute of Chicago and Northwestern University, Chicago, Illinois, following research on rat muscles (Kuiken, Childress, and Rymer 1995). Preparatory studies indicated that it should be possible to record independent, crosstalk-free myoelectric signals from independently innervated muscle sections, using surface electrodes only two or three centimeters apart, especially if the subcutaneous fat was removed to optimize signal transmition (Kuiken, Stoykov, M. Popović, Lowery, and Taflove 2001; Lowery, Stoykov, Taflove, and Kuiken 2002; Lowery, Stoykov, and Kuiken 2003; Kuiken 2003; Kuiken, Lowery, and Stoykov 2003). The first nerve transfer surgery was attempted shortly thereafter on one side of a patient with bilateral shoulder disarticulation, who needed revision surgery (Kuiken, Dumanian, and Lipschutz 2003; Kuiken, Dumanian, Lipschutz, Miller, and Stubblefield 2004; Hijjawi, Kuiken, Lipschutz, Miller, Stubblefield, and Dumanian 2006). During this operation, the large pectoral muscle and the small pectoral muscle were denervated, and the large one was divided into three segments (figure 3.51(a)). The four residual nerves that previously supplied the arm before the amputation were identified; they are the median, ulnar, radial, and musculocutaneous nerves (the first three travel all the way down to the hand, see section 2.1.3 in chapter 2; the last one is the nerve of elbow flexion and stops in the forearm). The nerves were surgically grafted to the newly-formed sections of the pectoral muscles, forming four nerve-muscle units (figure 3.51(b)). Then the subcutaneous fat was removed and the skin was closed.

After several months of recovery, the patient started to be able to contract voluntarily his chest muscles by thinking about moving his phantom limb: three of the four muscle segments responded correctly to their new innervation, meaning that reinnervation




(a) Diagram illustrating the target muscles




(b) Diagram illustrating the nerve transfers

Figure 3.51 – Targeted muscle reinnervation for a shoulder disarticulation amputee

was successful in them; it failed in the fourth one. The amputee was fitted with an experimental custom-built myoelectric prosthetic arm that used these new myoelectric control sites (Kuiken, Dumanian, Lipschutz, Miller, and Stubblefield 2004; Lipschutz, Kuiken, Miller, Dumanian, and Stubblefield 2006), and both objective testing and subjective opinion of the patient showed improved prosthesis control in comparison to the previous externally powered prosthesis. This is mainly because the nerve function correlates physiologically to the prosthetic function: the patient can think of actually using his hand rather than activating a muscle which has nothing to do with hand function. For example, when he thinks about closing his hand, the median nerve reinnervated segment of his large pectoralis muscle contracts, producing a myoelectric signal used by the prosthesis to close the hand. Also, simultaneous control of several degrees of freedom could be achieved, namely elbow flexion and hand closing. This is in contrast to conventional prostheses whose degrees of freedom must be operated sequentially, which makes for a frustratingly slow, awkward and cumbersome process. In a nutshell, operation of the prosthesis becomes easier, faster, more natural, more intuitive, and more functional after targeted muscle reinnervation.

Following this first success, targeted muscle reinnervation surgeries were performed on several other amputees having either shoulder disarticulations or transhumeral amputations. The surgeries and their detailed outcomes are reported and compared in a series of publications (Kuiken, Dumanian, Lipschutz, Miller, and Stubblefield 2005; Kuiken, Miller, Lipschutz, Stubblefield, and Dumanian 2005; O'Shaughnessy, Kuiken, and Dumanian 2006; Kuiken, Miller, Lipschutz, Lock, Stubblefield, Marasco, P. Zhou, and Dumanian 2007; Miller, Stubblefield, Lipschutz, Lock, and Kuiken 2008; O'Shaughnessy, Dumanian, Lipschutz, Miller, Stubblefield, and Kuiken 2008; Dumanian, Ko, O'Shaughnessy, P. Kim, C. Wilson, and Kuiken 2009). Since every amputation is different, the procedure must be adapted to virtually every case; consequently each new patient helped improve, refine and diversify this new technique.

Also, the researchers worked on myoelectric signal analysis to try and get more information from the new myoelectric control sites (P. Zhou, Lowery, Dewald, and Kuiken 2005; P. Zhou, Lowery, Englehart, H. Huang, G. Li, Hargrove, Dewald, and Kuiken 2007; H. Huang, P. Zhou, G. Li, and Kuiken 2008, 2009). Indeed, depending on which muscles are exploitable, how the residual nerves can be separated into their fascicles, and ultimately how many nerve-muscle units are feasible and reinnervate correctly, only a limited number of additional myoelectric sites are created, and therefore only a limited number of degrees of freedom are controllable. This is a shame because the nerves are able to transport a tremendous amount of control information from the brain. Pattern recognition in the myoelectric signal is therefore needed to extract as much information as possible.

Building on the above-cited work on signal processing, an experimental survey conducted with five targeted muscle reinnervation patients demonstrated the possibility for them to repeatedly perform ten different elbow, wrist, and hand motions with a virtual prosthetic arm, twelve myoelectrodes, and appropriate signal processing (Kuiken, G. Li, Lock, Lipschutz, Miller, Stubblefield, and Englehart 2009). The motions were "elbow flexion, elbow extension, wrist flexion, wrist extension, wrist pronation, wrist supination, hand opening, and three types of hand grasps", the mean classification accuracy was 88% and the motion completion times compared favorably to those of the control group. It is exceptional for high-level amputees to be able to control so many degrees of freedom, in particular those of the hand. Targeted reinnervated muscles thus prove their potential for real-time control of advanced, multifunction artificial arms and hands. As a matter of fact, Kuiken, G. Li, Lock, Lipschutz, Miller, Stubblefield, and Englehart (2009) also report that three targeted muscle reinnervation patients could test advanced upper arm prosthesis prototypes developed under the Defense Advanced Research Projects Agency's "Revolutionizing Prosthetics" program (DARPA 2006–2010b; Otto 2007, 2009, 2010, 2011): one made by the Johns Hopkins University Applied Physics Laboratory and collaborators (2007, 2009), with 7 degrees of freedom (figure 3.52), and another made by DEKA Research and Development Corporation and collaborators (2009), with 10 degrees of freedom [28]. Both prostheses have hands capable of a variety of grasp types, were tested with pattern recognition control, and yielded encouraging results for the future of prosthetics.

Targeted reinnervation has a sensory side too, consisting in nerve transfers to the skin: certain sensory nerves supplying chest skin areas are severed and their distal ends are surgically connected to the nerves of the missing limb (figure 3.53(a)), primarily

28. The second one received a lot of media attention and can be found all over the web, particularly in technophile blogs, amidst a great deal of inaccurate-at-best "cyborg" and "bionic" hype. It is usually known as the DEKA Arm, or Dean Kamen's Luke Arm. The other one is called the MPL Arm, short for Modular Prosthetic Limb, or sometimes JHU/APL Arm, from the names of the university and laboratory it comes from. Both had several successive versions.

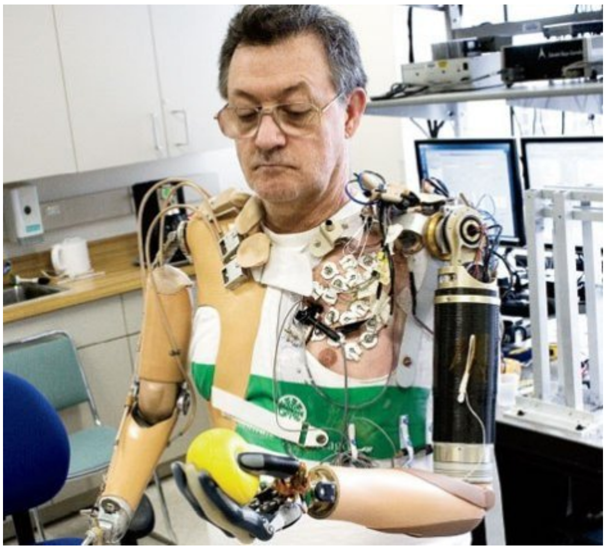
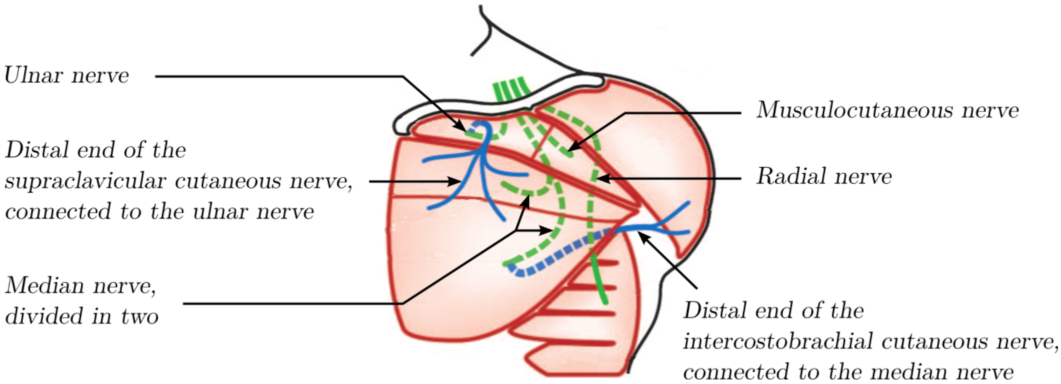


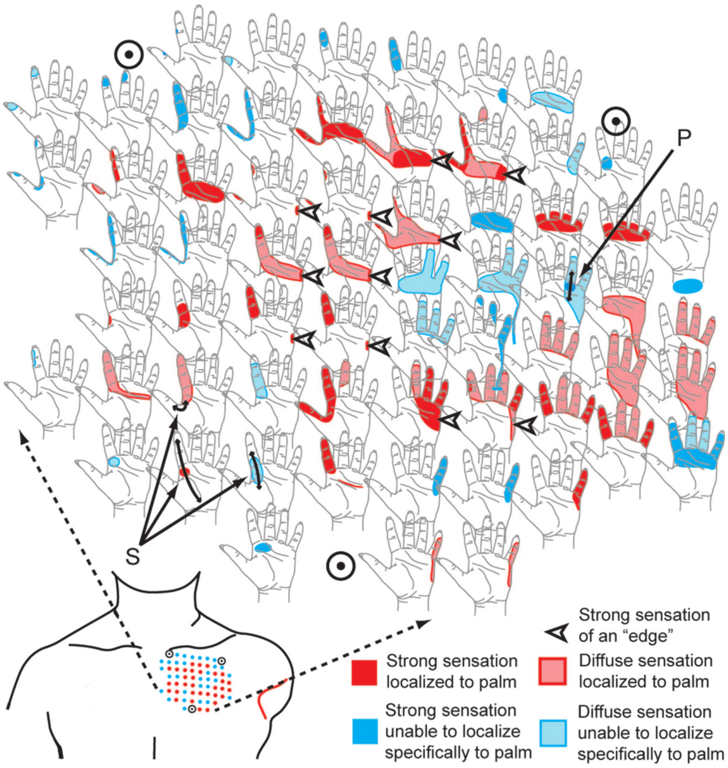
Figure 3.52 – Bilateral shoulder amputee Jesse Sullivan, the first tester of targeted muscle reinnervation surgery, operates an early version of the DARPA prosthetic arm system made by Johns Hopkins University Applied Physics Laboratory (his right arm is a more classic powered split hook). The electrode array on his chest indicates a pattern-recognition-based control.

the median and ulnar nerves since they have afferent fibers that used to innervate the palmar surface of the hand (see figure 2.27 about cutaneous innervation, in section 2.1.3, chapter 2). After recovery and nerve regeneration, the chest skin and hand sensory neurons are linked: when the skin is touched, the amputee perceives the sensation as coming from the missing hand and digits (figure 3.53(b)) (Kuiken 2006; Kuiken, Marasco, Lock, Harden, and Dewald 2007). This technique, called targeted sensory reinnervation, was an unexpected discovery and fortuitous outcome of the first targeted muscle reinnervation surgery: the patient could feel his missing hand touched when his chest skin was touched. This is because the chest skin had been denervated when the subcutaneous fat had been scraped off; subsequently, sensory fibers from the grafted nerves must have reinnervated the skin, somehow finding the cutaneous mechanoreceptors (Kuiken, Dumanian, Lipschutz, Miller, and Stubblefield 2004).

Targeted sensory reinnervation holds promises for providing high-quality, meaningful sensory feedback. Various tactile interfaces could be placed on the chest in order to provide sensations comparable to those captured by the sensors on the prosthetic hand (skin indentation, contact force, stretch and vibration, temperature, and so on). In that way, the amputees would be able to feel what they are touching with the prosthetic hand as if it was touched with their missing hand, to a certain extent at least. For that purpose, the physiological response of the reinnervated skin has to be investigated, in order to quantify its sensory capacity in force discrimination, point localization, vibration detection, and so on (respectively Sensinger, Schultz, and Kuiken 2009; Marasco, Schultz, and Kuiken 2009; Schultz, Marasco, and Kuiken 2009). Besides, in addition to its usefulness from a control point of view, physiologically relevant tactile feedback appears to drive "a perceptual shift towards embodiment of the device", according to the latest experimental trials to date (Marasco, K. Kim, Colgate, Peshkin, and Kuiken 2011). That is to say, it may help the amputees to




(a) In green, arm nerves for targeted muscle reinnervation; in blue, chest cutaneous nerves for targeted sensory reinnervation. Two sensory areas are created: below the clavicle, sensations from the ulnar part of the palm (because of the surgical connection to the ulnar nerve) and from the radial part of the palm (because of spontaneous sensory reinnervation); on the side of the trunk, sensations from the radial part of the palm only (because of the connection to the median nerve).




(b) Sensory map of the area below the clavicle. From Kuiken, Marasco, Lock, Harden, and Dewald (2007): "Sensations elicited by indentation of the skin by a cotton-tipped probe. Red, referred sensation points localized to the palm side of the hand. Blue, points where a general diffuse feeling of pressure was felt within the hand. Circled points orient the diagram. P, proprioceptive sensation of fourth finger joint position. S, sensation of skin stretch. Double-headed arrows, direction of stretch."

Figure 3.53 – Targeted muscle reinnervation and targeted sensory reinnervation for a short transhumeral amputee

incorporate the artificial limb into their own body image, “providing the possibility that a prosthesis becomes not only a tool, but also an integrated body part”.

## 3.3 A review of humanoid robot hands

A lot of the prosthetic hands reviewed in the previous section don’t seem unsuited to a humanoid robot. This is especially true for the most recent myoelectric hands, such as CyberHand, SmartHand, FluidHand, or the two hands made under DARPA funding for targeted muscle reinnervated users. Indeed, as we have explained, there is nowadays little difference, from a mechatronics point of view, between modern humanoid prosthetic hands and modern humanoid robot hands. In short, the differences are mainly size and weight. Since prostheses are supposed to be worn by a human, they must be as light as possible. Robots, on the other hand, are in general less restricted in weight bearing: this makes actuator size, battery weight, and computing power of the embedded electronics less critical issues, to a certain extent at least. Also, another difference lies in the control schemes, which are not shared with a human in the case of autonomous robots.

In this section, we present an overview of humanoid robot hands. Their history is, of course, shorter than that of the prosthetic hands, since robotics as a distinct engineering science has barely more than half a century of existence, and the first humanoid robot hands did not came into existence before the mid-1970s. In its first years, robot hand research was actually clearly influenced by hand prosthetics, as exemplified by the relation between the Belgrade Hand (prosthesis) and the Belgrade/USC Hand (robot), or the Utah Arm (prosthesis) and the Utah/MIT Hand (robot) (see the history overview of myoelectric hands in section 3.2.3). Before reviewing these early robot hands though, we start this section by a short account of the hands of automatons in the eighteenth century, a time which is usually regarded as the prehistory of robotics.

### 3.3.1 Automatons

The European eighteenth century saw a rapid development in sciences in general and in mechanical engineering in particular. As a product of progress in clockmaking, and because of the understandable fascination for these fine and sophisticated mechanisms, amazing automatons, mostly human-like, were produced by clockmakers to demonstrate their skill and know-how to the rich and powerful of these times. Considered today by roboticists and computer scientists as forerunners of modern-day robots (for their action on their environment and the perceived impression of artificial intelligence) and computers (for their possible programming, by camshafts and pins placed on revolving cylinders), their careful construction and ancient beauty are still the source of amazement, and Vaucanson, Jaquet-Droz, Kempelen or Maillardet are still well-known names (at least among roboticists).

Most of the time, the hands of these humanoid automatons were not mechanized, because of the technical difficulty of such a task and the little size of automatons, often as large as dolls. Therefore the possible implements these animated machines made use of were directly built into the material of the hands, for instance a wizard’s wand, a drummer’s sticks or a writer’s quill. The automatons could therefore move these implements by whole-arm motion only, that is to say, by using the shoulder, elbow and wrist joints, but not the digits. Consequently, when the task to perform was complex, such as writing or drawing, a long time was required. Still, the most advanced automatons would eventually complete impressive works. For instance Henri-Louis Jaquet-Droz's *Le dessinateur* (The draughtsman) can draw four different images [29], and Pierre Jaquet-Droz's *L'écrivain* (The writer, see figure 3.54) is able to write any custom text up to forty letters long, on four lines, the text being coded by exchangeable latches of different forms fixed on the cogs of a forty-cog wheel (Heudin 2008; Musée d'art et d'histoire de Neuchâtel 2010).


Figure 3.54 – *L'écrivain*, made in the early 1770s by Swiss clockmaker Pierre Jaquet-Droz, and examples of its writing. The automaton comprises about six thousand pieces.

The case of Henri-Louis Jaquet-Droz's *La musicienne* (The musician) is interesting because the digits of this automaton are actually actuated. The automaton is a female organ player, sitting in front of a miniature custom-built bellow organ, and playing it in five different tunes. As it plays, it follows its hands with its head and eyes and balances the torso in a real-player manner. It is important to note that the music is not faked as usually the case in most automatons, where a music box plays the tune: *La musicienne* actually plays its instrument by pressing the keys with its fingers. In that sense, it may really be considered as a "pre-robot" rather than only a tricky device. The automaton is illustrated on figure 3.55, together with the mechanism of its digits (one degree of freedom each). All three Jaquet-Droz automatons are still functional, on display in the Art and History Museum of Neuchâtel, Switzerland, and in action once a month.

Two other automatons notable for their hands are *Le joueur de flûte traversière* and *Le joueur de tambourin et galoubet* (The flute player and The player of pipe and tabor), constructed in the 1730s by French inventor and engineer Pierre Vaucanson [30] (Vaucanson 1738; Riskin 2002; Heudin 2008). According to Vaucanson's original description, the flute player had seven of its digits articulated at the joint between

29. Namely a portrait of Louis XV, a portrait of Louis XVI and Marie-Antoinette, a dog with "Mon toutou" (My doggy) written underneath, and a drawing of Cupid driving a chariot pulled by a butterfly. To produce these drawings, a system of cams codes the movements of the hand in two dimensions, and one cam lifts or pulls down the pencil.

30. Inventor of the famous *Canard digérateur* (Digesting duck), also known as Vaucanson's duck. Later appointed inspector of the manufacture of silk in France, he was charged by king Louis XV with reforming this industry, which had fallen behind that of England and Scotland. This lead him to promote automation of weaving and create the world's first completely automated loom, programmable by punched cards: therefore, a forerunner of both Joseph Jacquard's loom, that revolutionized weaving in the nineteenth century, and of the early computers of the twentieth century. His proposals were not well received by weavers though, who feared unemployment and were dissatisfied with their profession being belittled, since it could be done by machines. In revenge, they once pelted him with stones in the streets of Lyon, France's capital of silk at that time.

Figure 3.55 – *La musicienne*, made in the early 1770s by Swiss clockmaker Henri-Louis Jaquet-Droz (son of Pierre), and the mechanics concealed under its hands. The automaton comprises about two thousand and five hundred pieces.

the metacarpal and the phalanx: four at the right hand and three at the left hand. These joints were actuated by chains running through the arms to the automaton's mechanism. The fingertips were covered with leather "to imitate the softness of the real finger, so as to block the hole exactly" (Vaucanson 1738). The automaton as a whole received public acclaim and was favorably appreciated by the Academy of Sciences (Fontenelle 1738). The mechanism of the player of pipe and tabor is less extensively described by its inventor, but chances are that the hands were similarly actuated, with one degree of freedom per finger. Only three actuated fingers are necessary for this one, since the pipe in question is a three-hole instrument played with one hand (the other hand plays the tabor). Unfortunately, both automatons have been lost, probably at the start of the nineteenth century.

### 3.3.2 The first humanoid robot hands

#### 1970s origins

Humanoid artificial hands for robots came into existence in the mid-1970s from the dissatisfaction with traditional jaw-based grippers, seen as not versatile enough, to the point of being clumsy. Roboticists Erskine Crossley and Franklyn Umholtz, from the University of Massachusetts, reported that the shortcomings of the typical parallel-jaw end effector "have been whimsically compared to those of a garage mechanic who was forced always to use only a pair of pliers to do his work, even to the extent that, if he wished to use a screwdriver, he had to hold it with the pliers" (Crossley and Umholtz 1975a, 1977). Besides, traditional grippers paled in comparison next to the human hand, and this was striking in teleoperated systems, which were at that time an essential part of robotics[31]: the operator had to restrict himself to operate a one degree of freedom gripper, while his own hands could have done the work much better and much faster if the distant environment had not been dangerous. This made the case for anthropomorphic teleoperator hands: Crossley and Umholtz (1975a, 1977) stress that it is much better if the operator "can imagine his own hands projected there and rely on his built-in sense of feel to perform each task". Their work was about a remote manipulator in space for NASA's shuttle

31. Strictly speaking though, teleoperated systems are not robots. Still, they played a fundamental part in the emergence of modern robotics in the 1950s and 1960s.

program, but other situations are possible; in particular, Skinner (1975a) reminds that teleoperators "became extremely important just after World War II because of their applicability to the atomic energy industry", which had been developing at a very fast pace.

Also, at that time, it was already clear that "the development of hands for industrial manipulators [had proceeded] toward specialization rather than versatility" (Skinner 1975a), with "industrial robot hands specifically designed corresponding to shapes of workpieces" (Hanafusa and Asada 1977), thereby limiting the versatility of industrial robots. It was therefore considered that these robots could use more versatile end effectors; and what better model in versatility than the human hand? Virtually all the first attempts at anthropomorphic end effectors, or at least human-inspired grippers, mention their potential application to industrial manipulation or assembly processes: Frank Skinner's three-fingered "multiple prehension manipulator system" (1975a), Alberto Rovetta's "multipurpose mechanical hands" (1977), Hideo Hanafusa and Haruhiko Asada's "robot hand with elastic fingers" (1977), and Tokuji Okada's three-fingered robot hand (1979). Actually, during the following decade, robot hands were still considered apt to potential industrial applications, as explained in section 3.1.2; for instance, it was the case of the University of Bologna's UB Hand I and the Belgrade/USC Hand (respectively Bonivento, Caselli, Faldella, Melchiorri, and Tonielli 1988; Bekey, Tomović, and Zeljković 1990). As explained in that same section, humanoid robot hands finally did not find their way to the factory, where they still don't measure up nowadays to a well-selected set of specialized end effectors, in terms of operation speed, reliability, ease of control, and cost. But during the early years of robot hand research, this was not as clear as it is now, and the possibility of important industrial applications was a strong driving force.

In addition to the human hand, prosthetic hands were a source of inspiration for the first robot hands. Almost all the articles reporting early attempts at anthropomorphism in robot end effectors acknowledge this influence. For instance, Crossley and Umholtz (1975a, 1977) cite the body-powered Becker Hand and the myoelectric Russian and Belgrade Hands, presented in sections 3.2.2 and 3.2.3; they also cite prosthetic efforts in Sweden and in Japan. Hanafusa and Asada (1977) and Okada (1979) also mention the Belgrade Hand. Furthermore, prosthetic applications were not excluded: for instance, the teleoperator hand proposed by Erskine Crossley and Franklyn Umholtz was envisioned as having potential as a prosthetic device too, which was an additional reason for making it anthropomorphic.

**Crossley and Umholtz's three-fingered hand** The development of this hand began in the early 1970s at the University of Massachusetts, Amherst, United States, under NASA funding. The space agency wanted "a general-purpose end effector for use on the space manipulator proposed for the shuttle program", which was in its development phase at that time[32] (Crossley and Umholtz 1975b). A listing of hand actions and motions was made, from which the roboticists concluded that "the two most important manipulations (apart from grasps) are to be able to pick up a tool and draw it into a nested grip against the palm, and to be able to hold a pistol-grip tool such as an electric drill and pull the trigger" (Crossley and Umholtz 1975a, 1977). It was reasoned that three fingers are necessary for these tasks: two in

32. NASA started studies of space shuttle designs in the late 1960s, and the program was officially launched by Richard Nixon on January 5, 1972. The first shuttle launch occured on April 12, 1981: STS-1 mission with space shuttle Columbia.

apposition to hold the tool, and one to draw it against the palm or pull the trigger. A three-fingered hand was therefore designed for those capabilities; it also had “the standard parallel-jaw grip like any other end effector, between thumb and index”, and it was able to grasp “cylindrical objects and balls” thanks to the additional finger. The fingers made use of four electric motors, and their tips were “cushioned to accomodate themselves to various shapes [...] and to have as high a coefficient of friction as possible”. For this, “a layer about 3 mm thick of soft silicon rubber” was used. Figure 3.56 shows the completed prototype[33].

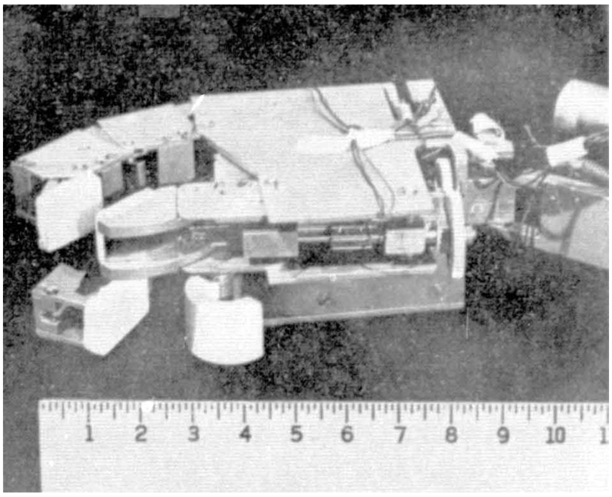



Figure 3.56 – Crossley and Umholtz’s three-fingered hand for teleoperated grasping in space (1975)

**Skinner’s three-fingered gripper** Before building their three-fingered hand, the research team at the University of Massachusetts had actually proposed five initial designs to NASA in December 1972 (Crossley and Umholtz 1975a). One of the mock-ups the space agency rejected was a hand with “three rotatable fingers, each having two bending joints”, designed by Frank Skinner, one of the lab’s graduate students. In their final report, Crossley and Umholtz (1975a) seem to regret this rejection and report that after leaving the project group, Skinner was encouraged first by Unimation[34], then by the Whirlpool Corporation[35] to continue work on his concept. He presented his ingenious design at two conferences and in a journal paper (Skinner 1974, 1975a,b), and patented it (Skinner 1975c).

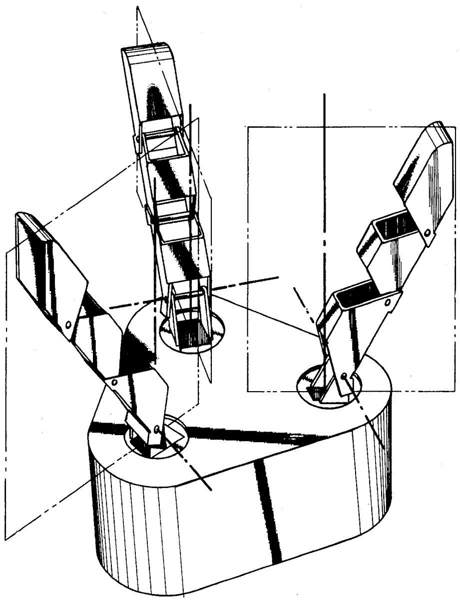
Figure 3.57 shows a drawing of Skinner’s device. Its anthropomorphism is low since the fingers are arranged in a triangle on a flat base, but at least the fingers themselves

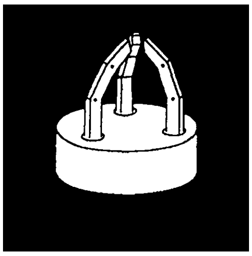
33. It doesn’t look like NASA used the hand, eventually. Instead, the shuttle was equipped with Canadarm, a teleoperated robotic arm contributed by Canada, which has a specialized three-wire snare end effector to grasp specific fixtures placed on payloads. This arm was used as early as the second shuttle mission, STS-2 on board Columbia in 1981. See figure 3.8 in section 3.1.2 for the current version of this arm, Canadarm-2.

34. The world’s first robot manufacturing company, founded by George Devol and Joseph Engelberger in Connecticut in 1956. They installed the first industrial autonomous robot, the world-famous Unimate, on a General Motors assembly line in New Jersey in 1961 (Murray, Z. Li, and Sastry 1994, page 3). It was used “to remove hot metal pieces from a die-casting machine and stack them”, according to Carroll (2007), who also notes that “it was a slow sell to the automotive industry and Unimation did not show a profit until 1975”.

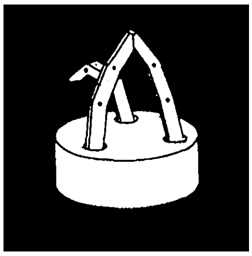
35. More famous for the home appliances it manufactures. Founded in Michigan in 1911, now a multinational corporation.

have three phalanges like the human hand. This kinematic structure makes it more than a simple jaw gripper, but not exactly a hand; Skinner calls it a “MPMS hand”, for “multiple prehension manipulator system”. The fingers are able to rotate to realize four grasp patterns “approximating the prehensile modes of the human hand”, described in figure 3.57. The hand requires four motors and the corresponding control inputs to operate: one for each finger and one to orientate the fingers. The driving mechanisms for the fingers are miniature compound pulleys. A simpler version of this hand was built with three one-phalanx fingers, each driven by a cross four-bar chain (Skinner 1975d); it was mounted on a Unimate robot for testing (Skinner 1975a).

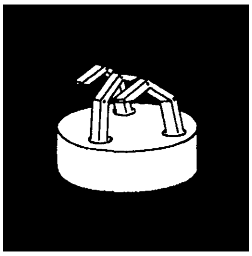




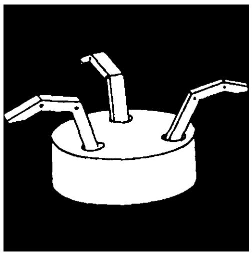
(a) Three-jaw mode for circular grasps



(b) Tip mode for two-finger pinch grasps



(c) Wrap mode for prismatic grasps



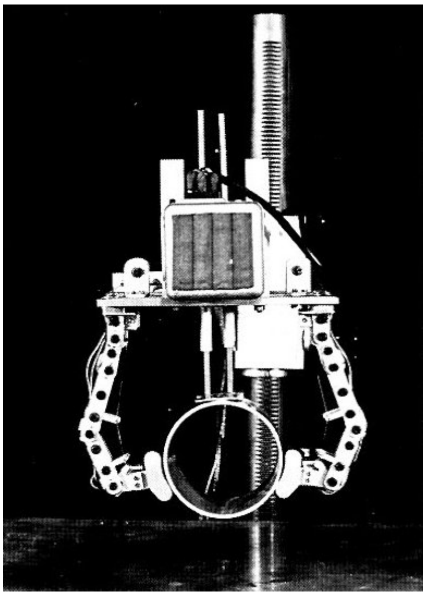
(d) Spread mode for gripping an object from within through an opening

Figure 3.57 – A drawing of Skinner’s three-fingered “multiple prehension manipulator system” and its four prehension modes (1975)

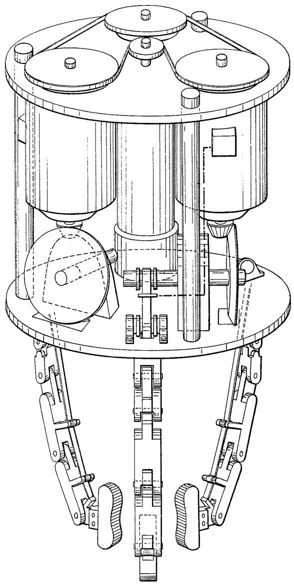
**Rovetta’s gripper** Skinner’s multipurpose device probably had an influence on the work of Alberto Rovetta, of the Polytechnic of Milan, Italy. The roboticist presented in 1977 what seems to be Europe’s first robot hand, even though it was less a hand than a gripper. Indeed, it is hardly anthropomorphic and not capable of manipulation, only grasping; but on the other hand, it has articulated fingers instead of one-linkage jaws, and can grasp a variety of object shapes. So it is more than a gripper but less than a hand, just like Skinner’s device. It is illustrated on figure 3.58.

Rovetta’s enhanced gripper was initially made of two fingers and one plat in the middle, with the function of a palm (Rovetta 1977; Rovetta and Casarico 1978; Bianchi and Rovetta 1980; Rovetta 1981, see figure 3.58(a)). A third phalanx was added afterwards (Rovetta, Franchetti, and Vicentini 1980; Rovetta, Vicentini, and Franchetti 1981, see figure 3.58(b)), and the whole design was patented in conjunction with Alfa Romeo[36] (Rovetta, Franchetti, and Vicentini 1982). It was in part inspired by the biomechanical study of the human hand (Rovetta 1979a,b).

36. The famous Italian manufacturer of cars. Founded in Milan in 1910.



(a) Two-finger design



(b) Three-finger design

Figure 3.58 – Rovetta's "multipurpose mechanical hand" (1977, 1980)

The driving system of the fingers is quite peculiar: only the distal phalanx is directly actuated, by a unique traction wire playing the role of a flexor tendon. Return springs in the joints of the fingers play the role of extensor tendons, returning the links back to their resting positions. Mechanical stops play the role of ligaments. The fingers have four phalanges. The first one bends conversely to the three others: it emulates hyperextension of the metacarpophalangeal joints, while the three others provide flexion (see sections 2.1.1 and 2.1.2 in chapter 2 for the description of the hand's musculoskeletal system). The "palm" is mounted on a spring, so it can go up and down to accomodate various shapes and sizes. A photoelectric cell is placed on the fingertips "[to detect] the presence of the workpiece: if it is absent, the automatic working does not begin" (Rovetta 1977). Because of the spring-based construction, the contact forces applied on the object are not function of the output torques of the actuators, but of the configuration of the system.

**Hanafusa and Asada's three-fingered hand with elastic fingers** Coincidentally, another spring-based device was presented at the same conference that Alberto Rovetta presented his own (the Seventh International Symposium on Industrial Robots, in Tokyo, Japan, 1977). Built by roboticists Hideo Hanafusa and Haruhiko Asada of Kyoto University, Japan, it was not exactly a hand either, but definitively more than a gripper (Hanafusa and Asada 1977, 1978, 1980, 1982a,b). In fact, it was not anthropomorphic at all, as can be seen on figure 3.59, but a planar construction of three "fingers" with one unique degree of freedom each in translation (a movement that is nowhere to be seen in our hands). This construction was not only capable of grasping objects of different sizes and shapes, but also of reorienting them by actuating the fingers independently. The previous devices were not capable of manipulation, only grasping. It is probably for this ability that Hanafusa and Asada's device is remembered as a hand.

More precisely, this hand has three coplanar fingers arranged to move linearly in three concurrent directions with intervals of 120°. Each finger is "driven by an individual

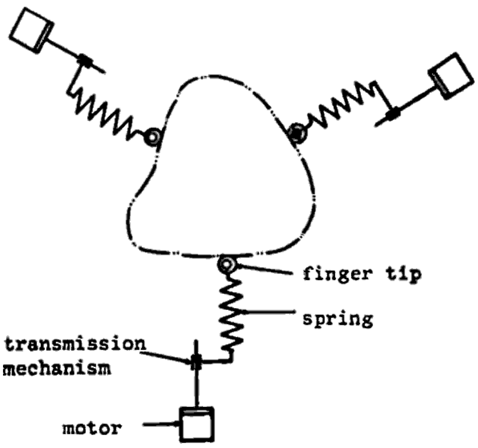



Figure 3.59 – A schematic drawing of Hanafusa and Asada's "robot hand with elastic fingers" (1977). It is a planar construction designed to grasp two-dimensional objects stably and to execute incremental motions of the object within the grasp.

step motor through a twisting coil spring inserted between the motor and the axis of the finger" (Hanafusa and Asada 1977). So each finger force is proportional to the deformation of its spring, and this deformation is function of the position of the step motor and the position and geometry of the object. "Fingertips which contact the peripheral surface of the gripped object consist of contact rollers in order to reduce friction in the tangential direction, thus the fingertips slide on the object periphery smoothly according to the movement of the object" (Hanafusa and Asada 1978). The contact forces can therefore be approximated as frictionless, i.e. normal to the periphery of the object [37]. The resultant force and moment on the object are called the "handling force". So if the object geometry is known, it becomes possible to change the object position incrementally by adjusting the handling force through the positions of the step motors. Furthermore, various prehension rigidities can be achieved by a combination of passive stiffness from the springs and active stiffness from the contact forces, in other words a certain object stiffness is synthetized by the system. In modern terms, Hideo Hanafusa and Haruhiko Asada had implemented stiffness control of the grasped object, or an incomplete form of impedance control, before these control strategies were formally defined by Kenneth Salisbury (1980) and Neville Hogan (1984, 1985c,b,a) (see section 5.2 in chapter 5 for a review of control strategies in robotic manipulation).

So their study is important for theoretical and practical reasons: practical because they had a multifingered hand realize for the first time dextrous, in-hand, fingertip robotic manipulations, and theoretical because of their early usage of stiffness and impedance control. Besides, they also formulated the first energy-based analysis of prehension stability, that is to say: using not only geometrical, but also physical considerations. In short, they defined prehension stability as the fact that "when a relative position between the hand and the object deviates from a certain situation, restoring force is generated by the fingers so that the relative position is brought back to the original situation" (Hanafusa and Asada 1977); then they defined a potential energy from the sum of the elastic and gravitational energies, and showed how the

37. In fact, there is friction to oppose the weight of the object, in the direction perpendicular to the plane of the figure 3.59. But there is no friction in this plane.

most suitable finger locations to grip the object could be found so as to minimize the potential energy and hence grasp the object as stably as possible. Their method was implemented in the control system of the robot hand, for it to be able to determine autonomously the most stable grasp and reorient the object accordingly. Their work would later be extended by Van-Duc Nguyen, who would investigate more generally the synthesis of stable grasps in the plane (1985b, 1986d) and in space (1987b, 1989).

In order to automate the hand, it was sensorized with a camera to acquire the geometry of the object (the image was converted to binary black-and-white data with a proper threshold level), a potentiometer inside each coil spring to measure the finger forces, and another potentiometer to measure the displacement of each fingertip. The control algorithms were implemented on "a minicomputer with 32 kw [38] main memory and a floppy disk", and the whole system was successfully tested for stable grasping (Hanafusa and Asada 1977) and assembly manipulations of two-dimensional mechanical parts (Hanafusa and Asada 1978, 1980).

**Okada's three-fingered hand** Unlike the previous devices, the hand reported in 1979 by Tokuji Okada, of the Electrotechnical Laboratory of the Japanese Government (Tokyo), was a strong attempt at anthropomorphism. Okada constructed a hand with a thumb, index finger, and middle finger, respectively of three, four, and four joints, capable of flexion-extension and abduction-adduction (Okada 1979, 1982). It is shown in figure 3.60, together with the arm on which it was mounted.

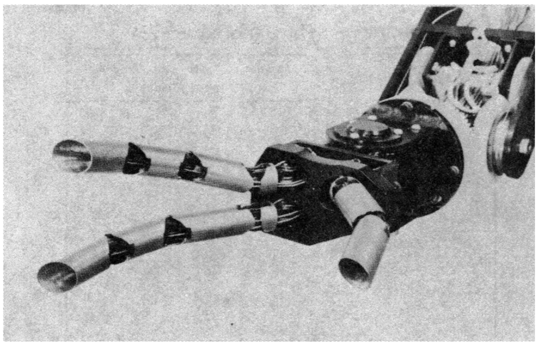
The hand is slightly larger than a human hand, with phalanges of circular cross section 17 mm wide in diameter, cut in a brass rod. Each joint is driven by two stainless steel cables (flexor and extensor tendons) which run through hoses (tendon sheaths), a bit like brake cables on a bicycle. This driving system makes it convenient to transfer motion from the motors to the joints, since there is no need to set holding points for the guidance of the cables at each joint of the hand, that is to say, "the path of power transmission can be selected freely" (Okada 1979). This is a good thing since "routing of tendons with pulleys over several joints can be a nightmare", with tendons sometimes falling of the pulleys; on the other hand, this system brings "severe friction problems of the tendons over the sheaths", which complicates control (J. Hollerbach 1982).

The motors for driving the finger joints are located in a separate unit, quite far from the fingers actually (see figure 3.60(c)): "the cables connecting each finger joint with the corresponding driving motor are about 170 cm long" (Okada 1979). The isolation of the large and heavy actuators makes the hand itself pretty light, only 240 g.

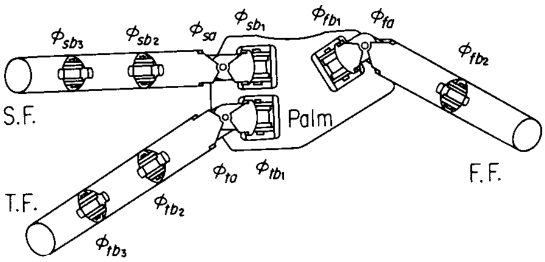
In addition to the tendons and their sheaths, the phalanges accommodate potentiometers to measure the joint positions, as well as the signal lines of those sensors of course. The joint torques are detected indirectly from the values of the motor currents.

From the point of view of kinematics analysis and control, the hand and the arm are considered two different subsystems. The arm is simply controlled in position to move the hand's workspace here and there. The hand is more subtly controlled.

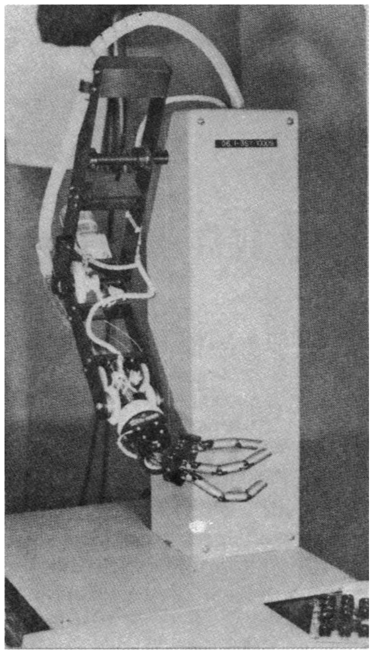
38. That's kilo-words, and minicomputers are computers that lie in the middle between mainframe computers and microcomputers. In those days, word size for minicomputers was usually 16 bits, for instance it is so on the PDP-11 minicomputer, released by DEC in 1970. That makes a main memory of 64 kilo-bytes for the computer used by Hanafusa and Asada.



(a) Close-up photograph of the hand. The finger ends may be stuffed with small rubber balls.




(b) The 11 degrees of freedom of the hand. F.F.: first finger; S.F.: second finger; T.F.: third finger. $\phi_{fb1}$: first finger, first bending motion; $\phi_{sa}$: second finger, abduction movement; and so on.



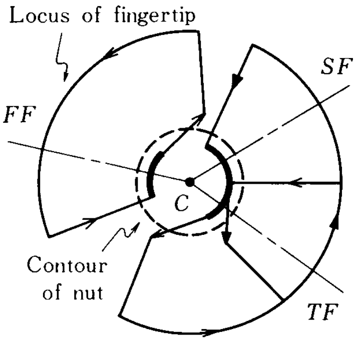
(c) The complete system. All the motors of the hand are inside the big box, and the tendons come out of it through the large hose, each in its own sheath, to go all the way down the hand.

Figure 3.60 – Okada's three-fingered hand (1979)

In his first paper, Okada (1979) derives the kinematics of each finger so that they can be controlled in position in the joint space after inverse kinematics resolution, that is to say that desired joint positions are deduced from the desired positions and orientations of the distal phalanges (this mainly involves solving a fourth-degree equation). Okada reports two successful three-finger dextrous manipulations with this position-only control scheme: the rotation of a bar and a sphere. He also acknowledges the benefits of force control in addition to position control, and reports a two-finger test manipulation under master/slave control: one finger moves actively under position control (master) while the other one moves passively under force control (slave), i.e. "the torque-controlled finger follows the position-controlled one". This force/position control strategy is typical of the 1970s and was originally meant for cooperative manipulators (see section 5.2.2 in chapter 5 for a review of control strategies in cooperative manipulation).

In his second paper, Okada (1982) presents an additional three-finger dextrous manipulation: picking up a nut, attaching it to a bolt, and turning it to tighten the two pieces. This manipulation is still realized under position control only, of each finger, independently from the other two fingers. Figure 3.61 shows the desired trajectories for each distal phalanx, and the resulting motion. In the same paper, Okada also introduces a cooperative position control scheme for two-finger manipulation. "Cooperative" means that the fingers are controlled as one unique system, not as two independent fingers. To realize this, he derives the kinematics of the system "two fingers plus one object", so that the fingers can be controlled in position after inverse kinematics resolution from the object to the joints, that is to say that desired joint positions are deduced from the desired position and orientation of the object.

Unfortunately, this analysis has a few limitations. First, it is entirely geometric, so it is different for each object; Okada deals with a flat box and a spherical object. Second, it is so complex that it is hardly extendable to three fingers. Also, it is specific to the kinematic structure of the fingers, so it cannot be generalized to other hands. Besides, the system dynamics is not taken into account since the modeling is purely geometric (no consideration of mass, inertia, forces, or anything physics-related), so only quasi-static manipulations are possible. Nevertheless, the control scheme was proven effective on a simple manipulation (tilting of a box), and in any case it remains at least historically significant, because of its fingertip dexterity in three dimensions.




The desired position of the fingertips passes through the inside of the nut, so that the hand grasps the nut by using the position error of the servo system to apply contact forces.

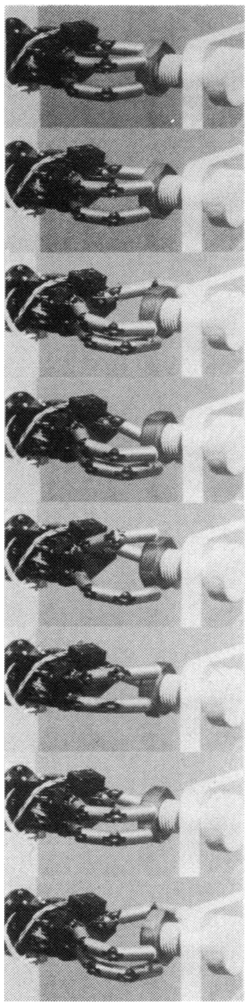


Figure 3.61 – A dextrous manipulation performed by the Okada Hand: attaching a nut to a bolt (1982)

**1980s developments**

If the 1970s can be rightfully considered the prehistory of robot hands, the 1980s mark the start of their history. This was indeed a decade of fast growth in robot hand research, almost exclusively in the United States. It witnessed the birth of the Stanford/JPL Hand (Kenneth Salisbury and Carl Ruoff), the Utah/MIT Hand (Stephen Jacobsen and John Wood), and the Belgrade/USC Hand (Rajko Tomović and George Bekey): three dextrous hands which left a deep impression on roboticists worldwide, and are still highly cited examples of robot hands.

The decade was also rich in theoretical advances related to the modeling and control of manipulation, and it is fair to say that work on fine manipulation began at that time. In particular, Kenneth Salisbury undeniably pioneered the field in the early 1980s: with John Craig and Bernard Roth, he introduced mathematical models of the possible contact types between the fingertips and the object, investigated the kinematics of manipulation, defined the grasp matrix (which relates applied finger forces to the resultant object wrench, see sections 5.1.6 and 5.2.3 in chapter 5), and proposed a geometric approach for determining the internal forces (that is to say the part of the contact forces which do not produce any motion of the object, but only tightening of it, see the above-mentioned sections) (Salisbury and Craig 1981, 1982; Salisbury 1982; Salisbury and Roth 1983; Salisbury 1985). Other significant theoretical contributions to dextrous manipulation were the works of Matthew Mason on object motion in the presence of friction (Mason and Salisbury 1985; Mason 1986), Jeffrey Kerr and Bernard Roth on internal force determination and rolling contact kinematics (1986, see also section 5.2.3 in chapter 5), and David Montana on sliding and rolling contact kinematics (1988, work used in section 7.1.4 of chapter 7). In the realm of control, the 1980s were also a time of novelty: after Marc Raibert and John Craig invented hybrid force/position control in 1981, various such control strategies were proposed for cooperative manipulators and multifingered hands, in particular by Oussama Khatib (1988), Yoshihiko Nakamura, Kiyoshi Nagai, and Tsuneo Yoshikawa (1987, 1989), and Zexiang Li, Ping Hsu, and Shankar Sastry (1989). This type of fundamental control scheme is nowadays a well-known, often used way to operate manipulators and robot hands; so is impedance control too, invented by Neville Hogan in 1984 (see section 5.2.3 in chapter 5 for a review of control strategies in dextrous manipulation). Finally, in the field of multifingered grasping (without manipulation), force closure and grasp stability were studied by Van-Duc Nguyen (1985a,b, 1987a,b, 1988, 1989), and grasp taxonomies were build by Mark Cutkosky and Thea Iberall (Cutkosky and Wright 1986; Cutkosky 1989; Iberall, Bingham, and Arbib 1986; Iberall 1987; Iberall and MacKenzie 1988, 1990, see also section 2.2.2 in chapter 2).

The emergence of multifingered dextrous manipulation as a distinct domain of robotics, as well as its importance, could already be perceived at the very start of the decade in the United States. In his report on the Workshop on the Design and Control of Dexterous Hands, held at the Artificial Intelligence Laboratory of the Massachusetts Institute of Technology, on November 5–6, 1981, John Hollerbach (1982) writes about a “confluence of activity at major research centers” which prompted to organize the workshop, especially since “the number of researchers in this new field is small, and they are dispersed at a few centers around the country”. At that time, Salisbury was finishing his graduate studies at Stanford University, during which he had taken part in the elaboration of the Stanford/JPL Hand, a joint project with NASA Jet Propulsion Laboratory. Also, the collaboration between the University of Utah and the Massachusetts Institute of Technology, to build the Utah/MIT Hand, had just started. The workshop brought together many of those who were going to play a prime role in the development of robot hand research, in particular Kenneth Salisbury, John Craig and Bernard Roth from Stanford University, Carl Ruoff from the Jet Propulsion Laboratory, Haruhiko Asada from Carnegie Mellon University, Ruzena Bacjsy from the University of Pennsylvania, Stephen Jacobsen and John Wood from the University of Utah, and Matthew Mason, Neville Hogan, John Hollerbach and Tomas Lozano-Perez from the Massachusetts Institute of Technology. Discussions were about four topics: "kinematics of hands, actuation and materials, touch sensing, and control". J. Hollerbach's report (1982) summarizes them and "attempts to identify a consensus on applications, mechanical design, and control". It testifies to the start of intense research on dextrous manipulation, and gives precious insight into the problems the researchers were facing, and the doubts they were having.

From a hardware perspective, much progress has been accomplished since those days, however some of the original issues are not yet entirely settled. For instance, electric motors are still the least inconvenient actuators, even though they remain large and heavy relative to their strength: it was rightly identified at the workshop that actuation technology was "the most serious, long term impediment to hand design". Consequently to their weight and size, motors are usually placed far from the joints they actuate, and as a result, hand construction still suffers from the issues associated with tendon-based transmission chains (primarily, additional wear and control difficulties). It is however fair to say that tendon technology has improved a lot, especially in terms of materials (for instance steel cables, used in those days, suffer from "a minimum bending radius which limits compactness"; they are seldom employed nowadays). Tactile sensor technology and tactile information processing have seen tremendous improvement too. A reason for this is that they were a relatively new research area at the start of the 1980s: J. Hollerbach (1982) reports that "current technology is far from satisfying tactile requirements" and that "lack of adequate touch sensors has inhibited research [into tactile information processing]". As a result, "the consensus at the workshop was that it [was] premature to incorporate touch sensors into hand designs given the current state of development" (implying, extrinsic tactile sensors, not intrinsic tactile sensors such as strain gauges: see figure 2.45 in section 2.4.1, chapter 2). Even though artificial tactile sensing still comes nowhere near the sensitivity of human perception, touch sensors are much more common in artificial hands nowadays. "The number of wires emanating from the sensors", though, remains the problem it already was. Section 2.4, in chapter 2, provides more information about the current technological hurdles roboticists face when designing an artificial hand.

In the rest of this section, we present the three characteristic hands of this period: the Stanford/JPL Hand, the Utah/MIT Hand, and the Belgrade/USC Hand. We also mention a few others that are worth not being forgotten.

**Stanford/JPL Hand** As explained previously, this hand was a collaboration between Stanford University (Stanford, California) and NASA Jet Propulsion Laboratory (Pasadena, California). It is described in Salisbury's thesis and articles (Salisbury and Craig 1981, 1982; Salisbury 1982, 1984, 1985; Salisbury and Roth 1983; Ruoff and Salisbury 1984), as well as in a book (Mason and Salisbury 1985) and a patent (Ruoff and Salisbury 1990).

The hand is illustrated on figures 3.62 and 3.63. It features two fingers and a thumb opposing them, and is roughly the size of a human hand. The three digits are identical in structure and include three revolute joints: two for flexions/extensions and one for abduction/adduction. All the joints are independently driven by tendons actuated by electric motors, which makes a total of nine active degrees of freedom. The DC motors, their speed reductors (25:1 ratio), and the control electronics are mounted remotely from the hand, usually on the forearm of the manipulator arm on which the hand is mounted. The fingers include pulleys to route the tendons, and cable tension sensing structures to measure the forces in the tendons. There are no joint position sensors but there are motor position encoders: joint positions are estimated from motor positions. Siegel (1991b) remarks that "due to compliance in the tendon system, this estimate is not very accurate".

The fingertips are the main areas meant to contact with the object, and research with this device focused indeed on fingertip manipulation. The tips are covered with "a resilient and pliable friction enhancing surface", for instance "a hard rubber compound which exhibits the desired properties of some flexibility and compliability while being somewhat firm and durable" (Ruoff and Salisbury 1990). In the words of the designers, friction "facilitates rotating all gripped objects, including those having surfaces of revolution, and reduces the necessary number of contact points for firmly grasping the object to be gripped" (in the absence of friction, this number is seven). A six-axis fingertip force/torque sensor was mounted inside each fingertip by Brock and Chiu (1985) at the Massachusetts Institute of Technology, to keep track of the contact forces and their orientations. It consists of eight strain gauges on a Maltese cross which connects the outer covering to the phalanx structure. The gauges are paired off with each other, one on each side of the beams that form the cross (Siegel 1991b).

An interesting fact about this hand is that the number of fingers, the number of degrees of freedom, and the kinematic structure were not arbitrarily chosen, but optimally determined, thanks to a careful analysis of how object restraint and object manipulability could be optimized in the design. Salisbury defined the "connectivity" between any two links as the number of independent parameters required to specify their relative position. For a satisfactory hand design, "the hand should be able to impart arbitrarily directed forces and velocities on the object", which requires a connectivity of six between the reference frame and the object, and it should also be able to "constraint an object completely", which requires a connectivity of zero (Agrawal 1991). Salisbury considered hand designs of two or three fingers with up to three degrees of freedom per finger (120 configurations) and up to five degrees of freedom at the interface with the object ($120 \times 5 = 600$ configurations). Only 39 of all these designs "were found to possess a connectivity of six with the joints active and a connectivity of zero with all the joints locked" (Agrawal 1991). Of those, 33 assumed five-degree-of-freedom contacts (e.g. frictionless point contacts): they were rejected "because it was determined that five-degree-of-freedom contacts do not allow moments to be exerted on arbitrary objects". Of the remaining 6 designs, Salisbury chose one with three fingers, three joints in each finger, and three-degree-of-freedom contacts (e.g. point contacts with friction), because it was determined that this design could overconstrain the object when all the joints were locked, which is advantageous since it allows for the constraint of internal forces in addition to the restraint of the object (i.e. control of tightening in addition to grasping).

Besides, Salisbury noted that there are certain points in the joint space of the hand where forces can be exerted and incremental finger movements can be controlled most accurately: points where the condition number of the jacobian matrix of the hand is at a minimum ("accuracy points" or "isotropic points", Salisbury and Craig 1981, 1982). The arrangement and the physical dimensions of the three fingers were optimized so that these points were situated on a grasped sphere one inch in diameter. So the hand was not meant to be anthropomorphic in design, and it was optimized

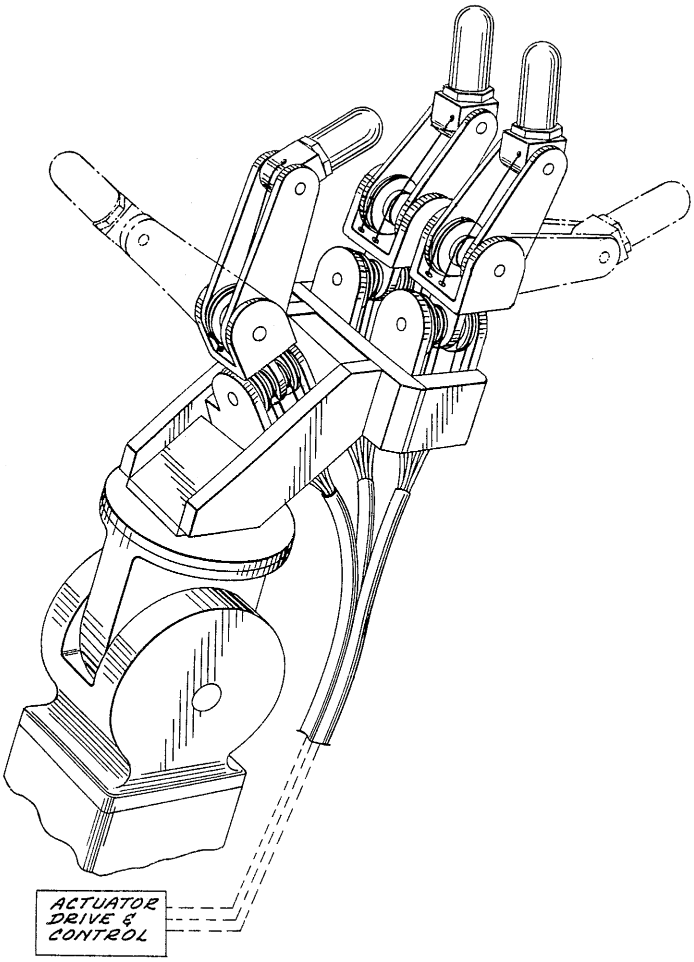
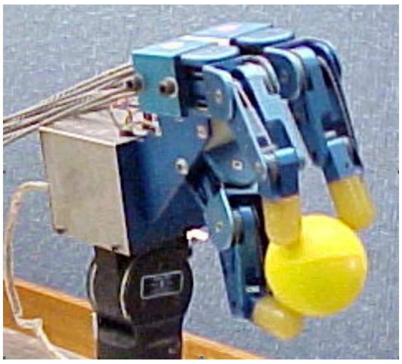



Figure 3.62 – A drawing of the Stanford/JPL Hand (1981). The three bundles of wires are the tendons, in their respective sheaths. From Ruoff and Salisbury (1990).

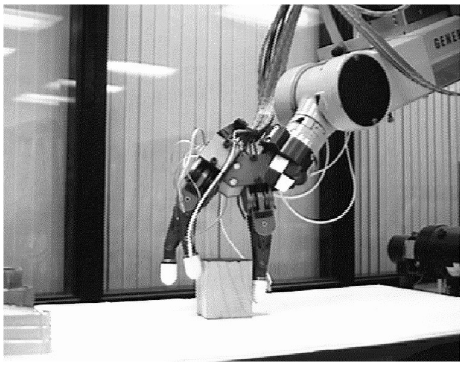
to manipulate objects roughly one inch in size. Larger or smaller objects can be manipulated too, of course, but "with a certain loss of precision in incremental movement ability" (J. Hollerbach 1982).

The tendon transmission system follows the so-called "$n + 1$ rule", which states that the minimum number of cables required to independently drive $n$ degrees of freedom in a serial kinematic chain is $n + 1$, assuming that the displacements of the cables are controlled independently. This rule was proven by Buśko (1978) and reported by Morecki, Buśko, Gasztold, and Jaworek (1980). It is illustrated in figure 3.64, together with the "$2n$ design" used in the Okada Hand and the Utah/MIT Dextrous Hand. So, since there are three degrees of freedom per finger, there are four tendons and four electric motors per finger.

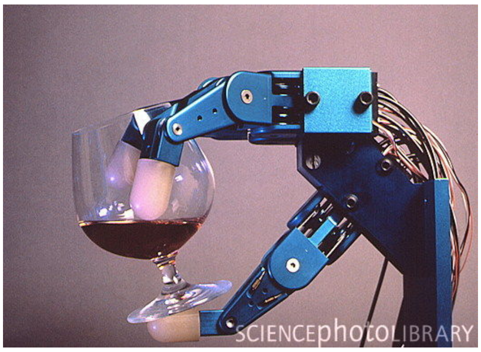
The tendons are teflon-coated steel cables, and from the motors to the hand, they pass through teflon-lined conduits. The sheaths eliminate the need for routing pulleys, which are especially a nuisance at wrist level, and the use of teflon reduces friction a lot. The tendons leave their sheaths at the base of the fingers, which do contain pulleys. In particular, they pass in the groove of an idler pulley mounted on a cantilever beam, as illustrated by figure 3.65. Two paired strain gauges are placed on



(a) The hand's kinematic structure is optimized for fingertip manipulation of one-inch wide spheres.



(b) It can be mounted as the end-effector of a manipulator arm.




(c) This photograph shows the importance of friction in dextrous manipulation.

Figure 3.63 – Grasping and manipulation with the Stanford/JPL Hand

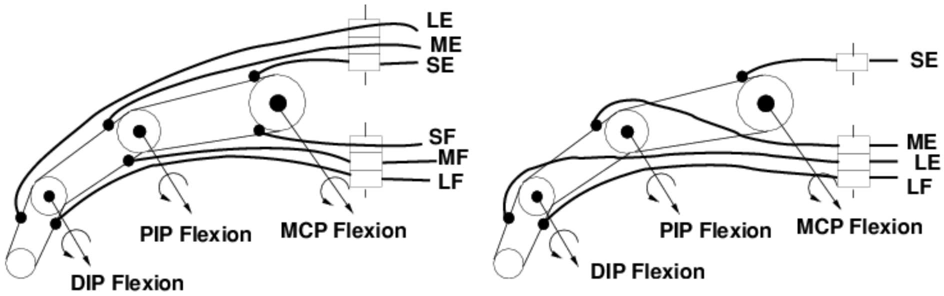
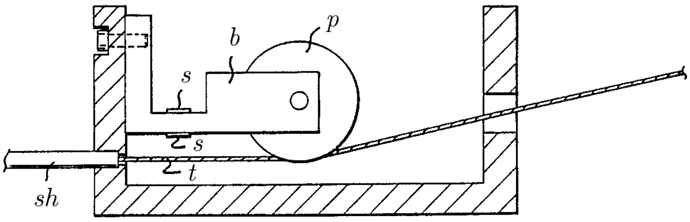



Figure 3.64 – Tendon actuation patterns: a "$2n$ design" and a "$n + 1$ design". MCP, PIP, DIP: metacarpophalangeal, proximal interphalangeal, distal interphalangeal. E, F: extensor, flexor. L, M, S: long, medium, short.

this cantilever beam and measure the beam deflection created by the cable, which is proportional to the tension in the cable. From these tensions it is possible to deduce the torques in the joints [39], and then the force exerted at the fingertip. However these relationships need not be used since the control of the Stanford/JPL Hand can be made at tendon level.




*sh*: tendon sheath, *t*: tendon, *p*: idler pulley,
*b*: cantilever beam, *s*: paired strain gauges

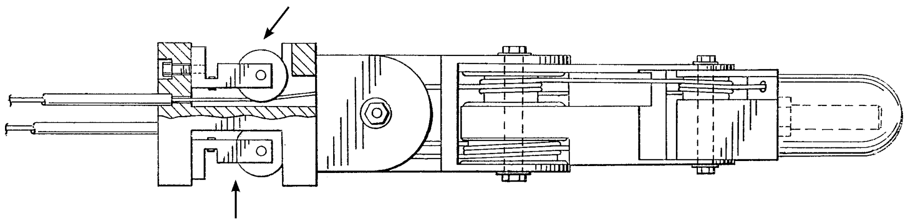


Figure 3.65 – Tendon tension sensors of the Stanford/JPL Hand, and their position at the base of the finger. From Ruoff and Salisbury (1990).

Salisbury and Craig developed algorithms for force and stiffness control of the object, as well as for sensing forces and object shape. J. Hollerbach (1982) reports that John Craig presented a hierarchical controller at the MIT workshop, "which achieves an incremental movement ability for the Stanford/JPL Hand". The controller consists of three levels. "The lowest level in the hierarchy is a tendon controller which achieves commanded forces in conjunction with feedback from a special force sensor on the tendon. The intermediate level is an individual finger controller which takes commanded finger forces and transforms them to tendon forces. The top level of the hierarchy coordinates finger movement by converting desired positions, velocities, and forces in cartesian space to commanded finger forces." In these days, a novel feature of the controller was that "the inverse jacobian is not required, due to [...] the resolution of cartesian forces to joint torques" via the transpose jacobian.

Agrawal (1991) reports that the hardware implementation of the controller consisted of "twelve 8086 microprocessors [40], each controlling one of the actuators", and a

39. The relationship between the joint torques $\tau_1, \tau_2, \tau_3$ and the tendon tensions $t_1, t_2, t_3, t_4$ is:

$$\begin{aligned}\tau_1 &= -t_1 r_1 + t_2 r_2 + t_3 r_2 - t_4 r_1\\ \tau_2 &= t_1 r_3 + t_2 r_2 - t_3 r_2 - t_4 r_3\\ \tau_3 &= t_2 r_2 - t_3 r_2\end{aligned}$$

with $r_1, r_2, r_3$ the three different radiuses of the drive pulleys used in the drive train of the fingers (Ruoff and Salisbury 1990).

40. The 8086 is a 16-bit microprocessor, with a clock rate of 5 MHz, launched by Intel in 1978 (for the price of US $ 360). It gave rise to the x86 microprocessor architecture, a family of which it is the first member. Nowadays the x86 architecture is the most common one for personal computers and servers.

VAX-11/750 minicomputer [41] communicating directly with the microprocessors. The minicomputer implements the two higher levels of the controller, and sends a new setpoint to the microprocessors, in terms of desired tendon tension, every 20 ms (tendon stretching errors are ignored). The microprocessors implement the lower level of the controller. They run at a servo rate of 1 kHz, faster than the setpoint input at 50 Hz: between two setpoint refreshs, they use a proportional derivative controller to make the actual tendon tensions follow their current setpoints.

Thanks to its particular kinematic structure and its innovative control scheme, the Stanford/JPL Hand could overcome the two limitations of the end-effectors of that time, namely that they were "*a*) unable to adapt to a wide range of object shapes; and *b*) unable to make small displacements at the hand without moving the entire manipulating arm" (Ruoff and Salisbury 1990). Together with the Utah/MIT Dextrous Hand, it set the standard for dextrous hands during at least the decade that followed its construction. Several copies were made for various laboratories around the United States; they were used for the study of dextrous manipulation control.

**Utah/MIT Dextrous Hand** The construction of the Utah/MIT Dextrous Hand was a joint project between the roboticists of the University of Utah (Salt Lake City, Utah) and the Massachusetts Institute of Technology (Cambridge, Massachusetts). It was prompted by the desire to have a "high performance, multifingered hand" with "many degrees of freedom", "intended to function as a general-purpose research tool for the study of machine dexterity" (Jacobsen, Iversen, Knutti, T. Johnson, and Biggers 1986). Indeed, there was in the early 1980s a lack of suitable research equipment to "permit the experimental investigation of basic concepts in manipulation theory" and to serve as a testbed for dextrous manipulation research. The recent Stanford/JPL Hand was the only potential candidate, and it couldn't really be considered generic enough given its particular, optimized kinematic configuration.

So the Utah/MIT Hand was built with the aim to "simplify research activities and allow investigators to proceed toward understanding issues and concepts rather than being continually sidetracked by problems with experimental devices". The hand went through two prototype stages, Version I and Version II, before reaching the final Version III. The first version and the final version were documented by Stephen Jacobsen, John Wood and their colleagues, at the University of Utah (Jacobsen, Wood, Knutti, and Biggers 1984b,a, Jacobsen, Wood, Knutti, Biggers, and Iversen 1985 for Version I; Jacobsen, Iversen, Knutti, T. Johnson, and Biggers 1986 for Version III). Two separate documents give more detail about the actuation system (Jacobsen, Knutti, Biggers, Iversen, and Wood 1985) and the low-level control (Biggers, Jacobsen, and Gerpheide 1986). While the robot hand itself was built at the University of Utah, the roboticists at the Massachusetts Institute of Technology were responsible for its control algorithms (J. Hollerbach, Narasimhan, and Wood 1986; Narasimhan 1988), and their software and hardware implementation (Siegel, Narasimhan, J. Hollerbach, Kriegman, and Gerpheide 1985; Narasimhan, Siegel, J. Hollerbach, Biggers, and Gerpheide 1986; Narasimhan, Siegel, and S. Jones 1987; Narasimhan 1988; Narasimhan, Siegel, and J. Hollerbach 1988a,c,b, 1989a,b, 1990).

Figure 3.66 shows the Version III Utah/MIT Hand. As can be seen, it carries three fingers and a thumb, in a very anthropomorphic configuration. Its size is the same

41. One of the first VAX minicomputers, based on the 32-bit microprocessor architecture of the same name, and released by DEC in 1980. Compact in size, it looked pretty much like a small fridge. VAX minicomputers were highly popular during the 1980s and even the 1990s.

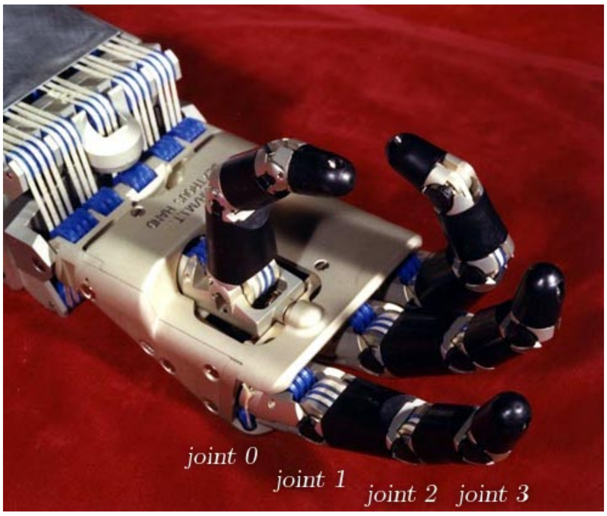



Figure 3.66 – The Utah/MIT Dextrous Hand (1986). The white bands are tendons, the blue rollers are pulleys, the black parts are removable covers.

as that of the human hand. Each digit has four revolute joints and four degrees of freedom, one for abduction/adduction and three for flexion/extension. The hand is driven by tendons actuated by pneumatic pistons, placed remotely from the hand. Each joint is independently driven by a pair of antagonist tendons, a flexor and an extensor, or an abductor and an adductor. Thus, not counting the wrist, there is a total of 16 joints, 16 degrees of freedom, 32 tendons, and 32 actuators.

Jacobsen, Iversen, Knutti, T. Johnson, and Biggers (1986) explain that they chose the anthropomorphic geometry for three reasons. First, the potential dexterity of this geometry, if adequately actuated, means that research could focus on control and sensing issues "without being hampered by marginal performance of end effector machinery": in other words, a simpler design could restrain possibilities, which is a pity for a hand intended to be a general-purpose research tool. Second, anthropomorphism is convenient from an experimental standpoint, because "it allows the human researcher to compare operations of the robot hand with operations of his own natural hand". Third, it has "potential application as a slave element in a teleoperation system". That being said, a few concessions had to be made (Jacobsen, Iversen, Knutti, T. Johnson, and Biggers 1986):

1. The little finger was "eliminated to avoid complexity".

2. The first two degrees of freedom of each digit were separated into two joints "in order to allow tendons to be routed in a manner which would result in reliable operation". They are not separated in the human model, where they form the finger metacarpophalangeal joints and the thumb carpometacarpal joint (see section 2.1.1 in chapter 2). Consequently, the digits of the robot hand have four phalanges, one more than our fingers.

3. The axes of finger abduction/adduction are in the plane of the palm rather than perpendicular to the palm, again because of tendon routing difficulties. On the bright side, this change "allows the fingers to achieve significant side-to-side excursions", via the mobility of the first joint, "when the second joint is flexed to the 90° position". In contrast, in our hands, abduction/adduction is blocked when the fingers are flexed. The robotic alternative improves the mobility of the

fingertips when they are flexed and oppose the thumb, although the motions involved are not human-like.

4. The thumb is placed in the palm, in permanent opposition, instead of on the side, and its abduction/adduction axis is orthogonal to its flexion/extension axis. This is once again due to tendon routing problems. The hand's designers note that "the thumb does maintain sufficient [abduction/adduction] to interact with all fingertips in a near natural manner".

5. The wrist joint is "larger than desired" to facilitate the routing of the tendons. The appearance problem caused by this enlargement is compensated by the possibility to place 32 tendon tension sensors in the enlarged area. The output of these sensors is used for estimation of individual joint torques and control of the actuation system.

Despite those "deviations from anthropomorphic geometry", the anthropomorphism of the Utah/MIT Hand remains pretty good, especially in comparison with the previous robot hands.

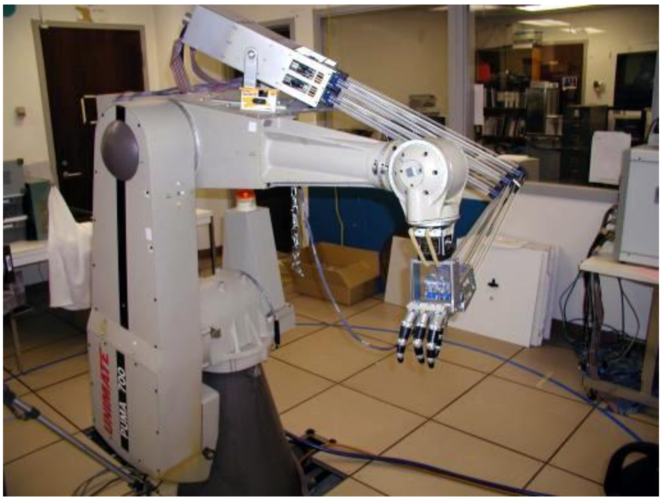


Figure 3.67 – A Utah/MIT Hand mounted on a Puma manipulator arm (1990s). The actuator package is fixed on the forearm of the manipulator; another possibility is to place it on an external mounting.

Figure 3.67 shows the entire Utah/MIT Dextrous Hand system, mounted on a manipulator arm. It comprises the hand itself, its actuator package, and a complex remotizer used to carry the 32 tendons from the actuators to the hand while maintaining their length and tension whatever the hand's position in the workspace. This pulley-based remotizer is the price to pay for the placement of the actuators outside the hand and the use of flat belt tendons, which cannot be enclosed in lubricated sheaths as easily as round cable tendons. Actually, the remotizer would have been unnecessary if it had been possible to mount both the hand and the pneumatic actuators as the manipulator's terminal device. But "due to the limited lifting capabilities of existing robots it was unlikely that the entire dextrous hand and its actuation package could be accurately and quickly moved around in space" (Jacobsen, Iversen, Knutti, T. Johnson, and Biggers 1986). The rectangular assembly of the actuator modules is indeed about 11 cm × 11 cm × 61 cm and weights about 9 kg. And yet this is "fairly compact" in comparison to the "large external air source required for power", according to Siegel (1991b, page 20).

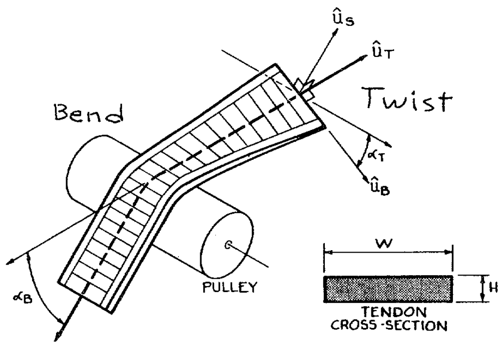
As usual, the remotization of the actuators allows for their strength, the independence of the joints, "more volume within the hand to be used by structures, joints and sensors", and "greater design flexibility for the actuators" (Jacobsen, Iversen, Knutti, T. Johnson, and Biggers 1986). Pneumatic actuators were chosen for their intrinsic properties, in particular, compliance and low output impedance at substantial frequencies. As a matter of fact, the actuator elements "have been designed to exhibit desirable qualities as a result of intrinsic characteristics, rather than via attempts to modify actuator performance through the use of compensating feedback loops"; in other words, good actuator design simplifies control requirements. These actuator elements include, for each actuator, one custom-designed pressure-controlling valve and two pneumatic cylinders, one for actuation and one for adjustable damping, both made of glass with lightweight graphite pistons. The resulting actuators are fast, have low actuated masses, and can generate relatively high forces: consequently the fingers can move quickly, high-speed contacts produce minimal impact, and the hand has a strength comparable to the human hand.

The actuators work in 16 agonist/antagonist pairs to drive the 16 degrees of freedom. They allow independent and simultaneous control of both torque and stiffness at each joint: torque through the difference of tendon tensions, and stiffness through the sum of tendon tensions (co-contraction of agonist and antagonist actuators). Contrary to the Stanford/JPL Hand, the Utah/MIT Hand uses the "$2n$ configuration" of the tendons, instead of the "$n + 1$ rule" (see figure 3.64). This choice "consumes additional volume and imposes higher levels of complexity within the hand", but the control of torque and stiffness is much simpler, and it is also "the more conservative approach, [and] since the system was to be aresearch tool, maximum levels of flexibility in operation should be maintained".

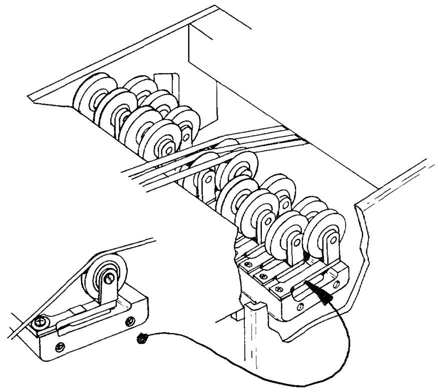
Flat belt tendons were selected "for reasons of strength and fatigue life". They are made of dacron fibers woven around multiple longitudinal kevlar fibers; "the dacron outer sheath serves to align and protect the internal load bearing kevlar fibers". At some point, polyethylene tendons were used too, according to Narasimhan (1988, pages 19–20). As illustrated in figure 3.68(a), the tendons are routed throughout the system via a series of axial twists and bends over pulleys. As a matter of fact, the hand and wrist include "184 low-friction pulleys for the purpose of tendon routing", and "the entire remotizer utilizes 288 pulleys from the actuation package up to tendon tension sensors in the wrist".

Figure 3.68(b) shows the tendon tension sensors, located in the wrist joint. They are based on strain gauges and a bending beam, as in the Stanford/JPL Hand (see figure 3.65). Other proprioceptive sensors include joint angle sensors, located at each joint. These are based on Hall effect: a magnetically sensitive Hall effect device is located in the proximal link, and two magnets operating in a dipole configuration are attached to the distal link. Both parts of the sensor face each other and the variation of the magnetic field as they move relative to each other makes the Hall effect device produce an output current corresponding to the angular deflection. This system is reliable, proportional, compact, non-contact, low-noise, and the signal it produces is "smooth enough for direct differentiation to provide velocity information".

There are no exteroceptive sensors, but the covers of the phalanges are removable and can accommodate such sensors: "depending on the particular experiment, selected sections of these rather disposable elements can be machined away to allow space for tactile sensing transducers; for example, detectors to sense direct contact, normal




(a) The routing is complex since it requires axial twists in addition to pulley-induced bends.



(b) The tendon tension sensors of one half of the tendons (flexors or extensors).

Figure 3.68 – The flat tendons of the Utah/MIT Hand (Jacobsen, Iversen, Knutti, T. Johnson, and Biggers 1986)

pressure, shear stress, temperature" (Jacobsen, Iversen, Knutti, T. Johnson, and Biggers 1986).

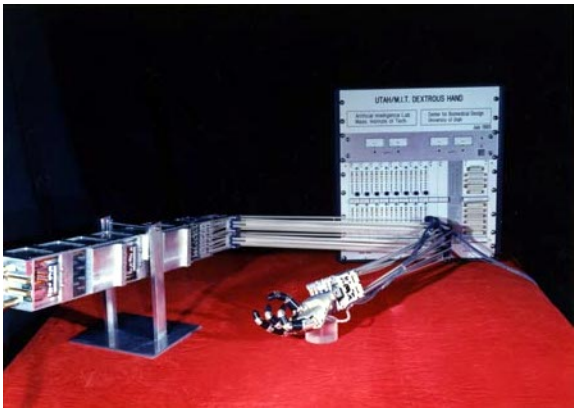



Figure 3.69 – The whole Utah/MIT Dextrous Hand system: actuators, remotizer, hand, and low-level control system in the background (it is a box of control circuits, only the front side is visible).

Figure 3.69 shows the entire Utah/MIT Dextrous Hand system and the console of its low-level control system. A sign of the times, the control of the Utah/MIT Hand was indeed not entirely digital: its lower level was performed by analog feedback control circuitry. This was considered advantageous because "[it reduced] computational requirements on the [higher-level] digital control systems".

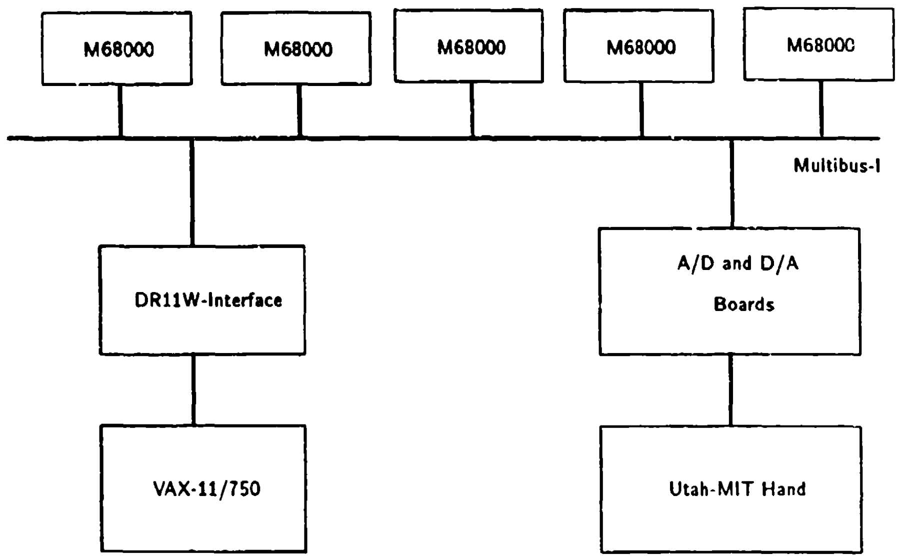
In short, the low-level control system includes "16 variable-loop-gain position servos to operate finger joints and 32 variable-loop-gain tension servos to modulate actuator behavior such that tendon tensions can be closely controlled". So its main inputs, which can be manually set on the control pannel, are: "*a*) 16 inputs for control of angular position; *b*) 32 inputs for control of desired tendon tension; *c*) 16 inputs to vary position servo loop gain; and *d*) 32 inputs to vary tendon tension servo loop gain". A number of auxiliary inputs are also available, "to control damping, co-contraction levels and to allow direct control of servo valve currents". As for the outputs, they are “all sensor signals generated within the hand”. A whole bunch of multicolor light-emitting diodes completes the control panel, for diagnostic information.

Instead of manual control, the low-level analog control system can be interfaced to higher-level digital control systems, using “40 channels of digital-to-analog conversion and 320 channels of analog-to-digital conversion”. There were two successive hardware architectures of the high-level control, schematically illustrated in figure 3.70 and documented by Sundar Narasimhan, David Siegel, and John Hollerbach (Siegel, Narasimhan, J. Hollerbach, Kriegman, and Gerpheide 1985; Narasimhan, Siegel, J. Hollerbach, Biggers, and Gerpheide 1986; Narasimhan, Siegel, and J. Hollerbach 1988a,c,b, 1989a,b, 1990). Version I of the control hardware consists of a VAX-11/750 minicomputer and five Motorola 68000 microprocessors, both interconnected together and with the analog/digital converters via a Multibus-I communication bus. Version II of the control hardware consists of a Sun-3/160 microcomputer and six Motorola 68020 microprocessors with Motorola 68881 floating-point co-processors, and the communication bus is a VMEbus[42]. Both versions have in common that they were state-of-the-art at the time; indeed, controlling a complex device with as many degrees of freedom and actuators as the Utah/MIT Hand was an extremely computationally-intensive task for the hardware of these days. Narasimhan, Siegel, and J. Hollerbach (1988a,b) explain that a servo rate of the order of 400 Hz is required for the control of the device; this necessitates “reading 19 200 sensor values per second” ($400 \times 32$ tendon tension sensors + $400 \times 16$ joint position sensors) and “outputting 12 800 actuator values per second” ($400 \times 32$ servo valves).

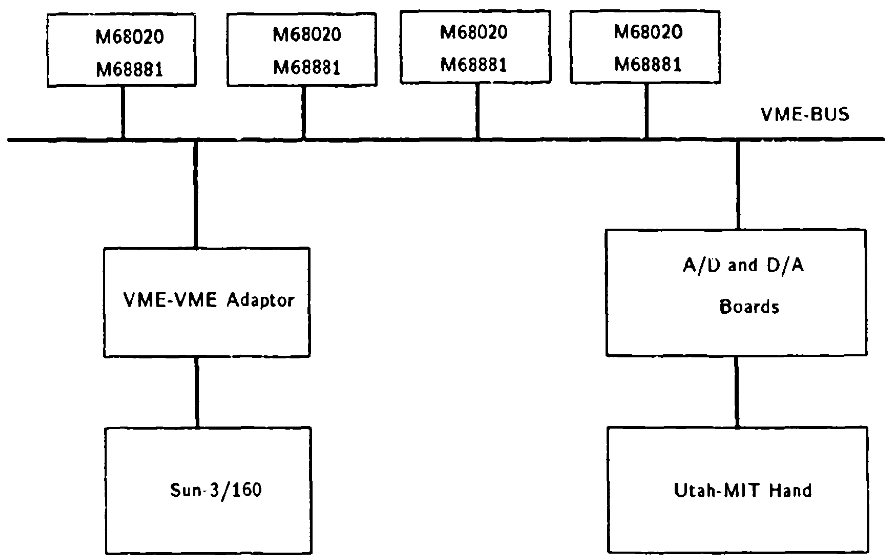
In each version of the control hardware architecture, the computer is used for the development of the control code, in C programming language, while the multiple processors are used to run the control code in real time. Indeed, the central processing units of the computers were not powerful enough for this task: additional, dedicated units were need for it. Simply put, the code is written and compiled on the host computer (the “development” environment), then “downloaded onto the slave microprocessors, where it is actually run” (in the “run-time”, or “real-time” environment) (Narasimhan 1988, page 84). Siegel, Narasimhan, J. Hollerbach, Kriegman, and Gerpheide (1985) note that this multiprocessor computational architecture used to control the hand is actually “a general system which is potentially useful for other robotics applications”.

Like the Stanford/JPL Hand, the Utah/MIT Hand was never intended for near-tearm exploitation in industrial environments (long-term applicability was thought about, though). It was a research tool mainly intended for the study of machine dexterity and tactile sensing (Jacobsen, Iversen, Knutti, T. Johnson, and Biggers 1986). Several

42. All this hardware is typical of the 1980s. A VAX-11/750 was used for the control of the Stanford/JPL Hand too; it was one of the first VAX minicomputers, released by DEC in 1980. The Sun-3 series of microcomputers, made by Sun Microsystems, was launched in 1985. They were computer workstations and servers based on the VMEbus communication bus and using a Motorola 68020 microprocessor, in combination with a Motorola 68881 floating-point unit. Their operating system was usually SunOS, a kind of BSD Unix (nowadays Solaris), while VAX computers were usually used with VAX/VMS (nowadays OpenVMS). The Motorola 68000 family of microprocessors was widely used during the 1980s and early 1990s, especially in desktop computers, where it competed against Intel’s x86 architecture. For instance, the Apple Macintosh, the Commodore Amiga, and the Atari ST were powered by a 680x0 microprocessor; so were the Sega Mega Drive video game console and Texas Instrument calculators, in the 1990s. As for Multibus and VMEbus, they were industry-standard computer buses of the 1970s and 1980s, that could provide a very high bandwidth connection between the components they interconnected.




(a) Version I of the hardware




(b) Version II of the hardware

Figure 3.70 – Block diagrams of the hardware architecture of the Utah/MIT control system (Narasimhan 1988, pages 81–82). Among the multiple control processors, one is a master processor (system supervisor), another controls the experimentation table where the objects are placed (this table is motorized), and the others run the servo code (control of the fingers).

Utah/MIT Hands were made and used to these aims: for instance, the design and construction of tactile sensors and contact detectors, and their integration into a tactile sensing system for the hand, were investigated by Siegel, Garabieta, and J. Hollerbach (1985, 1986), Siegel (1986), McCammon and Jacobsen (1988, 1990), and Johnston, P. Zhang, J. Hollerbach, and Jacobsen (1996). Planning of complex dextrous manipulations and high-level control strategies were studied by Speeter (1990a, 1991) and Michelman and Allen (1994). Pose determination of a grasped object was investigated by Siegel (1991b,a), using only limited sensing: mainly joint angle sensing and torque sensing. Also, teleoperation was another application of the Utah/MIT Hand: Rohling, J. Hollerbach, and Jacobsen presented a new master system and Farry, I. Walker, and Baraniuk investigated the use of electromyography to control the slave hand (Rohling and J. Hollerbach 1993; Rohling, J. Hollerbach, and Jacobsen 1993; Farry and I. Walker 1993; Farry, I. Walker, and Baraniuk 1996).

**Belgrade/USC Hand** In many respects, the Belgrade/USC Hand is the opposite of the Stanford/JPL and Utah/MIT Hands. It was built with only a few electric motors, housed directly in the wrist, it could not control its joints independently, and it was intended for grasping, not for dextrous manipulation: all the contrary of the Stanford/JPL and Utah/MIT Hands, with their large separate drive units, numerous tendons, independent degrees of freedom, and sophisticated controls.

The Belgrade/USC Hand grew out of the Belgrade Hand, a prosthesis created by Rajko Tomović at the turn of the 1960s at the University of California in Los Angeles, and then further developed in Belgrade, Yugoslavia. The Belgrade Hand was anthropomorphic, had five fingers, was made of aluminium, used a single electric actuator, and had pressure-sensitive pads placed on the surface of the palm and phalanges. It was intended for adaptive grasping, that is to say, automatic adjustment of the grasp to objects of different shapes and different sizes. When the prosthesis was brought in contact with an object, contact detection by the pressure-sensitive pads switched the motor on and the hand closed the fingers until pressure was approximately equal among the sensors. That meant the grasp was safe (Tomović and Boni 1962; Rakić 1962; see also the history of electric hand prostheses in section 3.2.3 for more references and information).

In the late 1980s, probably as a result of the intensification of research activities in robotic manipulation and multifingered hands, it was decided to produce a new version of the Belgrade Hand. A cooperation began between Rajko Tomović of the University of Belgrade, and George Bekey of the University of Southern California, in Los Angeles. The resulting hand, which became known as the Belgrade/USC Hand, is illustrated in figures 3.71 and 3.72. It was designed and fabricated at the University of Novi Sad in Yugoslavia [43], and its sensing and control algorithms were developed at the University of Southern California (Bekey 2005, pages 378–385). Three versions of the hand were actually produced, Model I to Model III. The one that is most remembered nowadays is the Model II Belgrade/USC Hand (Bekey, Tomović, and Zeljković 1988, 1990).

Like its prosthetic ancestor, the Belgrade/USC robot hand is anthropomorphic, underactuated, and adaptive. It features only four actuators: four electric motors, clearly visible below the palm area in figures 3.71 and 3.72. It has four identical three-jointed fingers; each pair of fingers is driven in flexion/extension by one motor.

43. Novi Sad is a city in Serbia (the second largest after Belgrade).

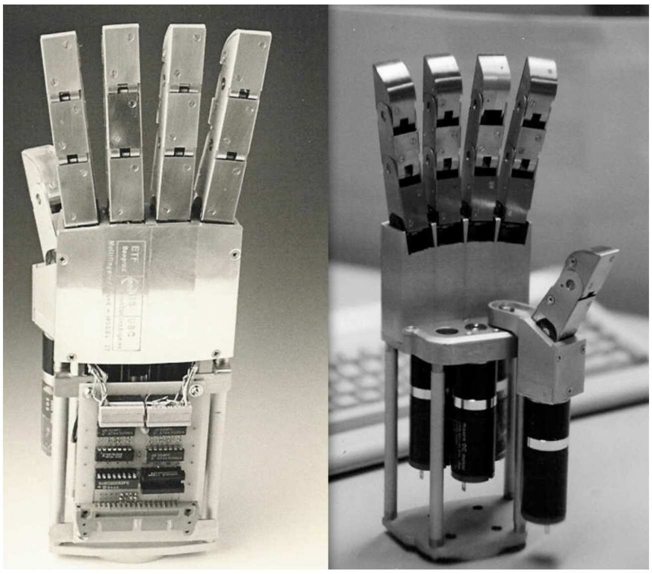


Figure 3.71 – The Belgrade/USC Hand (1990), without its external contact/force sensors

The articulated thumb has two phalanges and two joints, driven in flexion/extension by another motor. The thumb can also move in an arc into opposition with the second, third, and fourth fingers, thanks to the last motor. Even though there are the fifteen joints in the hand, most of them are coupled, and there are only four independent degrees of freedom: one for each pair of fingers, two for the thumb. The design is self-contained, except for the power supplies.

Since they are so close to the fingers, the servomotors can drive them directly (through reduction gears): no cables or tendons are used. A rocker arm mechanism couples the index and middle fingers mechanically, another ones does the same with the ring and little fingers. These mechanisms are visible on figure 3.72. They ensure that the grasp adapts automatically to the shape of the object: the rocker arms are "designed in such a way that if the motion of one finger of the driven pair is inhibited, the second finger continues to move, thus achieving some shape adaptation without external control" (Bekey, Tomović, and Zeljković 1988). The three phalanges of the fingers are connected to each other by means of linkages, also visible on figure 3.72; so their motions are not individually controllable. The whole actuation and transmission architecture determines a hand well-suited to adaptive grasping but lacking the dexterity and controllability required for in-hand manipulation.

The hand is equipped with three sets of sensors: contact/force sensors, position sensors, and slip sensors. The contact/force sensors are the most important, because the hand is meant for "reflex" grasping like the prosthetic Belgrade Hand: the primary feedback loop of its control closes the hand and controls the strength of the grasp based on contact detection and force sensing. Therefore, there are twenty-three contact/force sensors, made of a pressure-sensitive thick-film resistive polymer material [44], and located on the volar and dorsal sides of the digits and palm.

44. Namely, force sensing resistors, a technology invented in the mid-1980s by Interlink Electronics, a Santa Barbara, California corporation. Subsequently patented and trademarked. Basically, a force sensing resistor consists of a conductive polymer whose electric resistance decreases when the force applied to its surface increases. They are low-cost and simple to use, but rarely accurate.

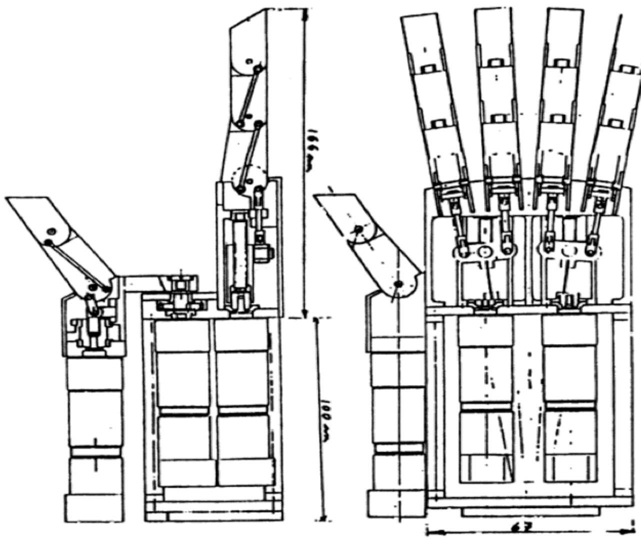


Figure 3.72 – The rocker arm mechanisms coupling the fingers are visible on the right, in the palm area. The linkages coupling the phalanges are visible on the left.

Beattie, Iberall, Sukhatme, and Bekey (1994) report that "the characteristics of these sensors are highly nonlinear [45], and [the sensors] have much greater sensitivity for small pressures than for large ones; hence, they are very useful for detecting small contact forces". Besides these sensors, there are four small potentiometers to indicate the angular position of the proximal phalanges with respect to the palm, and slip sensors at the fingertips, implemented first by thermistors which detect temperature changes, then by small rotating drum sensors. An external vision system completes the sensorization; it is described by Rao, Medioni, H. Liu, and Bekey (1988, 1989) and used during the planning of the grasp.

The control of the Belgrade/USC Hand is representative of a control philosophy which favors prior knowledge to have robotic systems accomplish motions and actions. In contrast, the role of numerical algorithms and standard control theory is downplayed: according to Bekey and Tomović (1990), "human beings do not solve the differential equations of motion of their legs before taking a step, or of finger motion before grasping an object". Instead, knowledge-based control strategies are preferred, especially in grasp planning (Bekey, H. Liu, Tomović, and Karplus 1993): grasp postures can be selected "by reasoning from symbolic information on target object geometry and the nature of the task" to be performed; to this aim, the grasp planner has to combine information about object geometry, acquired by the external vision system, with "several task attributes" and "heuristics from human motor skills".

This knowledge-based, biologically-inspired, non-numerical control approach goes hand in hand with an emphasis on local autonomy of the robotic system (Bekey and Tomović 1986). As explained by Iberall, Sukhatme, Beattie, and Bekey (1993a), "in contrast with the approach taken [...] in the development of the Utah/MIT four-fingered hand, where control of its sixteen degrees of freedom is performed at a high level in the computer", the Belgrade/USC Hand controller "[uses] local autonomy as much as possible, hence, grasp control should reside within the hand itself, using

45. In general, force sensing resistors approximately follow an inverse power-law characteristic (in terms of resistance versus force).

position, pressure, contact and slippage sensors". The underlying philosophy is that of reflex control: "each aspect of the grasping task is initiated and terminated using sensory data and rules of behavior derived from human expertise in such tasks" (Tomović, Bekey, and Karplus 1987); in other words, the reflexes are coded by a knowledge base and triggered by sensor events. For instance, one such reflex is the automatic increase in grip force when slip is detected.

This standpoint about the importance of prior knowledge and local autonomy is developed by the roboticists not only for the control of the hand (Tomović, Bekey, and Karplus 1987; Bekey and Tomović 1990; Bekey, H. Liu, Tomović, and Karplus 1993), but more generally for any robotic system where artificial reflexes are relevant notions (Bekey and Tomović 1986, 1990). In the case of the hand, the resulting control architecture is divided into two phases: a "target approach phase including target identification, hand structure and grasp mode selection, selection of approach trajectory, hand preshaping and orientation", followed by a "grasp execution phase including shape and force adaptation" (Tomović, Bekey, and Karplus 1987). Knowledge-based grasp planning, performed during the first phase, requires significant computational power and is therefore implemented on a powerful workstation. On the other hand, the reflex-based control itself, performed during the second phase, is much less computationally intensive and can be run on a standard IBM Personal Computer [46]. The hand configuration is transferred from the workstation to the control computer, which is also fed back sensor values from the hand via analog-to-digital converters.

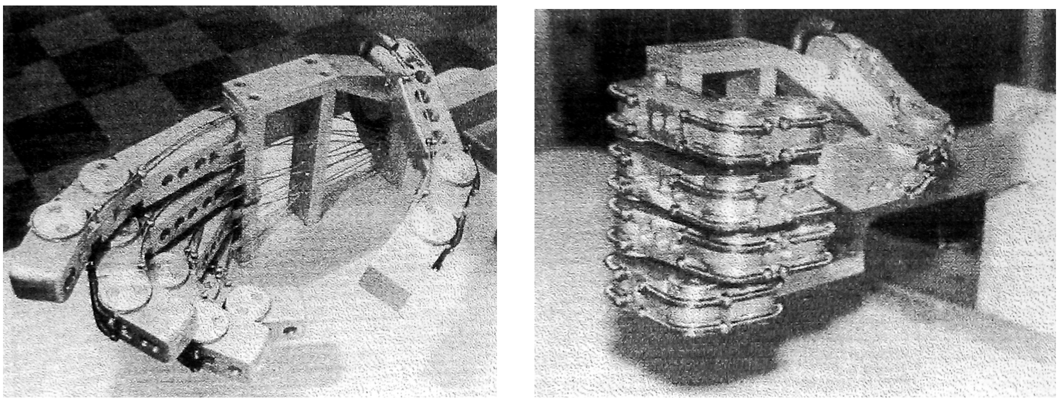
Because of its self-contained design, its emphasis on grasping rather than manipulation, its autonomous adaptativity, its reflex-based control, and also probably because of its prosthetic ancestry, the Belgrade/USC Hand was investigated for myoelectric interfacing and possible use as a prosthesis (Iberall, Sukhatme, Beattie, and Bekey 1993b,a, 1994; Beattie, Iberall, Sukhatme, and Bekey 1994). Although he considers that the control philosophy for using this robotic hand as a prosthetic device was good, George Bekey remembers experimental problems "related to the difficulty of controlling [the hand] from the stump of an amputee and the general lack of reliability of the hand itself". Unfortunately, he was unsuccessful in "[raising] the funds to design and build a more sophisticated and reliable hand" (Bekey, reported by Fermoso 2008).

The hand described above is the Model II Belgrade/USC Hand. The previous Model I seems to have been very similar, except that the thumb "is rigid and rotates about an axis normal to the palm", hence only three motors were used (Bekey, Tomović, and Zeljković 1988). The existence of a Model III with six motors, one for each finger and two for the thumb, is also reported, but no further information seems available (Iberall, Sukhatme, Beattie, and Bekey 1993a, and Fermoso 2008, citing Bekey).

46. First an IBM Personal Computer/XT (Bekey, Tomović, and Zeljković 1988), then an IBM Personal Computer/AT (Iberall, Sukhatme, Beattie, and Bekey 1993a). Both were evolutions of the original IBM Personal Computer, introduced in 1981. The company had decided on an open computer architecture for this machine: they created it from off-the-shelf parts from a variety of different manufacturers, rather than designing their own components as usual, and they published extensive technical documentation, complete with circuit schematics and a listing of the ROM BIOS source code. Because of that, the IBM Personal Computer could be reproduced by others, and a wide variety of "IBM PC compatible" microcomputers soon hit the market. The PC architecture quickly became the de-facto standard for personal microcomputers, and nowadays, descendants of the IBM PC compatibles make up the majority of personal microcomputers on the market (including Apple's computers since 2006). The operating systems MS-DOS, Windows, OS/2, GNU/Linux were created in particular for PC architectures, and many others were adapted to support it as well.

**Other hands of the 1980s** A few other multifingered hands were proposed by other researchers during the 1980s, but none of them comes close to the Stanford/JPL or the Utah/MIT Hands. For instance, there was a large anthropomorphic five-fingered hand built by Mike Caporali and Mohsen Shahinpoor at Clarkson College of Technology in Potsdam, New York (Caporali 1982; Caporali and Shahinpoor 1984), and also the Pennsylvania Articulated Mechanical Hand, a three-fingered articulated gripper made at the University of Pennsylvania in Philadelphia (Abramowitz, Goodnow, and B. Paul 1983).

The first one is illustrated in figure 3.73. It is about twice the size of an average human hand, "for simplicity and to ease construction", and despite its bulky look it is fairly well articulated, with fifteen degrees of freedom. Namely, each finger has three flexion/extension axes and the thumb has one opposition/retroposition axis and two flexion/extension axes. All the joints are tendon-driven by electric motors, although some of them share the same actuator. These motors are provided for flexion only (and thumb opposition): extension (and thumb retroposition) is performed by return springs. A wrist, elbow and shoulder complete the system with four additional degrees of freedom. The purpose of this construction is not really stated, other than "because simulating the human hand was an exciting challenge" (Caporali and Shahinpoor 1984); besides, there is no record of it being either improved or put to use under some control scheme, and sensorization is totally absent. So we are left to think that it was done just for the fun of it.

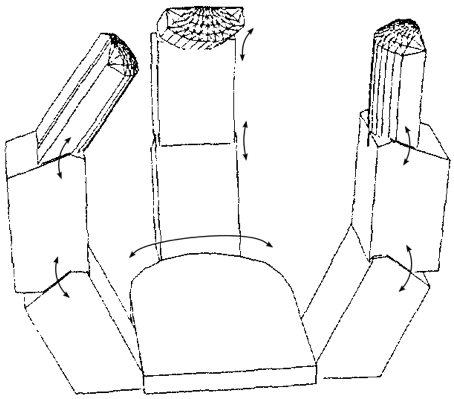


(a) In half-open position. The tendon cables and pulleys are visible on the side of the fingers.

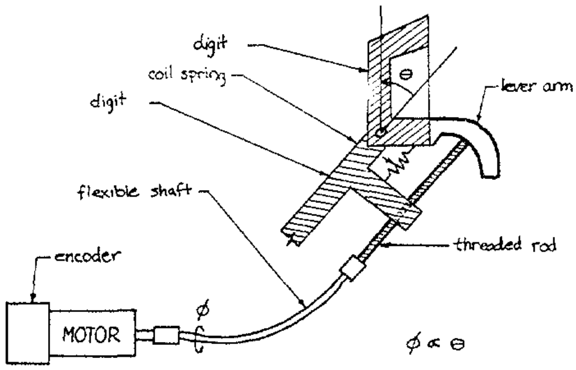
(b) With all the fingers closed. The return springs are visible on the back of the fingers.

Figure 3.73 – Caporali and Shahinpoor's hand (1984)

The Pennsylvania Articulated Mechanical Hand, on the other hand, was built with a particular goal in mind: the investigation of three-dimensional tactile perception, through the use of tactile sensors, which were a recent innovation at that time (Abramowitz, Goodnow, and B. Paul 1983). The hand is schematically illustrated in figure 3.74, with its seven degrees of freedom and peculiar transmission system. Despite its name, it is not really anthropomorphic. It is equipped with "63 resistive-type tactile sensors, 21 on each finger. There is a three-by-three planar array of sensors on the ventral surface of each of the second and third [phalanges] of all three fingers. The remaining nine sensors are placed on each fingertip in three-by-one planar arrays" (Bajcsy, McCarthy, and Trinkle 1984). Using the output of these sensors, it is possible to determine the size and geometry of the grasped object, and control the pressure of the grasp. The hand is not adapted to dextrous manipulation, though, because of its lack of dexterity in both structure and control. Its conceptors made a good point that hands are used in tactile exploration of objects, but this function does not usually occurs independently from manipulation; rather, both functions happen at the same time, and manipulation makes exploration easier and more thorough.



(a) The two digits in the foreground act in opposition to one another. The third one can rotate around the semi-circular portion of the palm to better explore the object.




(b) In this actuator design, the angle of the joint rotation is proportional to the angle of rotation of the motor. This simplifies the synthesis of the control algorithms.

Figure 3.74 – A drawing of the Pennsylvania Articulated Mechanical Hand (1983). From Bajcsy, McCarthy, and Trinkle (1984).

A more famous hand is the Hitachi Hand, developed in Japan by researchers of that company's mechanical engineering research laboratory (Y. Nakano, Fujie, and Hosada 1984). It remains famous to this day because of its actuation system, based on shape memory alloys: it was the first artificial hand to make use of this technology. A photograph of this hand is included in figure 3.75, and the principle of its actuators is illustrated in figure 3.76. The hand was characterized by its high power-to-weight ratio, more thanks to the lightness of its actuators than to the force they outputed. The alloy used was nickel titanium, also known as nitinol [47]: a compound made of roughly equal atomic proportions of the two elements. It is one of the most common shape memory alloys, although it is difficult to manufacture. Wires made from nickel titanium shrink when heated, usually by an electrical current, and revert to their original length when cool. More hands actuated by shape memory alloys were built after the Hitachi Hand; a few bibliographic references are given in section 2.4.1, chapter 2. They are mainly research prototypes.

At the very end of the 1980s, a couple of planar hands were made for the study of manipulation in the plane (easier than in space). There was the NYU Hand, made at the Courant Institute, New York University (Demmel, Lafferriere, J. Schwartz, and Sharir 1988), and also the Styx Hand, made at the University of California in Berkeley (Murray and Sastry 1989; K. Hollerbach, Murray, and Sastry 1992).

47. For "Nickel Titanium Naval Ordnance Laboratory", after its composition and the name of the US Navy laboratory where it was discovered in 1962. The observation of the shape memory effect in general is older though, dating back to 1932 for gold-cadmium alloys. Other alloys with various degrees of memory effect, at different temperatures and different percentages, include brass (copper-zinc), copper-aluminium-nickel, copper-zinc-aluminium, iron-platinum, iron-nickel, nickel-aluminium, and even stainless steel (iron-carbon-chromium).

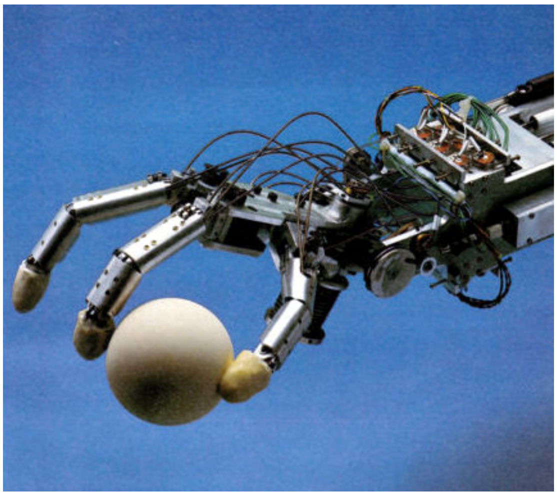
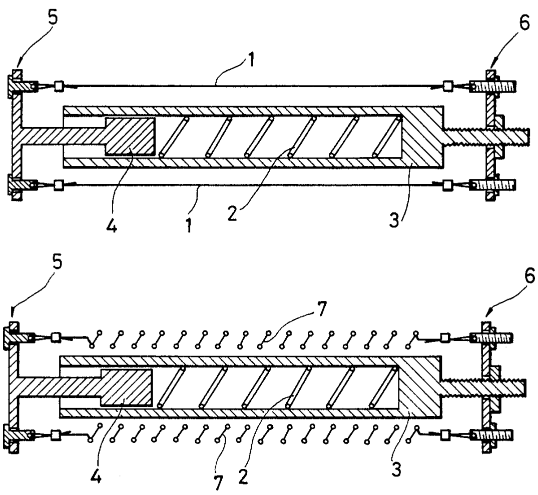


Figure 3.75 – The Hitachi Hand (1984), actuated by shape memory alloys




The actuator consists of a coil spring (*2*) placed in a tube housing (*3*) closed by a piston (*4*), between a movable part (*5*) and a stationary part (*6*). Multiple thin shape memory alloy wires (*1*) are arranged in parallel around the periphery of the guide. They contract against the force of the spring when heated by an electrical current, and return to their original length on cooling, so the position of the piston can be adjusted according to the balance between the force in the spring and the force in the wires.

By using a large number of wires, the strength of the actuator can be increased to the desired value. The thickness of the wires is important too: thin wires heat and radiate heat faster than thick wires, hence an increase in operation speed. Also, since a large length of wire is required to create significant motion (a limitation of shape memory alloys), it is possible to shape the wires as coil springs (*7*), or make then go back and forth between pulleys, to increase their length.

Figure 3.76 – Shape memory alloy actuator developed by Hitachi (Hosada, Kojima, Fujie, Honma, T. Iwamoto, Y. Nakano, and Kamejima 1986)

Both were non-anthropomorphic of course; the NYU Hand had “four fingers moving in a plane, driven by stepper motors” (Murray, Z. Li, and Sastry 1994, page 13), and Styx had two identical fingers about 27 cm long, each with two revolute joints, direct-driven by four small DC motors mounted directly at the joints, and with small rubber circles at the end (figure 3.77). These fingertips were modeled as simpler point contact though, “to avoid the added computational complexity required to model the rolling contacts” (Murray and Sastry 1989). Styx was mainly used as a testbed to compare the performance of different control laws.

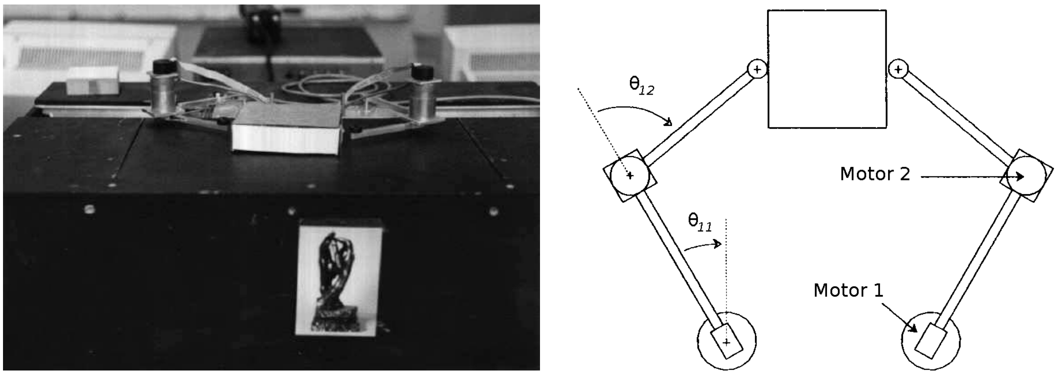



Figure 3.77 – Styx Hand (1988). Photograph from Murray, Z. Li, and Sastry (1994, page 12), drawing from Murray and Sastry (1989).

### 3.3.3 Modern humanoid robot hands

Starting from the end of the 1980s, more and more robot hands were built and investigated by roboticists worldwide. The pace of research markedly quickened, with an increase in the number of robotics laboratories involved in dextrous manipulation. Besides, dextrous manipulation research spread from the United States to other countries. In particular, Japan became more active in this field, and dextrous hands appeared in Europe too, mainly in Italy and Germany. In fact, these four countries seem to remain the most active ones to the present day in this field of robotics.

The development of dextrous manipulation research during the 1990s and 2000s involves theoretical advances just as much as new robot hands, of course. And there was indeed much progress and novelty in the modeling and control of manipulation. For a start, a lot of control laws based on hybrid force/position control, invented in 1981 by Marc Raibert and John Craig, were proposed for multifingered hands. They have in common the fact that they all realize the desired position trajectory of the object and the desired value of the internal grasp force, that is to say, they can ensure simultaneously the motion of the object and its tightening. Early examples of such control laws are proposed by Zexiang Li, Ping Hsu, and Shankar Sastry (1989) and by Yoshihiko Nakamura, Kiyoshi Nagai, and Tsuneo Yoshikawa (1987, 1989); the first one assumes fixed point contacts with friction at the interface between the fingers and the object, while the second one enforces non-sliding at the contacts through appropriately designed internal force objectives. Another hybrid force/position control law, proposed by Tsuneo Yoshikawa and Xin-Zhi Zheng (1990, 1993), realizes simultaneously the motion of the object, the internal forces, and the interaction force between the object and its environment, in the case of non-sliding contacts. Speaking of non-sliding, hybrid force/position control can include considerations about the relative motion of the fingers and object, whether it is rolling, sliding, or both. For instance, certain control methods were proposed which model explicitly rolling kinematics, in order to compensate for the motion/force errors caused by rolling changing the location of the contact points during manipulation (Cole, Hauser, and Sastry 1989; Remond, Perdereau, and Drouin 2002). Other control schemes realize intentional, controlled rolling (Sarkar, Yun, and Kumar 1993) or intentional, controlled sliding (Cole, P. Hsu, and Sastry 1992; X.-Z. Zheng, Nakashima, and T. Yoshikawa 1994, 2000; T. Yoshikawa 2000a) as part of their objectives. A different approach, impedance control, was also investigated for dextrous manipulation during the 1990s, following its invention by Neville Hogan in 1984. One notable impedance control scheme, for instance, is the one based on the "virtual object" concept, proposed by Stefano Stramigioli, Claudio Melchiorri, and Stefano Andreotti (Stramigioli 1998, 1999; Stramigioli, Melchiorri, and Andreotti 1999; Melchiorri, Stramigioli, and Andreotti 1999). For a more complete review of the control strategies in dextrous manipulation, see section 5.2.3 in chapter 5.

Among the theoretical novelties of the 1990s and 2000s, we must also mention grasp quality measures and grasp force optimization. Even though early studies can be found in the preceding decade (for instance Kerr and Roth 1986), most of the research on these problems is relatively recent. For instance, aside from a duality-based linear programming method proposed by Fan-Tien Cheng and David Orin (1989, 1990), not much had been proposed to solve the force optimization problem (that is to say, find optimal contact forces against some known external force applied on the object) until the formulations based on convex optimization and linear matrix inequalities of Martin Buss, Hideki Hashimoto, and John Moore (1995, 1996) and Li Han, Jeffrey Trinkle, and Zexiang Li (1999, 2000). More recently, another non-linear programming method was proposed by Stephen Boyd and Ben Wegbreit (2007, 2008), as well as simpler methods based on quadratic programming, by Jean-Pierre Gazeau, Saïd Zeghloul, and Gabriel Ramirez (2005) and Jean-Philippe Saut, Constant Remond, Véronique Perdereau, and Michel Drouin (2005). As for grasp quality measures (quantitative indications of how good a grasp is, for instance with respects to the forces it can generate), the most common and most popular, which is also one of the firsts, was introduced by David Kirkpatrick, Bud Mishra, and Chee-Keng Yap (1990, 1992) and by Carlo Ferrari and John Canny (1992). This quality measure, known as the "criteria of the largest ball", had several variations thereafter, in particular the one proposed by Xiangyang Zhu, Han Ding, and Jun Wang (2003). More information about it, as well as more detailed reviews of grasp quality measures and grasp force optimization, are given in the section 6.1.2 of chapter 6.

Last but not least, the 1990s and 2000s saw important advances in the modeling and understanding of grasp stiffness. The cartesian stiffness matrix, which codes the restoring force of a grasp against a small displacement of the object in the six dimensions of space (three translations and three rotations), came under investigation: in particular, its symmetry and asymmetry properties were discussed by Namik Ciblak and Harvey Lipkin (1994), Thomas Pigoski, Michael Griffis, and Joseph Duffy (1998), and Miloš Žefran and Vijay Kumar (1996, 1997, 2002). At the turn of the century, Shih-Feng Chen and Imin Kao (1999, 2000a) corrected a flaw in Kenneth Salisbury's relationship between the joint and cartesian stiffness matrices of a manipulator (1980); there was a missing term. The new cartesian stiffness matrix they yield is assymetric, even though the joint stiffness matrix is symmetric: a result which is in keeping with the theoretical analyses of Ciblak and Lipkin and Žefran and Kumar. We give more information about these issues in the section 7.2.3 of chapter 7.

Regarding the hardware now, there was, of course, much discrepancy in the amount of time, funding, and workforce that the various research laboratories were able and willing to put in the construction of a robot hand, not to mention the differences in research priorities and application focus. This remains obviously the case nowadays. Thus the robot hands that have been and are being developed are very diverse in their capabilities and purposes. They range from simple constructions, such as the wooden Thing Hand from the University of Florida (Grimm, Arroyo, and Nechyba 2002), to very complex and fully dextrous devices, such as the DLR series of hands developed at the Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center) or the hand built by the Shadow Robot Company in England (DLR 2010; Shadow Robot Company 2011). Also, some of them are merely articulated grippers with limited dexterity, often not very anthropomorphic either, and intended for custom or semi-custom applications: for instance, the Barrett Hand from the American company Barrett Technology (2010), or the four-fingered hand for space applications developed at the Space Systems Laboratory of the University of Maryland – which is in reality a gripper "optimized for cylindrical grasping", even though a multifingered, articulated one (Foster 2001; Akin, Carignan, and Foster 2002).

Long story short, it becomes more and more difficult, if not progressively impossible, to keep track of all the hands and dextrous grippers that have come into existence since the end of the 1980s. The task is further complicated by the term "robot hand" being synonymous with "end effector", which results in grippers sometimes being called hands, even those with zero manipulation dexterity and zero grasp versatility. In this section, the last one of this chapter on artificial hands, we present some of the most well-known and most representative robot hands of the last two decades. To make matters simple we break them loosely into four arbitrary groups according to anthropomorphism and dexterity, as indicated by the table 3.3.

| | Low dexterity | High dexterity |
|---|---|---|
| Low anthropomorphism | Adaptive grippers | Dextrous grippers |
| High anthropomorphism | Adaptive hands | Dextrous hands |

Table 3.3 – Four categories of multifingered articulated grippers

**Adaptive grippers** are the simplest multifingered articulated grippers. They are neither very anthropomorphic nor very dextrous, even though they are called hands nonetheless (admittedly, their articulated jaws often remind of fingers). The primary function of these grippers is adaptive grasping, that is to say they aim at grip versatility. Their limited actuation makes them incapable of significant in-hand manipulation. Most articulated and underactuated grippers fall in this category, for instance the Barrett Hand and the Sarah Hand.

**Adaptive hands** differ from the previous category by their anthropomorphic shape only. They aren't more dextrous and are restricted to adaptive grasping, again because of their limited actuation. The Belgrade/USC Hand is emblematic of this kind of devices; subsequent adaptive hands include the TUAT/Karlsruhe Hand, the hands of most current humanoid robots, and more generally all underactuated humanoid hands (not including those whose underactuation is limited to the coupling of each finger's last two joints).

**Dextrous grippers** are exactly what the name implies: multifingered, articulated, non-anthropomorphic grippers capable of in-hand manipulation to a significant level. All their degrees of freedom are actuated and controlled, or most of them, contrary to the grippers of the previous two groups. That is the reason of their dexterity. The Stanford/JPL Hand is such a gripper; other dextrous grippers are the Karlsruhe Dextrous Hands and the High Speed Multifingered Hand.

**Dextrous hands** are highly anthropomorphic and sufficiently articulated and actuated to exhibit high potential dexterity and be able to perform actual in-hand manipulations, if their control keeps pace. Typical examples include the Utah/MIT Dextrous Hand, Robonaut's hands, the DLR series of hands, the UB Hands, the Gifu Hands, and the Shadow Dextrous Hand. There are a few comparative studies of this kind of hands, most notably those by Biagiotti, Lotti, Melchiorri, and Vassura (2002) and Alba, Armada, and Ponticelli (2005); the more general review by Zeghloul, Arsicault, and Gazeau (2007) is also of interest. At the moment, dextrous humanoid hands are found only in robotics laboratories, and their applications are limited to research activities. As a matter of fact, aside from the Shadow Dextrous Hand, they are all built in universities or public research institutes.

The market for all these multifingered, articulated grippers is very small. In particular, the one for dextrous hands is almost non-existent, or at least it is a niche market. Indeed, potential clients are mostly research laboratories in universities and public research institutes. So, it is not uncommon for a robotics laboratory which has developed a hand to create a small robotics company or team up with an existing one in order to manufacture more hands and sell them to other research laboratories. For instance, Kenneth Salisbury was the president of Salisbury Robotics, which presumably sold the Stanford/JPL Hand, and Stephen Jacobsen founded Sarcos, which sold the Utah/MIT Dextrous Hand (Mason and Salisbury 1985; Sarcos 1998). Both companies are defunct nowadays. Currently, the DLR/HIT Hand I is sold by the leading German firm Schunk (DLR 2010; Schunk 2008), the Gifu Hand III is sold by the Japanese company Dainichi (2010), and hands derived from the prosthetic CyberHand and SmartHand are made by the Italian company Prensilia (2010). As for the Barrett Hand, sold by Barrett Technology (2010), it is actually derived from research conducted at the University of Pennsylvania in the late 1980s (Ulrich 1989; Puttré 1995; Stringer 1997). The only commercially-available multifingered hand which does not seem to come from more-or-less direct application of academic research is the Shadow Dextrous Hand. Still, the clients of the Shadow Robot Company (2011) are mostly universities and research institutes.

### Adaptive grippers

**UPenn and Barrett Hands** As mentioned above, the history of the Barrett Hand starts in the late 1980s at the University of Pennsylvania. There, Nathan Ulrich and his colleagues were developing a "medium-complexity" end effector: something that would be a compromise between simple grippers and humanoid hands (Ulrich and Kumar 1988; Ulrich, R. Paul, and Bajcsy 1988; Ulrich 1989, 1990; Ulrich, Kumar, R. Paul, and Bajcsy 1990). The result was dubbed the UPenn Hand. It was "less complicated, less expensive, and easier to control than existing robot hands, yet more complicated, more expensive, and harder to control than simple grippers" (Ulrich 1989). The hand is illustrated on figure 3.78: it consists of three identical two-phalanx fingers arranged around a small flat palm. The whole device is approximately the size of a human hand, and can be mounted on the wrist of a manipulator. The central finger is fixed with respect to the palm, but the other two are able to rotate symmetrically around it, towards and away from one another. The two joints of each finger are coupled, so each finger is actuated by a single electric actuator, not two (and a mechanism decouples the joints when a certain torque is exceeded). With the actuator of the finger rotation, that makes a total of four actuators for seven degrees of freedom: not enough for real dextrous manipulation, but sufficient for a wide variety of grasp patterns, from cylindrical power grip to spherical fingertip precision grip. To enable sensor-driven control of this grasping, the hand is designed to be equipped with proximity, position, force, tactile, and thermal sensors, with “much of the cabling [...] outside of the mechanism envelope” to make changing the chosen sensors easier.

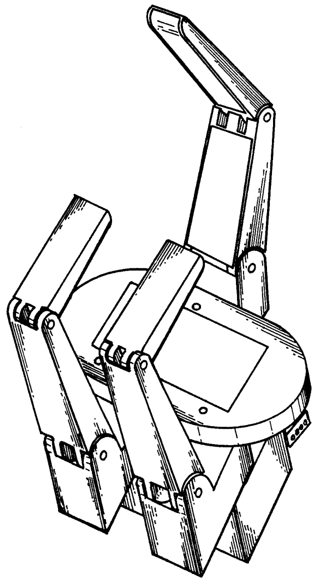


Figure 3.78 – A drawing of the UPenn Hand (1988), from Ulrich (1990)

At the same time that the UPenn Hand was being developed, Barrett Technology was founded in Cambridge, Massachusetts by William Townsend, as a spin-off from the Artificial Intelligence Laboratory of the Massachusetts Institute of Technology (Barrett Technology 2010). Townsend had just finished his graduate studies there, during which he had worked under the direction of Kenneth Salisbury on transmission problems in robot manipulators. He had also led the construction of a robot manipulator to exemplify his work: the MIT/WAM manipulator, where WAM stands for Whole Arm Manipulation (Townsend 1988). Barrett’s initial goal was to bring this product to the market. To complete the arm, they got a license for the UPenn Hand from the University of Pennsylvania (Puttré 1995; Stringer 1997). A few years of development later, the first Barrett Hands were sold, mainly to automotive manufacturers in Japan, for a price of US $ 30 000 each – which is “more expensive than conventional grippers that only cost several thousand dollars”, but nonetheless “reasonable when you take into account all the tools that must be purchased in order to keep switching tasks with less flexible simple grippers” (Stringer 1997, citing a study by the Ford company). The Barrett Hand was officially introduced commercially in 1999, as a multifingered programmable grasper (Townsend 2000).

The current version of the Barrett Hand is illustrated on figures 3.79 and 3.80; it is described in detail by Townsend (2000), Townsend, Hauptman, Crowell, Zenowich, Lawson, Krutik, and Doo (2007), and Barrett Technology (2010). The external design and actuation system are much like the UPenn Hand, with three identical two-link fingers, two of which can move lateraly around the palm, a total of eight axes, seven degrees of freedom, and four electric motors. The hand is entirely self-contained, yet compact and light enough to fit easily on the end of a robotic arm (it weights about 1.2 kg). The actuators, servo-controllers, and communications electronics are housed under the palm; a host computer running Linux or Windows is required for high-level control software. All the joints have high-precision position encoders, and the hand can optionally be equipped with strain-gauge-based torque sensors at the last joint of each finger, and tactile sensors arrays on the palm and fingertips (Barrett Technology 2010). Using this hand, a wide variety of object sizes and shapes can be handled without tool-changing interruptions, since the device can reconfigure itself very quickly.

It can be noted that the German robotics and automation company Schunk produces a “three-finger gripper hand with seven programmable degrees of freedom”, that looks relatively similar to the Barrett Hand (Schunk 2008). It is sold under the name SDH (Schunk Dextrous Hand, even though it doesn’t look like a hand and is unlikely to be dextrous). Their device looks a bit like a mix between the Barrett Hand and Skinner’s three-fingered gripper (see figure 3.57 in section 3.3.2).


Figure 3.79 – The Barrett Hand (1999). Also known as BH8, 8 for the number of axes.

**Mars and Sarah Hands** There are many other adaptive grippers than the Barrett Hand and its look-alikes. In particular, the robotics laboratory of Laval University in Québec, Canada is famous for its expertise in underactuated hands and grippers. Figures 3.81 and 3.82 show two of their experimental accomplishments in this domain, the Mars and Sarah Hands.

The Mars Hand was developed in the mid-1990s, with objectives of robustness and grasp versatility for tasks in industrial hostile environments. Twice the size of the human hand, heavy, and strong, this gripper has twelve degrees of freedom and six electric motors: three for the closing/opening of the fingers and three for orienting the fingers. It is equipped with tactile sensors and is capable of a variety of power and precision grips (Laliberté and Gosselin 1998; Gosselin and Laliberté 1998, 2006; Laliberté, Birglen, and Gosselin 2002; Laval University Robotics Laboratory 2010).

Its successor, the Sarah Hand, is slightly smaller and much lighter, and features an important reduction in the number of actuators, through the use of more complex

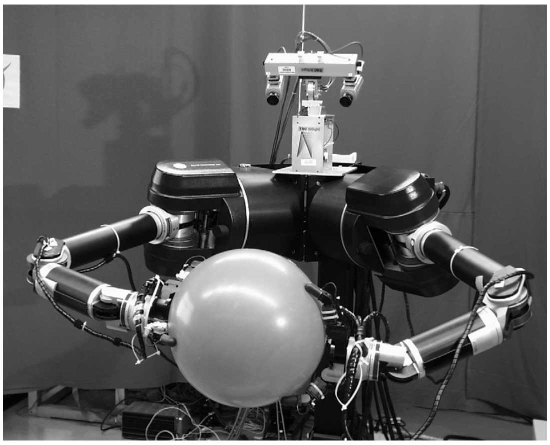


Figure 3.80 – The robot Dexter, at the University of Massachusetts, is a platform for studying bi-manual dexterity. Its limbs are Barrett Arms with Barrett Hands at the end.

underactuation mechanisms: only two electric motors are needed for ten degrees of freedom and the same mobility as the Mars Hand. One actuator opens and closes the fingers, the other one changes their orientation to achieve different grip patterns (Rubinger, Fulford, Gregoris, Gosselin, and Laliberté 2001; Rubinger, Brousseau, Lymer, Gosselin, Laliberté, and Piedbœuf 2002; Laliberté and Gosselin 2001, 2003, 2009; Laliberté, Birglen, and Gosselin 2002; Myrand and Gosselin 2004; É. Martin, Lussier-Desbiens, Laliberté, and Gosselin 2004; Laval University Robotics Laboratory 2010). This highly underactuated adaptive gripper was developed in the late 1990s, in collaboration with the Canadian Space Agency, to be an end effector for Dextre, the two-arm telemanipulator that can be hooked up to Canadarm-2 on the International Space Station (see figure 3.8(a) in section 3.1.2). Another version was developed for general purpose, and it was also adapted into a gripper for cleaning nuclear sites, for the United Kingdom Atomic Energy Authority, in the mid-2000s (Gosselin and Laliberté 2010; Laval University Robotics Laboratory 2010).

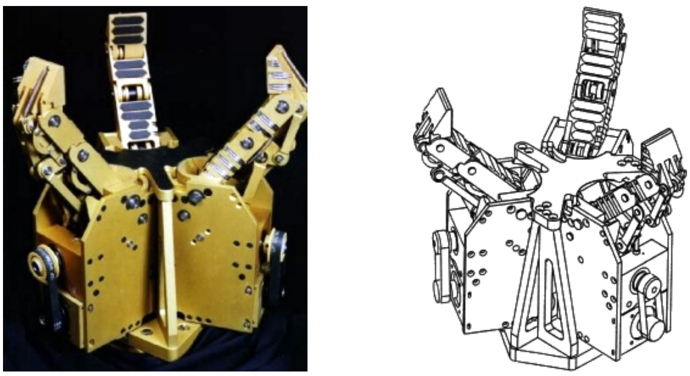


Figure 3.81 – The Mars Hand (1996). The name stands for “main articulé robuste sous-actionnée”, French for “robust underactuated articulated hand”. From Laval University Robotics Laboratory (2010).

**Other adaptive grippers** Figure 3.83(a) illustrates a three-fingered articulated gripper developed in the early 1990s at the University of Poitiers in France, and

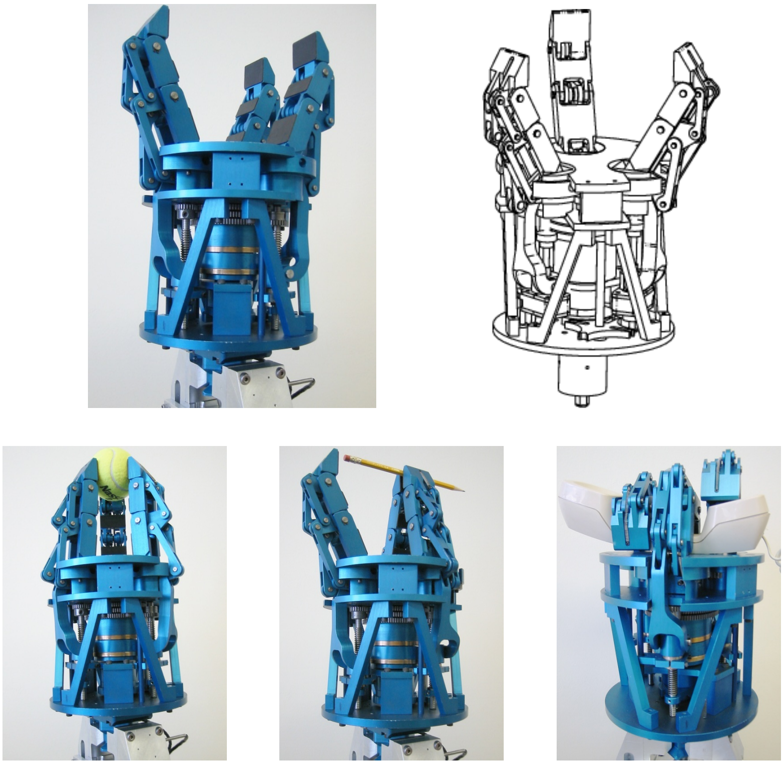




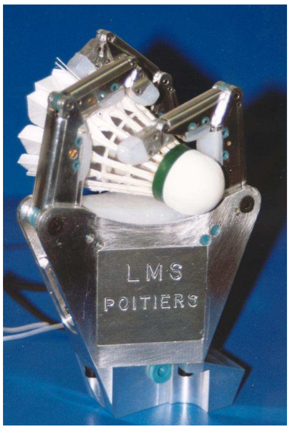
Figure 3.82 – The Sarah Hand (1999). The name stands for "self adaptive robotic auxilary hand". The linkage-based underactuation mechanisms are visible on the back of each finger. From Laval University Robotics Laboratory (2010).

figures 3.83(b) to 3.85 show a few more recent underactuated grippers. Figure 3.83(b) shows the Twix Hand, a two-fingered adaptive gripper developed at the University of Montpellier in France (Bégoc, Krut, Dombre, Durand, and Pierrot 2007a,b). Figure 3.84 shows the SDM Hand, an adaptive gripper from Harvard University in Cambridge, Massachusetts (Dollar 2006; Dollar and Howe 2005, 2006a,b, 2007, 2009, 2010; Dollar, Jentoft, Gao, and Howe 2010). The Delft Hand series, from Delft University of Technology in the Netherlands, is illustrated on figure 3.85 (Meijneke and Wilbers 2009; Meijneke, Kragten, and Wisse 2011; Kragten 2011; Kragten, Meijneke, and Herder 2011).

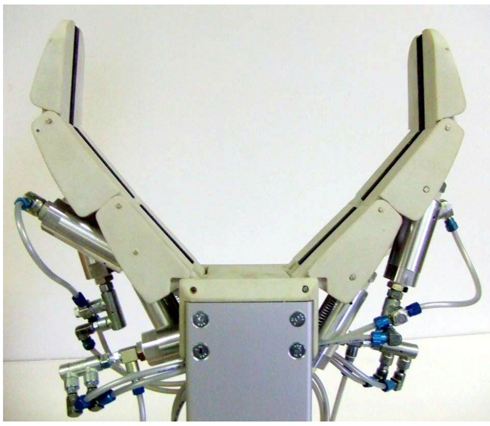
### Adaptive hands

All the aforementioned adaptive grippers are called "hands", but this is a misnomer since they don't really look like hands. Strictly speaking, they are multifingered, articulated, underactuated, adaptive, non-dextrous, non-anthropomorphic grippers. Adaptive hands share the same characteristics, except for the anthropomorphism: they look more like human hands. For instance, prosthetic hands are typically adaptive hands, independently of their actuation (body-powered or externally-powered). We reviewed a lot of them in section 3.2. The Belgrade/USC Hand is also an adaptive hand. It was developed in the late 1980s and we described it in section 3.3.2.

**Crowder Hand** At about the same time as the introduction of the Belgrade/USC Hand, Richard Crowder from the University of Southampton proposed an adaptive

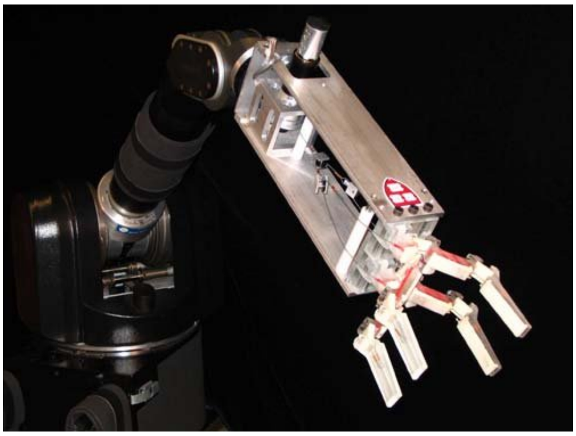


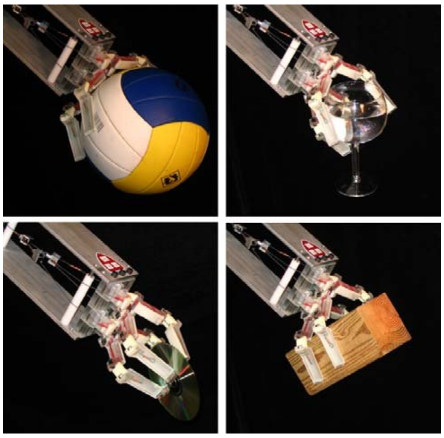

(a) An adaptive three-fingered hand with three phalanges per finger and one actuator for the whole device, developed at the University of Poitiers (1991). From Zeghloul, Arsicault, and Gazeau (2007).

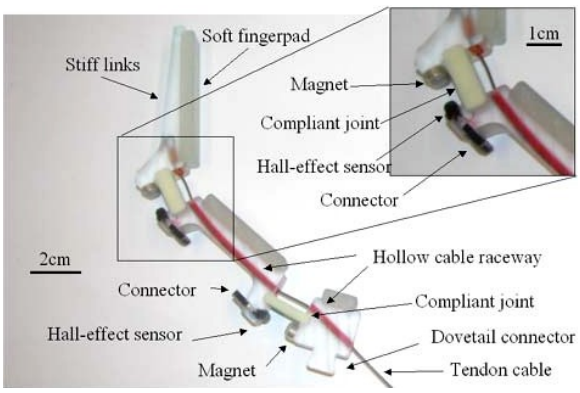


(b) The Twix Hand, made at the University of Montpellier (2007). Each phalanx is actuated by its own air cylinder, but all cylinders are connected to the same source of pressured air, hence the underactuation. The gripper is probably named after the Twix candy bars, shaped like fingers and sold in pairs. From Bégoc, Krut, Dombre, Durand, and Pierrot (2007a).

Figure 3.83 – Articulated grippers from two French laboratories

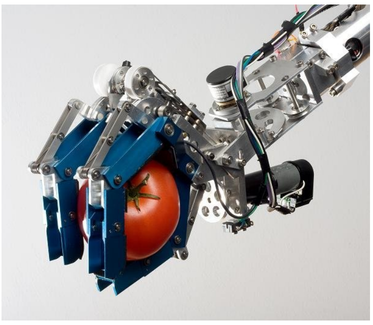




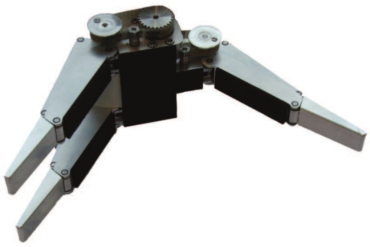



SDM means "shape deposition manufacturing", a technique of rapid prototyping used to manufacture the fingers. They are made all in one piece by the deposition of successive layers of polymeric materials: stiff polymers to create hard links and soft polymers to create fingerpads and compliant joints (elastomeric flexures). Sensing and actuation components are embedded in the fingers during their fabrication. The whole gripper is robust, lightweight, inexpensive, very compliant, and highly underactuated: one single actuator for eight joints.

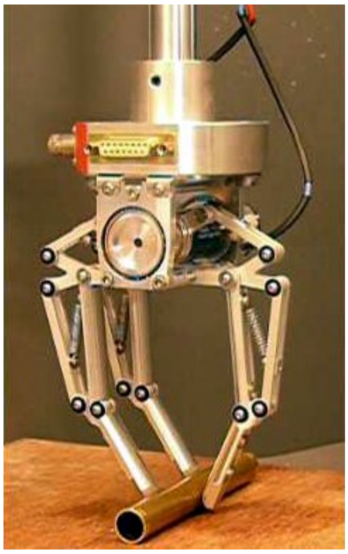
Figure 3.84 – The SDM Hand (2006). From Dollar and Howe (2006b).



Delft Hand 1 (Meijneke and Wilbers 2009)



Delft Hand 2 (Meijneke, Kragten, and Wisse 2011)



Delft Hand 3 (Kragten 2011)

These articulated grippers have six degrees of freedom, one single low-wattage actuator, and no sensors. The underactuation mechanism and the weakness of the actuator mean that the grasp doesn't damage the object, so the technology has been adapted by a Dutch company into a gripper for pick and place tasks of fruits and vegetables in the food industry (Lacquey 2011).

Figure 3.85 – The Delft Hands (respectively 2009, 2010, 2011).

anthropomorphic hand for a robot manipulator meant to work using a glove box in the nuclear industry (Crowder 1987, 1991a,b; Crowder and Whatley 1989). Since the gloves are human-sized, anthropomorphism of the end effector was a design requirement. The hand is illustrated in figure 3.86. It has four articulated adaptive fingers and a one-piece thumb in "pseudo-opposition". Three motors and their gearboxes are in the palm, with connections to the finger segments through mechanical linkages. At the time of its construction, the University of Southampton had already developed a range of adaptive finger mechanisms, and built the underactuated prosthetic Southampton Hand. The robotic hand was based upon this work, and indeed it looks like the Southampton Hand (compare with figure 3.35(b) in section 3.2.4). Subsequent to this hand, the finger design was modified again for the development of a three-fingered non-anthropomorphic gripper intended to work in nuclear reactors (Dubey, Crowder, Chappell, and Whatley 1997; Crowder, Dubey, Chappell, and Whatley 1999; Dubey and Crowder 2002, 2004).

**TUAT/Karlsruhe Hand** Another typical adaptive hand is the TUAT/Karlsruhe Hand, illustrated in figure 3.87. It was developed in 2000 at the Tokyo University of Agriculture and Technology in Japan (Fukaya, Toyama, Asfour, and Dillmann 2000, 2001), for the humanoid robot Armar that had just been introduced by the University of Karlsruhe [48] in Germany (Asfour, Berns, and Dillmann 1999, 2000). This hand has as much as twenty-one degrees of freedom, but it is driven by only one actuator through a flexor tendon and several yoke-like coupling beams. Nevertheless, it is

48. Now Karlsruhe Institute of Technology, after the merge with the Forschungszentrum Karlsruhe.

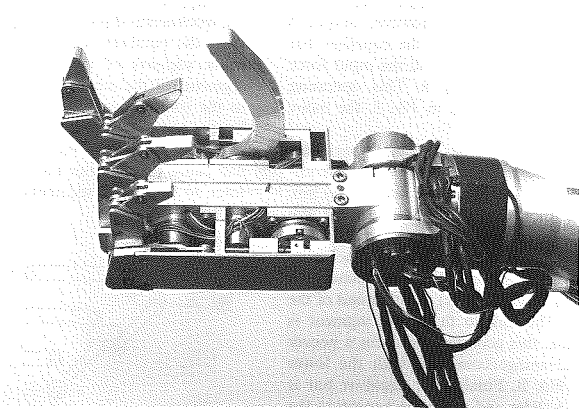


Figure 3.86 – Crowder's hand for a glove box manipulator (1987)

capable of the six basic grasp types identified by Schlesinger (1919) (see figure 2.36 in chapter 2, section 2.2, and photographs of the hand in action in the above-cited references). A unique feature is the articulation of the palm, which is not a one-piece segment: all five metacarpals are individualized, and they are connected and coupled together by one-degree-of-freedom joints that emulate the (limited) intermetacarpal mobilities of the human hand (see chapter 2, section 2.1.1 for bone and joint anatomy of the human hand). The thumb metacarpal is connected to the index metacarpal by a two-degree-of-freedom joint though, to reproduce the carpometacarpal mobility. More generally, the TUAT/Karlsruhe Hand was designed for anatomical consistency with the human hand in "the number of fingers, the placement and motion of the thumb, the proportions of the link lengths and the shape of the palm". Visual appearance was probably a minor concern as the result looks more like a hand skeleton than a hand.

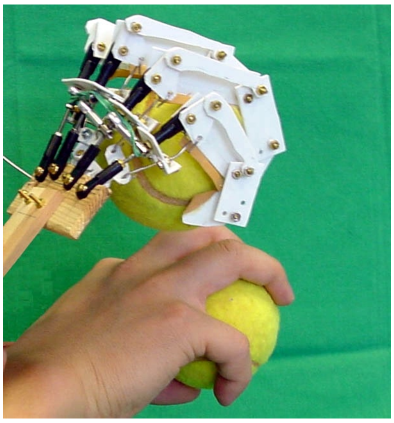


Figure 3.87 – The TUAT/Karlsruhe Hand (2000). The intermetacarpal joints are clearly visible, and the actuator tendon is also visible on the left.

**FRH-4 Hand** The humanoid robot Armar does not use TUAT/Karlsruhe Hands any more. Instead, its present-day version, Armar III, uses two FRH-4 Hands, which are five-fingered humanoid hands actuated by air bellows, the "flexible fluidic actuators" developed at the Forschungszentrum Karlsruhe [49] and already used in the

49. Now Karlsruhe Institute of Technology, after the merge with the University of Karlsruhe.

prosthetic FluidHand (see figures 3.42 and 3.43 in section 3.2.4, and also figure 3.11(b) in section 3.1.3). FRH-4 Hands have eleven degrees of freedom: two for each digit and one for the palm; but those of the ring and little fingers are coupled, so there are only eight independent degrees of freedom. The hands are very versatile in their grasping abilities, but dextrous in-hand manipulation remains difficult with only eight controlled degrees of freedom, so they qualify as adaptive hands, not dextrous hands. A characteristic feature is their regular kinematic structure: the fingers are parallel, the joints are equally spaced, and the thumb is mounted opposite of the fingers exactly in the middle between the index and middle fingers. This arrangement makes the programmation of grasping patterns easier and allows the first three digits to behave like a three-jaw gripper, making the hand a hybrid between a humanoid hand and a robotic gripper. A FRH-4 Hand is illustrated in figure 3.88, the description of its hardware is given by Gaiser, Schulz, Kargov, Klosek, et al. (2008), and its force and position control is explained by Bierbaum, Schill, Asfour, and Dillmann (2009). See Schulz, Pylatiuk, Kargov, Oberle, and Bretthauer (2004a,b), Kargov, Asfour, Pylatiuk, Oberle, Klosek, Schulz, Regenstein, Bretthauer, and Dillmann (2005), and Kargov, Pylatiuk, Klosek, Oberle, Schulz, and Bretthauer (2006) for information about the previous hands used by Armar robots (all based on flexible fluidic actuators), and see Morales, Asfour, Azad, Knoop, and Dillmann (2006), Vahrenkamp, Wieland, Azad, Gonzalez, Asfour, and Dillmann (2008). Also, see Asfour, Azad, Vahrenkamp, Regenstein, Bierbaum, Welke, Schröder, and Dillmann (2008) for a description of the high-level grasp control architecture and results of grasping and mobile manipulation in a kitchen environment.

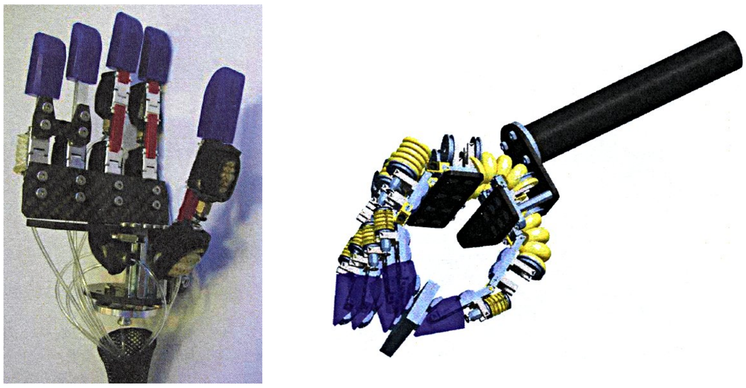
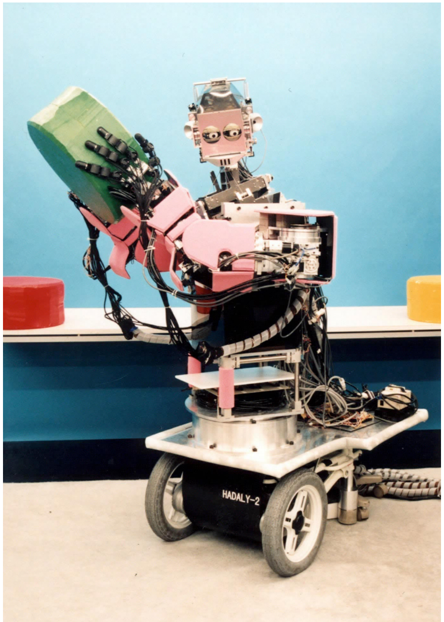


Figure 3.88 – FRH-4 Hand (2008). The picture on the right illustrates the three-jaw gripper behavior. We are left to think that FRH stands for "fluidic-driven robotic hand".

**Adaptive hands for humanoid robots** The fact that the hands of Armar III are adaptive hands, not dextrous hands, is actually very common for humanoid robots. As a matter of fact, most current humanoid robots have such hands. This is the case, for instance, of Hadaly-2 and Wendy, two 1990s wheeled half-humanoids built at Waseda University in Tokyo and pictured in figure 3.89. It is also the case of Asimo by the Japanese company Honda (2011), the HRP series by Japan's National Institute of Advanced Industrial Science and Technology (AIST 2010) and Kawada Industries (2010), the Hubo series by the Korea Advanced Institute of Science and Technology (KAIST 2011), the Mahru and Ahra robots by the Korea Institute of Science and Technology (KIST 2008), the small humanoids Nao by French company

Aldebaran Robotics (2011) and UiNiKi by the University of Poitiers in France, the toy robot RoboSapien v2 by Hong Kong company WowWee (2011), and Topio and Topio Dio by Vietnamese company Tosy Robotics (2011). All these robots (and others) have humanoid adaptive hands, described in figures 3.90 to 3.93, and also in figures 3.11(a) and 3.11(d), section 3.1.3.




Hadaly-2 (left) is approximately 170 cm tall and weights about 180 kg. Its name is derived from that of a female humanoid in *L'Ève Future* (*The Future Eve*), a nineteenth-century symbolist novel by the French author Auguste Villiers de l'Isle-Adam (1886), and a seminal work of science fiction. The robot was completed in 1997 (T. Morita, Shibuya, and Sugano 1998).

Its hands have four fingers and thirteen degrees of freedom each, but only one actuator, an AC servomotor. The thumb has four degrees of freedom like the human thumb, and the fingers have three degrees of freedom each (no distal interphalangeal joint). "At the base of each finger are six-axes force/torque sensors for whole finger compliance control, [enabling] physical interactions with humans, such as shaking hands and handing objects over" (S. Hashimoto, Narita, Kasahara, Shirai, Kobayashi, Takanishi, Sugano, et al. 2002).

Wendy (Waseda ENgineering Designed sYmbiont, right) was developed in 1999 by improving Hadaly-2, with an emphasis on human/robot interaction. Its performances were evaluated by "experiments of object transport and egg breaking, which require high level integration of the whole body system" (T. Morita, Iwata, and Sugano 1999).

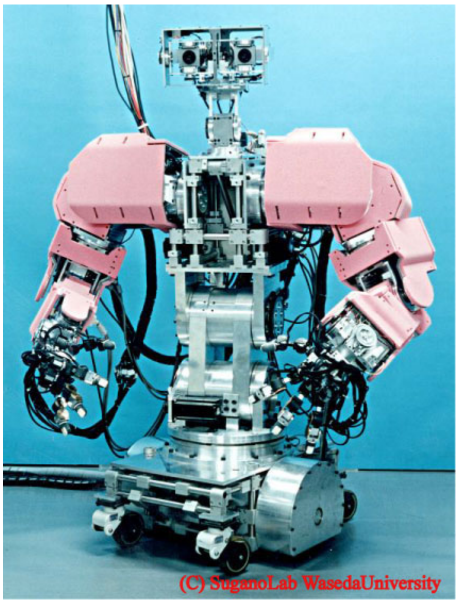
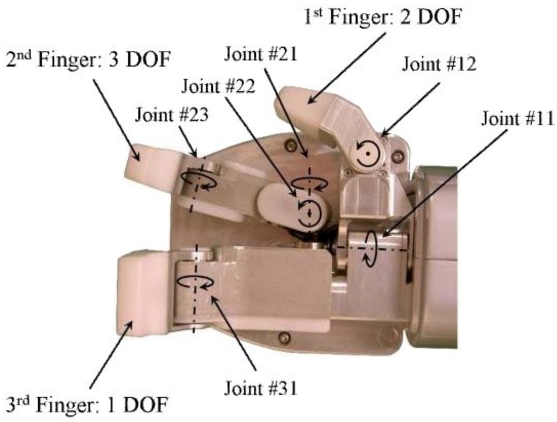




Figure 3.89 – Hadaly-2 and Wendy (1997, 1999). Waseda University has one of the longest histories on humanoid robotics, starting in the early 1970s with the development of Wabot-1 (Waseda Robot 1). This activity was initiated by Ichiro Kato, a pioneer of Japanese robotics.


On the left, the current version of Asimo, introduced in 2005. It is 130 cm tall and weights 54 kg (Honda 2011). The first version was introduced in 2000, after fourteen years of research and ten experimental prototypes (Hirose, Haikawa, Takenaka, and Hirai 2001; Sakagami, R. Watanabe, Aoyama, Matsunaga, Higaki, and Fujimura 2002; Honda 2011). Officially, the name is not a reference to Isaac Asimov, and means instead "Advanced Step in Innovative Mobility". It is pronounced "ashimo", which is a pun because it means "feet, too" in Japanese.

Asimo's hands have five digits and independent opposable thumbs. Their payload is 300 g each and up to 1 kg using both hands. There are two degrees of freedom per hand: thumb and fingers. The first version had only one degree of freedom.

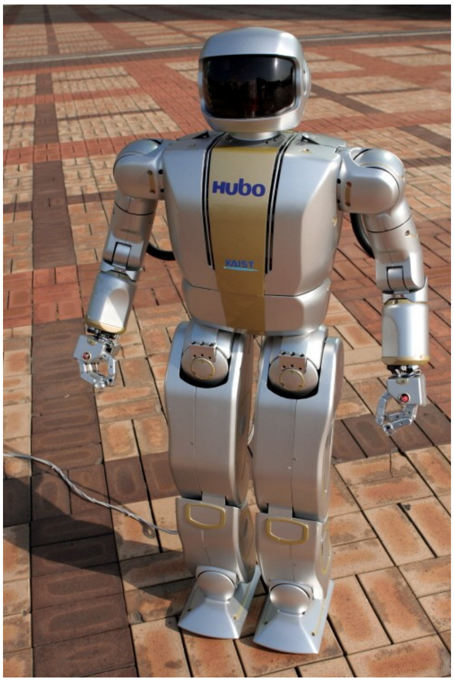
On the right, the palm view of the right hand of HRP-3: three fingers, six degrees of freedom (K. Kaneko, Harada, Kanehiro, Miyamori, and Akachi 2008). It is an evolution towards dexterity since the prototype version HRP-3P had three-degree-of-freedom hands (Akachi, K. Kaneko, Kanehira, Ota, Miyamori, M. Hirata, Kajita, and Kanehiro 2005), and the previous version HRP-2 had one-degree-of-freedom grippers performing only "discouragingly limited" application tasks (K. Kaneko, Kanehiro, Kajita, Hirukawa, T. Kawasaki, M. Hirata, Akachi, and Isozumi 2004).




K. Kaneko, Harada, and Kanehiro (2007) had even developed a multifingered dextrous hand for this robot, with four fingers and seventeen joints (thirteen active joints, four linked joints). But it was considered premature to adopt this hand into the final product. Besides, the development schedule was too tight to make it waterproof and dustproof (a design goal of HRP-3), and its cost was also an issue (K. Kaneko, Harada, Kanehiro, Miyamori, and Akachi 2008).

HRP means "Humanoid Robotics Project"; it was launched in 1998 and supported for five years by the Ministry of Economy, Trade and Industry of Japan.

Figure 3.90 – Japanese humanoid robotics: hands of Asimo and HRP-3



On the left, a Hubo KHR-4. Hubo is short form for "humanoid robot" and KHR means "KAIST Humanoid Robot". KHR-4 is the current version: the first Hubo was KHR-3 (I.-W. Park, J.-Y. Kim, J. Lee, and J.-H. Oh 2005, 2007). Unlike the proprietary Asimo, Hubo was developed as a research platform, and KAIST is more willing than Honda to share the mechanical details and source code of its robot for research purposes.

Hubo KHR-3 is 125 cm and 56 kg; Hubo KHR-4 is 130 cm and 45 kg. Each hand has five independent anthropomorphic fingers actuated by five servomotors through tendons. There is only one extrinsic sensor per hand, a strain-gauge-based three-axis force/torque sensor located at the wrist (KAIST 2011).

Two identical PC/104 embedded computers with solid state hard disks are installed in Hubo's chest; one is for walk and motion control and the other is for speech, vision and navigation algorithms (Guizzo 2010). On the contrary, Mahru and Ahra are "network-based humanoids" in the sense that most of the actual processing is not embedded, but occurs on external computers over the network (KIST 2008).

The picture on the right shows Mahru III, introduced in 2007 (W. Kwon, H. Kim, J. K. Park, C. H. Roh, J. Lee, J. Park, W.-K. Kim, and K. Roh 2007). The previous versions Mahru II and Ahra II were introduced in 2005 (You, Y.-J. Choi, Jeong, D. Kim, Y.-H. Oh, C.-H. Kim, J.-S. Cho, M. Park, and S.-R. Oh 2005; You, D. Kim, C.-H. Kim, Y.-H. Oh, Jeong, and S.-R. Oh 2008). The whole humanoid is 150 cm tall and weights 62 kg; each hand has five fingers and eight degrees of freedom. The names Mahru and Ahra have a meaning similar to "male" and "female" in Korean. Both robots are similar, with differences in color, programmed interactions, and artificial voice.

Figure 3.91 – Korean humanoid robotics: Hubo and Mahru

(a) The toy robot RoboSapien v2 and its oversized four-fingered articulated hands. Released in 2005, it is 56 cm tall and weights 3.6 kg (WowWee 2011).

(b) Small four-fingered hand for the 70 cm humanoid robot UiNiKi of the University of Poitiers, France (Zeghloul, Arsicault, and Gazeau 2007). The hand has one actuator.

Figure 3.92 – Articulated hands of two mini-humanoids: RoboSapien v2 (toy) and UiNiKi (research)

Figure 3.93 – Vietnamese robot Topio Dio at the robot fair where it was introduced (Munich, Germany, 2010). It is a small three-wheel humanoid, 125 cm, 45 kg, with five-fingered hands. It is envisioned as a service robot acting as waiter or bartender (Tosy Robotics 2011). Little information is available at the moment.

The humanoid robots that don't have adaptive hands usually have even simpler end effectors [50], but a few exceptions are worth mention: the hands of the robots Twendy-One by Waseda University, Reem-B by Spanish company PAL Robotics, and iCub by the European project RobotCub are articulated and actuated enough to exhibit some dextrous manipulation abilities. However, apart from one particular instance of fingertip manipulation performed by Twendy-One, there is no record of these robots conducting complex, significant multifingered manipulations; only adaptive and versatile grasping have been reported at the moment. This is not the case of DLR's Justin and NASA's Robonaut, of course, which are to our knowledge the only humanoid robots [51] equipped with "fully dextrous" humanoid hands, that is to say, hands dextrous both in structure and control. The hands of these five robots are described further, with the other dextrous hands.

### Dextrous grippers

Just like humanoid hands are not necessarily dextrous, non-anthropomorphic grippers are not necessarily clumsy and limited to grasping. Some of them are capable of dextrous manipulation; they are called dextrous grippers.

Unlike adaptive grippers, dextrous grippers are not underactuated. Most of their joints, if not all, are active, that is to say there are about as many actuators as degrees of freedom. That, and adequate control, is the reason of their dexterity.

So dextrous grippers are able to perform internal manipulations just like the human hand, only without the human-like structure and motion. Actually, from the roboticist standpoint, the non-anthropomorphic structure has a good side: instead, dextrous grippers have usually a symmetric structure which simplifies planning and control. Because of these specific design and optimized control, some dextrous grippers can even exceed the human hand at certain specific actions; this is the case, for instance, of the High Speed Multifingered Hand.

A typical example of dextrous gripper is the Stanford/JPL Hand: its fingertip dexterity is high and its anthropomorphism is low. It was developed in the early 1980s and we described it in section 3.3.2. Other dextrous grippers were developed afterwards, in particular in Europe in the 1990s. They are often simply named after their university of origin, and called "hands" in spite of their non-anthropomorphic structure: the Karlsruhe Dextrous Hands, the Leuven Hand, the Darmstadt Hand, the TUM Hand (Munich), and the Teleman Dextrous Gripper (Delft). More recently, the High Speed Multifingered Hand was developed in Japan. We give here some general information about each of these grippers.

**Karlsruhe Dextrous Hands** The first Karlsruhe Dextrous Hand, and its control strategies, were developed in the late 1980s and during the 1990s at the University of Karlsruhe [52] in Germany (Doll 1987, 1989; Doll and Schneebeli 1988; Wöhlke

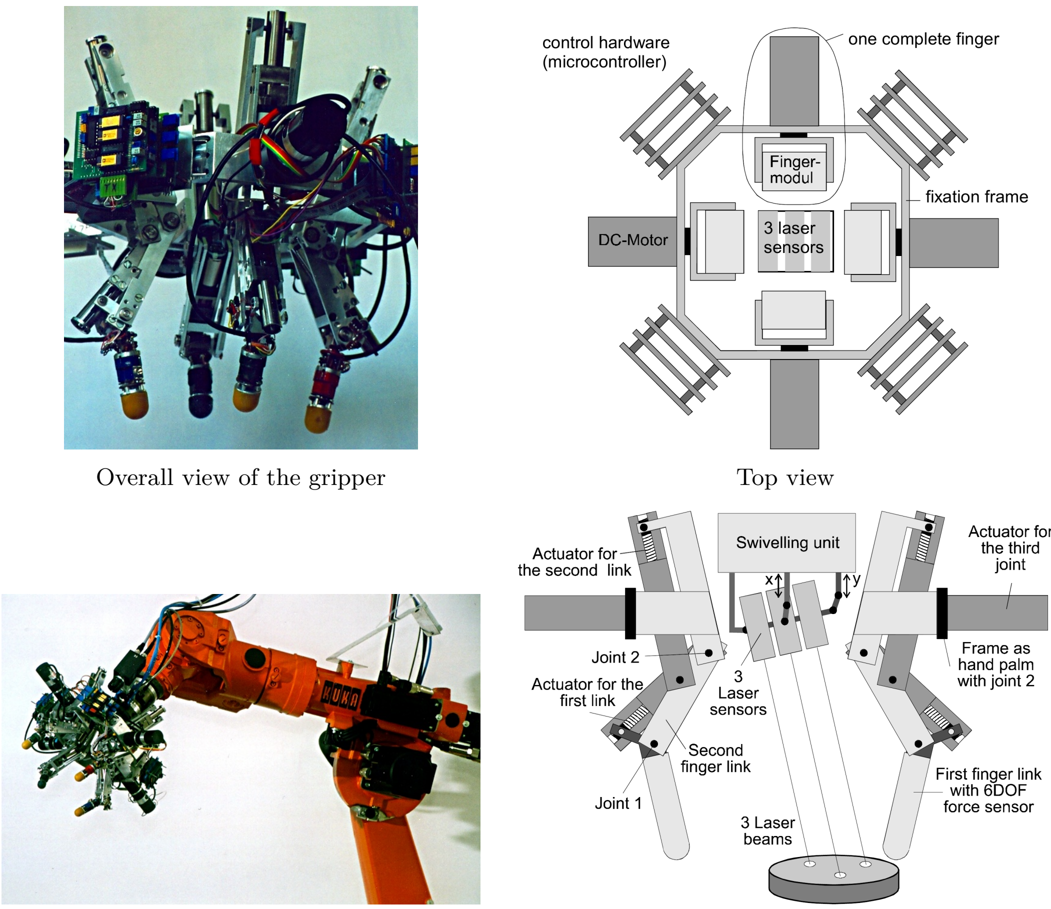
50. For instance, some humanoid robots are equipped with simple non-articulated grippers (e.g. WowWee's toy robot RoboSapien v1). Others have single-purpose low-degree-of-freedom humanoid hands, for instance for playing a particular musical instrument in public demonstrations, or grasping a marker pen (e.g. Toyota Partner Robots, see TPR-Robina in figure 3.11(c), section 3.1.3). And those that are not supposed to grasp anything have only cosmetic hands (e.g. Mitsubishi's Wakamaru), or nothing at all (e.g. Flame by Delft University of Technology, Lara by Darmstadt University of Technology).

51. Half-humanoid to be precise, they have no lower limbs.

52. Now Karlsruhe Institute of Technology.

1990, 1992, 1994; Magnussen and Dörsam 1995; Dörsam and T. Fischer 1998). It is a non-anthropomorphic three-finger dextrous gripper with nine degrees of freedom. The three fingers are identical and each finger has three links and three degrees of freedom. All the joints are actuated: DC electric motors, reduction with harmonic drives, transmission with belts. Sensorization is quite classical, with potentiometers for joint positions and strain gauges and tactile sensors for fingertip forces, also there is a distance sensor in the palm. The goal of this project was to investigate dextrous fingertip manipulation, in particular task-oriented approaches.

In the mid-1990s a new Karlsruhe Dextrous Hand was built with an additional finger to study regrasping motions (T. Fischer and Seyfried 1997; T. Fischer and Wörn 1998; Osswald and Wörn 2001). It is indeed difficult to regrasp objects with only three fingers, given that two-finger grasps (when the third finger is changing contact location) require a lot of friction and large contact areas. The Karlsruhe Dextrous Hand II is illustrated in figure 3.94. Aside from the fourth finger, a few other things change compared to the Karlsruhe Dextrous Hand I, for instance, placement of the actuators on the phalanges and direct drive of the joints. An example of manipulation with regrasping performed by the hand is given in figure 3.95; it illustrates fairly well the notion of dexterity for non-anthropomorphic grippers.




Overall view of the gripper — Top view

Gripper mounted on a robot arm — Side view

Figure 3.94 – The Karlsruhe Dextrous Hand II (1997).
From Osswald and Wörn (2001).

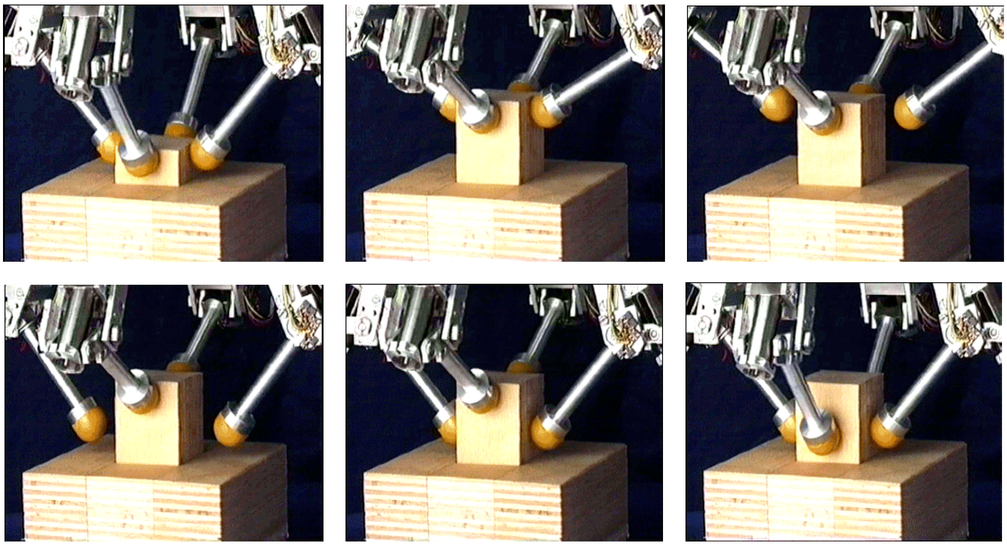


Figure 3.95 – Translation with regrasping: the Karlsruhe Dextrous Hand II pulling of a peg out of a hole (Osswald and Wörn 2001)

**Leuven Hand** This dextrous gripper was developed at the Catholic University of Leuven in Belgium, in the late 1980s like the first Karlsruhe Dextrous Hand. It was introduced by Hendrik van Brussel, Budi Santoso, and Dominiek Reynaerts (1989) at a conference on space telerobotics organized by NASA in the United States. The aim of the Belgian roboticists was "to build a dextrous multifingered gripper with extensive grasping and manipulative capabilities, with a limited computer budget, as is common for space applications". More precisely, they wanted "to demonstrate that a multifingered gripper provided with force sensor feedback, even when using a rather small controlling computer, really can perform the desired manipulative dexterity" (Brussel, Santoso, and Reynaerts 1989).

And indeed, the control strategy, a three-level hierarchically structured scheme (finger controller, hand controller, task controller), is implemented on a simple IBM Personal Computer/AT. The construction is simple and non-anthropomorphic, with three identical fingers and nine degrees of freedom in total (figure 3.96). Miniature motor drive systems are embedded into the fingers to suppress transmission mechanisms, and the hand makes use of incremental position encoders attached to the axis of every motor and three-axis force sensors using strain gauges in every finger.

Basically, "each finger of the robot hand is controlled as an active stiffness system, where the finger tips are programmed as two linear springs (vertical and radial) and one rotational spring" (figure 3.96). This is the task of the finger controller. The hand controller coordinates the position of all the fingers in order to move the object (actually, the contact plane, formed by the contact points) according to the operations described by the task controller. The resulting manipulative dexterity of the gripper was experimentally demonstrated by the translation and the rotation of an egg in any direction in space (subject to the limited workspace of the gripper of course), and also by a peg-in-hole insertion.

**Darmstadt Hand** The Darmstadt Hand was developed and built at the Darmstadt University of Technology, Germany, by Wolfgang Paetsch and Makoto Kaneko (1989, 1990). Like the contemporary Karlsruhe Dextrous Hand I and Leuven Hand, it is a

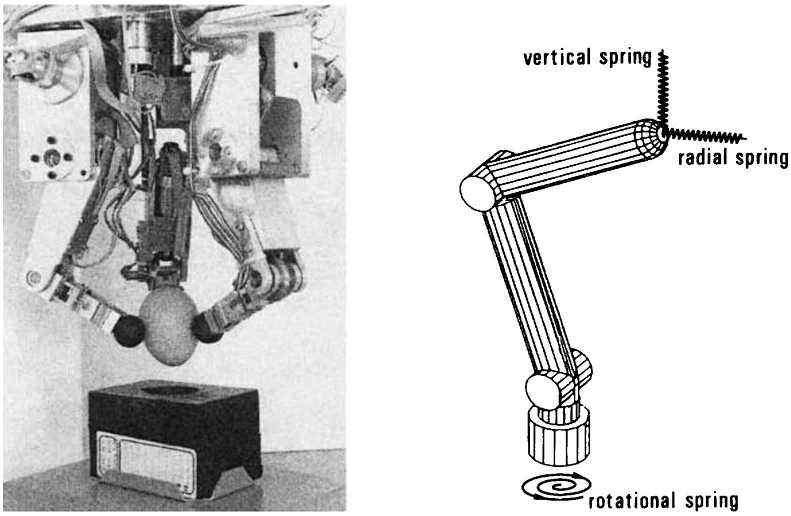



Figure 3.96 – The Leuven Hand (1989) and a schematic representation of the low-level control of a finger

three-fingered multijointed gripper that was mounted on a robot arm; figure 3.97 shows the gripper. It was used to "develop and evaluate different approaches of stable grasping and object manipulation". Larger than a human hand, it is capable of both fingertip and power grasps. Experiments about grasping and object motion are reported by Paetsch and M. Kaneko (1990), Paetsch, Krug, and Tolle (1991), and Paetsch, Buck, Weigl, and Tolle (1993); in particular, peg-in-hole insertion tasks were experimented by Paetsch and Wichert (1993) and Kleinmann, Bettenhausen, and M. Seitz (1995). Kleinmann, Hormel, and Paetsch (1992) present a grasp control approach based on artificial learning, "able to maintain a stable grasp even if disturbances are applied", and Paetsch and Weigl (1993) investigate the integration of the hand into a hand/arm system, by coordinating stiffness control approaches for both hand and arm subsystems.

Figure 3.97 – The Darmstadt Hand (1989)

**TUM Hand** This multifingered dextrous gripper was developed at the Munich University of Technology in the early 1990s (TUM stands for Technische Universität München). It consists of three to four identical fingers, approximately human-sized, laid out symmetrically on a hand palm, and driven by a hydraulic system sensorized with piston potentiometers and oil pressure sensors (figure 3.98). Each finger has three joints and three degrees of freedom: one combined degree of freedom for the distal joints and two degrees of freedom at the proximal joint, which is quite an anthropomorphic configuration actually. The hand's hardware, low-level control, and high-level grasp strategies are described in detail by Roland Menzel, Kurt Woelfl, and Friedrich Pfeiffer (Menzel, Woelfl, and F. Pfeiffer 1993, 1994; Menzel 1994; Woelfl 1994; Woelfl and F. Pfeiffer 1994; F. Pfeiffer 1996). The TUM Hand was used for experiments in grasping and manipulation research: manipulation primitives (object rotations and translations) and regraspings are reported. More recently, roboticists at Bielefeld University (Germany) used a modified TUM Hand to test and validate a grasp strategy, and compare with a Shadow Dextrous Hand (Röthling, Haschke, Steil, and Ritter 2007).

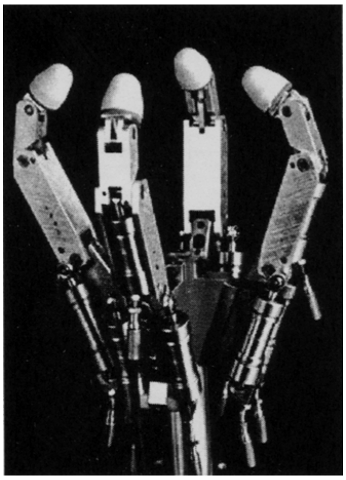


Figure 3.98 – The TUM Hand (1993)

**Teleman Dextrous Gripper** Unlike the previous devices, which were research platforms or concept proofs, this dextrous gripper developed at Delft University of Technology was meant for practical application in a nuclear environment. It is twice the size of a human hand and has a three-fingered concentric design with an active palm in the middle. The palm also features a tool adaptor "to extend the gripper abilities by drilling, screwing", and so on (Jongkind 1993a, page 28). The gripper, illustrated in figure 3.99, is originally described by Jongkind (1993a,b), Ham, Holweg, and Jongkind (1993), and Ham (1997, chapter 2). It is sometimes referred to as the "Delft Hand" in the scientific litterature, with a risk of confusion with the articulated adaptive grippers of the same name (figure 3.85).

The nature of the intended application environment restricts the choice of actuators, sensors, and electronics. Indeed, the gripper "is required to tolerate radiation, heat, corrosive chemicals, water, steam, dust, electromagnetic interference, vibration and contamination" (Jongkind 1993a, page 19). Thus the gripper was chosen to feature water hydraulic actuators, infrared proximity sensors, and inductive position and force sensors (linear variable differential transformers). Also, "no semiconductor-based electronics [is] allowed on the gripper because of its sensitivity to radiation" (Jongkind 1993a, page 22).

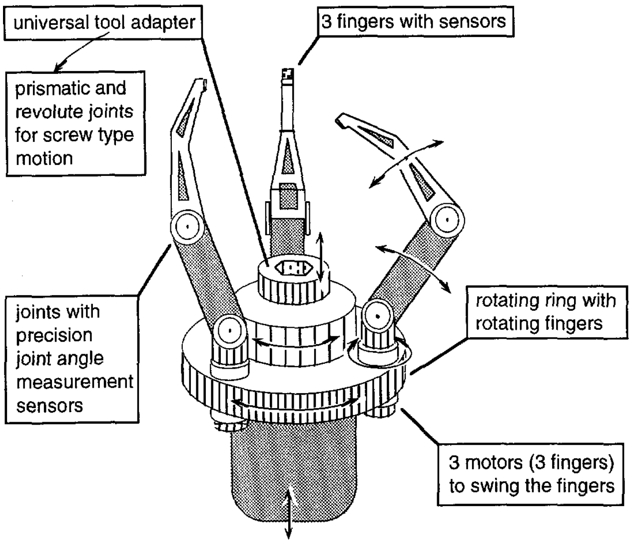



Figure 3.99 – A drawing of the Teleman Dextrous Gripper (1993) and its degrees of freedom. From Ham (1997, page 14).

Besides, the nuclear environment also influences the control strategy: although all the joints of the gripper are independently actuated, “the emphasis is placed on the safety, security and stability of grasps” (Jongkind 1993a, page 19), rather than on dexterity in manipulation. Indeed, the unstructured nature of the robot environment after a nuclear accident requires that the gripper be able of versatile and secure grasping; dextrous manipulation is not a priority. Still, the independent control of the 11 degrees of freedom of the gripper makes it potentially dextrous.

The gripper was meant as a semi-autonomous teleoperated system, with “a task/motion planning system using artificial intelligence techniques [and] a lower control level which stabilizes the grasping action”, and also “a manual control system which [incorporates] a bilateral master/slave controller” (Ham, Holweg, and Jongkind 1993).

**High Speed Multifingered Hand** This dextrous gripper, which looks a bit like a Barrett Hand but has more actuators and sensors, was built in the early 2000s at the University of Tokyo, Ishikawa/Oku Laboratory. Its key feature is the use of an extremely fast vision system and accordingly fast electric actuators. Thanks to these, grasping and manipulation can be achieved at speeds as high as and even higher than what we can do with our own hands.

The High Speed Multifingered Hand actually stems from the experience of the Ishikawa/Oku Laboratory with high frame-rate computer vision. Indeed, the researchers there were trying in the 1990s to overcome the low maximal frame-rate of conventional vision systems. At that time, most of these systems were using CCD [53] cameras for image sensing, and these devices output images at a video rate of 25 Hz or 30 Hz, depending on the norm (PAL or NTSC). Also, the video rate is limited anyway by the serial transmission of the video signal over a small number of lines, usually just one, from the CCD sensor to the image processing electronics. Indeed,

53. CCD stands for “charge-coupled device”. This kind of image sensor is used in astronomy, cameras, video cameras.

CCD sensors output their pixels sequentially, and the image information consists of a lot of pixels.

To settle this frame-rate issue, M. Ishikawa, A. Morita, and Takayanagi (1992) proposed an architecture where each photodetector in the image sensor is directly connected to a programmable processing element, containing 24 bits of local memory, capable of 8-bit arithmetic and logical functions, and able to communicate directly with four neighboring processing elements. Taken together, photodetectors and programmable processing elements realize a vision system which can perform a variety of image processing algorithms at extremely high speeds, because of the parallel transmission of the video signal (edge detection using four neighbors, for instance, can be done in a few microseconds).

The researchers implemented this concept with a $16 \times 16$ photodiode array as the image sensor and 256 processing elements integrated in groups of eight into 32 custom-made integrated circuits (Yamada and M. Ishikawa 1993; Ishii, Nakabo, and M. Ishikawa 1996; Nakabo, Ishii, and M. Ishikawa 1996). This first high-speed artificial vision system is illustrated in figure 3.100. Although it was limited to binary images (black and white) and had a low resolution ($16 \times 16$ pixels), it made it possible for the researchers to achieve high-speed tracking of a white object on a dark background, with high-speed visual feedback at a sampling period of 1 ms. That is to say, the image sensor is mounted on a motorized pan/tilt unit, visible in figure 3.100, and this unit is controlled at a 1 kHz servo rate to track the white object, with feedback about the position of this object coming from the high-speed vision system.

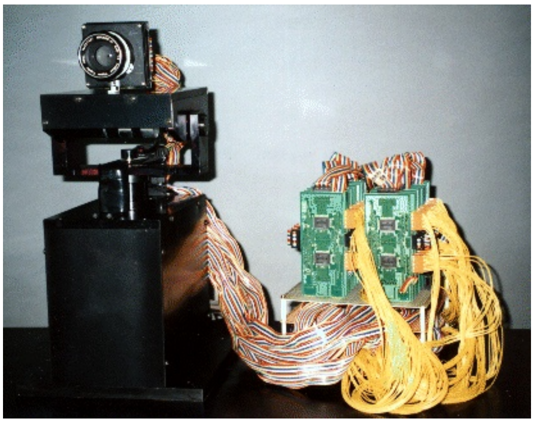


Figure 3.100 – First high speed vision system from the University of Tokyo, Ishikawa/Oku Laboratory. The image sensor, located on top of its pan/tilt unit, is connected to the processing electronics via parallel lines.

Also, this vision system was used as a subsystem in a larger system, illustrated in figure 3.101 and meant for high-speed grasping of objects (Namiki and M. Ishikawa 1996; Namiki, Nakabo, Ishii, and M. Ishikawa 1999b,a). This larger system consists of a seven-axis robot arm, a sensorized four-fingered robot hand, the high-speed vision system (image sensor and processing elements) and its active pan/tilt unit, and control electronics in the form of seven digital signal processors [54] and many input/output ports. The multifingered hand, which has fourteen joints actuated independently by

54. Digital signal processors are specialized microprocessors with an architecture optimized for the fast operational needs of digital signal processing.

DC servomotors via sheathed tendons, is equipped with potentiometers and strain gauges in each joint for position and torque control. The robot arm has joint position and joint torque sensors too, as well as a six-axis force/torque sensor installed at the wrist. The large quantity of sensory information coming from the arm, the hand, and the vision system is inputed and processed by the control electronics, which then output control values for the actuators of the arm, hand, and pan/tilt unit. All this sensory integration and motor control is done at a rate as high as the rate of the vision system, 1 kHz, hence the name of the whole system: a "1 ms sensory-motor fusion system". The result of this architecture is a robot controlled with high-speed visual, position and force feedback, responsive and adaptive in real time to dynamic changes in the environment. It was demonstrated that the robot was able to reach for and grasp a white object placed in front of it by an operator, in a split second, with the hand pre-shaping the fingers differently whether the object is recognized as a sphere or a box by the image processing algorithms (figure 3.102).

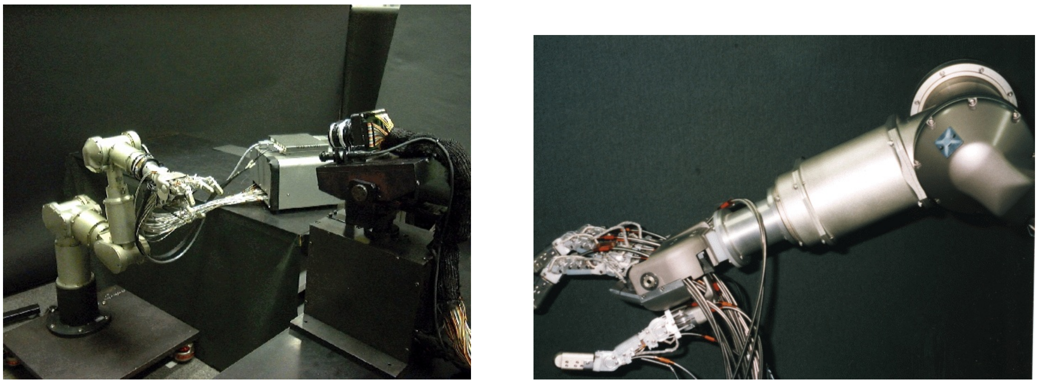


Figure 3.101 – High speed sensory-motor fusion system, University of Tokyo, Ishikawa/Oku Laboratory. On the left: robot arm, multifingered hand, actuator package for the hand, high-speed vision system. On the right: close-up of the hand.

Further research at the Ishikawa/Oku Laboratory aimed to built a compact version of the vision system by reducing it to a single integrated circuit. Indeed, the first vision system was a scaled-up model meant to be miniaturized. The result is a "vision chip": an integrated circuit embedding both the photodetectors and the processing elements, directly connected in parallel. The image sensor embedded in the vision chip is a CMOS [55] sensor, because the pixels in these sensors can be accessed simulatenously, i.e. in parallel, making them indicated for high-speed image acquisition. Several vision chips were developed over the years, with resolutions increasing from $8 \times 8$ to $64 \times 64$ pixels. Some of them have general-purpose processing elements that can be programmed to carry out various kinds of image processing (Komuro, Ishii, and M. Ishikawa 1997; M. Ishikawa, K. Ogawa, Komuro, and Ishii 1999; Komuro and M. Ishikawa 2001; Kagami, Komuro, Ishii, and M. Ishikawa 2002; Komuro, Kagami, and M. Ishikawa 2002, 2004). Others are specialized for one single application, for instance high-speed target tracking (Komuro, Ishii, M. Ishikawa, and Yoshida 2000, 2003). Their processing elements are simpler and smaller because of the specialization, so the chip is cheaper and more compact. Alternatively, another

55. CMOS stands for "complementary metal-oxide-semiconductor". This kind of image sensor is used in webcams, camera phones, security cameras.

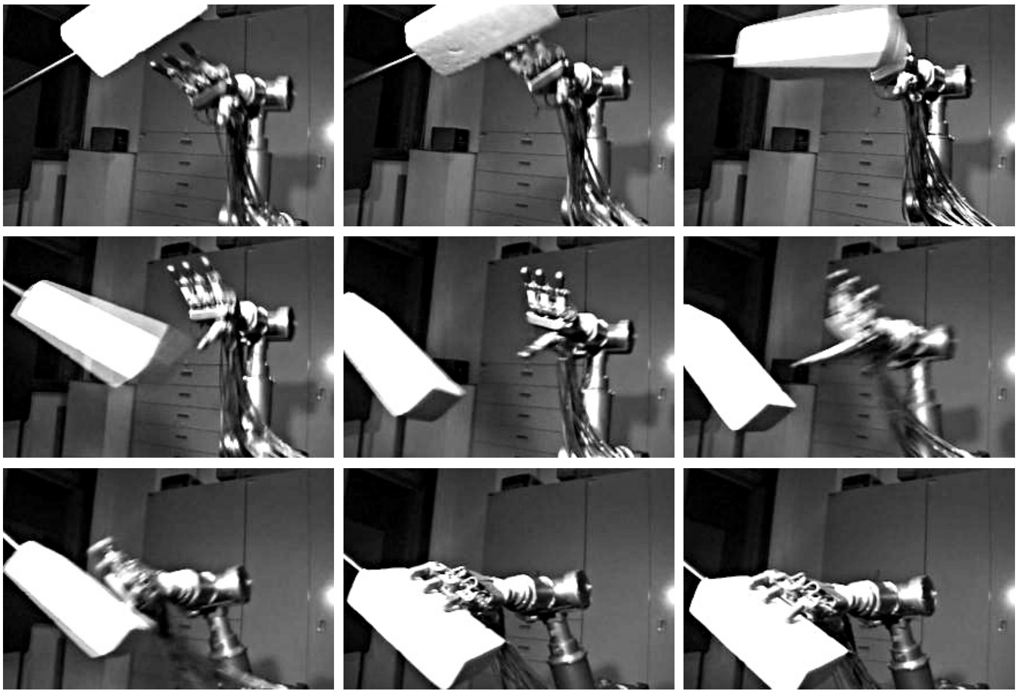
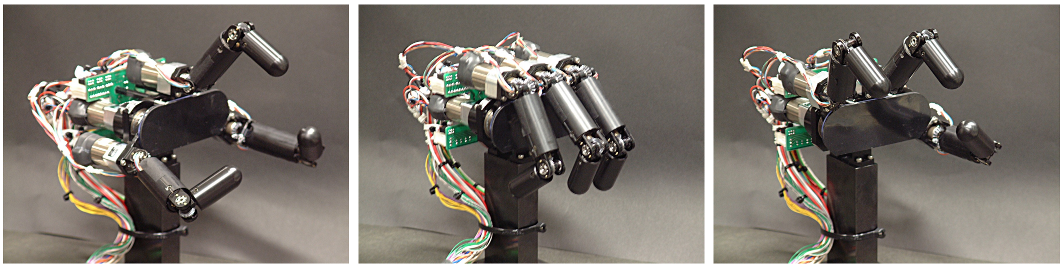


Figure 3.102 – Grasping an object with the high-speed sensory-motor fusion system (M. Ishikawa, Komuro, Namiki, and Ishii 1999). The photographs are taken at intervals of 0.1 s (i.e. from $t = 0$ s to $t = 0.9$ s).

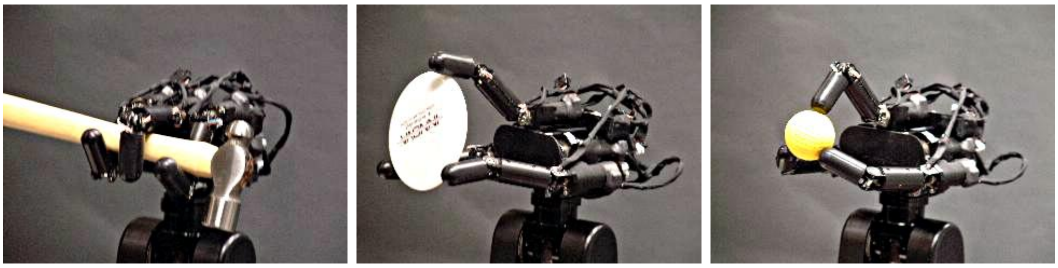
vision system was developed where "sensors and processors are not integrated into one chip, but implemented on separate chips and boards" (Nakabo, M. Ishikawa, Toyoda, and Mizuno 2000; Toyoda, Mukohzaka, Mizuno, Nakabo, and M. Ishikawa 2001). In this system, the images are transmitted from the photodetectors to the processing elements parallel in the columns and sequentially in the rows, hence the name of "column parallel vision system". It can achieve better resolution than vision chips ($128 \times 128$ pixels) while still being fast enough for high-speed vision.

Following all those advances, the "1 ms sensory-motor fusion system" was upgraded to the new vision sensing possibilities, and high-speed grasping of an object, among other experiments, was again realized to illustrate the performance of the approach (M. Ishikawa, Komuro, Namiki, and Ishii 1999; Namiki, Nakabo, Ishii, and M. Ishikawa 2000; Namiki and M. Ishikawa 2001).

Last but not least, the High Speed Multifingered Hand, developed in cooperation with the University of Hiroshima and introduced in 2003, is a further application of the laboratory's researches in high-speed vision and sensor fusion (Namiki, Imai, M. Ishikawa, and M. Kaneko 2003; Namiki, Imai, M. Kaneko, and M. Ishikawa 2004). It is a dextrous gripper with three fingers, eight joints, and a roughly rectangular flat palm; figure 3.103 illustrates a few of its possible kinematic configurations. The joints are driven by small DC motors located behind the palm and inside the proximal phalanges; small harmonic drive gears are used for reduction and bevel gears for transmission. The actuators are custom-made to output a torque higher than what is usually possible for their size, by increasing the winding density of the coil. In compensation, they can generate their maximum power only for a short period of time (about 0.1 s), and the current flow must be controlled to prevent overheating. Sensorization consists of strain gauges in each joint for force control; in addition, six-axis force/torque sensors and tactile sensors can be mounted on each fingertip. However, the main source of feedback is of course a 1 kHz parallel vision system, or two of them for three-dimensional vision. The overall hand module is lightweight (less than 0.8 kg) and powerful (maximal force at fingertip 28 N), so it becomes possible to achieve high velocity and high acceleration while preserving stability. The design goal about speed was that the hand would close and open its joints at 180°/0.1 s: it was indeed achieved.



(a) A few of many different kinematic configurations. Each finger has two flexion/extension degrees of freedom. The middle finger is fixed on the palm; the other ones can rotate around it.



(b) One power prismatic grasp and two precision circular grasps

Figure 3.103 – Tokyo/Hiroshima High Speed Multifingered Hand (2003)

The dexterity of the High Speed Multifingered Hand was demonstrated in various experiments involving a white object moving at a high speed on a dark background (visual feedback is in grayscale). These experiments, and the necessary control algorithms, are reported in a series of publications, beginning with catching a ball or a cylinder in freefall directly into precision grasps (Namiki, Imai, M. Ishikawa, and M. Kaneko 2003; Namiki, Imai, M. Ishikawa, M. Kaneko, Kameda, and Koyama 2003; Imai, Namiki, K. Hashimoto, and M. Ishikawa 2004, see figure 3.104), catching an egg in free fall without breaking it (Ugai, Onishi, Namiki, and M. Ishikawa 2004; Onishi, Namiki, K. Hashimoto, and M. Ishikawa 2004, soft fingertips filled with gel are used to mitigate the large impact forces), dribbling a rubber ball very fast using one or two fingers (Shiokata, Namiki, and M. Ishikawa 2005), and regrasping an object by throwing it up in the air and catching it when it falls back (Furukawa, Namiki, Senoo, and M. Ishikawa 2006). Experiments of more dextrous, in-hand manipulations include spinning a stick between the fingers (Ishihara, Namiki, M. Ishikawa, and Shimojo 2006, see figure 3.105) and tying a knot in a rope using only one hand (Y. Yamakawa, Namiki, M. Ishikawa, and Shimojo 2007, 2009). More recently, the researchers had the hand pick a rice grain using tweezers and catch a 6 mm plastic ball in high-speed motion, still using tweezers (Mizusawa, Namiki, and M. Ishikawa 2008; Yoneyama, Senoo, Namiki, and M. Ishikawa 2009). Videos of all those experiments can be found on the website of the Ishikawa/Oku Laboratory (2011).

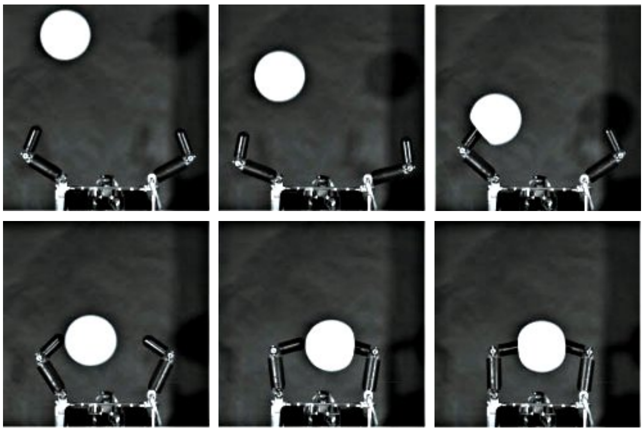


Figure 3.104 – High Speed Multifingered Hand catching a rubber ball in freefall directly into a two-finger fingertip precision grip. The photographs are taken at intervals of 15 ms (i.e. from $t = 0\,\text{s}$ to $t = 0.075\,\text{s}$).

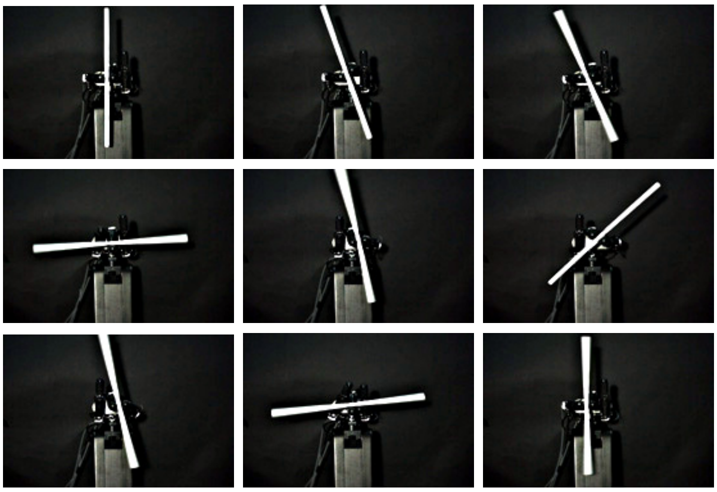


Figure 3.105 – High Speed Multifingered Hand spinning a stick between its fingers. The photographs are taken at intervals of 50 ms (i.e. from $t = 0\,\text{s}$ to $t = 0.4\,\text{s}$).

#### Dextrous hands

Dextrous hands are nothing more than dextrous grippers shaped as hands, just like adaptive hands, reviewed previously, are human-like adaptive grippers. The first one was undoubtedly the Utah/MIT Dextrous Hand, built in the 1980s; we described it in section 3.3.2. Many others followed, among which the UB Hands, the DLR Hands, Robonaut's hands, the Gifu Hands, and the Shadow Dextrous Hand. They are all very anthropomorphic, and sufficiently articulated and actuated to exhibit high potential dexterity and be able to perform actual in-hand manipulations. Whether this potential dexterity becomes real is, as usual, a matter of sensorization and control.

In this section, we give some information about the most well-known dextrous hands of the last two decades. For the sake of presentation, we divide them into three groups, quite arbitrarily. First we describe a few hands intended for teleoperation, in particular teleoperation in space. Then we present hands that are mostly meant to be used as research platforms, and are unlikely to be found outside the laboratory – that is, most dextrous hands to date. In the end, we mention three dextrous hands actually used by a few recent humanoid robots: Twendy-One, Reem-B, and iCub. These hands are recent exceptions, given how most humanoid robots use adaptive hands rather than dextrous hands, as explained previously.

**Dextrous hands for teleoperation** Even though teleoperation has been around since the early days of robotics, anthropomorphic hands did not come to be used very often in this context. Non-anthropomorphic end effectors were preferred for a long time, and even today remain prevailing. This is understandable: anthropomorphism means more axes and more actuators, hence added complexity, bulk, and weight to a system that is already difficult to operate and doesn't need additional hurdles. But at the same time, anthropomorphism is attractive because of the shorter training time and easier operation a close match between the master and slave systems makes possible, as already mentioned in section 3.1.3. Therefore, with the increasing disponibility and performance of master systems which measure the configuration of the operator's hand, such as hand exoskeletons and data gloves, it has become more and more relevant to go for anthropomorphic slave systems, able to reproduce the hand's configuration in the distant environment.

When used in a teleoperation setting, a humanoid hand has a high level of dexterity, not only because of its kinematics, but also because of the intelligence of its high-level control, performed by a human. That being said, in particular because of sensory feedback limitations, teleoperation remains slow and impractical. Besides, the distant environment is hazardous or difficult to operate into, so teleoperated interventions rarely feature amazing demonstrations of high-speed dexterity. For instance, we will not see Robonaut outside the International Space Station work with its tools as fast and casually as a mechanic would on Earth[56]. In short, despite good kinematics and good control, teleoperated dextrous hands can only be as dextrous as their environment and mode of operation permit.

One of the first teleoperated dextrous hands was a five-fingered hand built in the late 1980s in Tsukuba, Japan by Yuji Maeda, Susumu Tachi, and Akio Fujikawa (Maeda, Tachi, and Fujikawa 1989; Maeda 1990, 1991). This hand, illustrated in figure 3.106, is the same size as a human hand and is equally articulated, with twenty degrees of freedom and sixteen electric actuators. A wrist adds two degrees of freedom and two actuators. Abduction/adduction of the digits is provided, and the proximal interphalangeal and distal interphalangeal joints are coupled, as is often the case. The actuators, DC motors, are located in the forearm; motion and force are transmitted by tendons routed over pulleys. The researchers also developed an exoskeleton-type master unit, a controller, and software for graphic display, but they didn't report about dextrous manipulations being performed with their system, so we cannot tell how useful it was. Given the absence of sensory feedback, it is unlikely that tasks involving fingertip dexterity were easy to perform. But in any case, this first attempt demonstrated the feasability of teleoperation with a humanoid dextrous hand.

56. Contrary to what people may think, tools used by astronauts during extra-vehicular activities are not very different from those used on Earth. Many are standard Earth tools that have been modified for space use: cutters, wrenches, hammers, pliers, hex keys, ratchets, and so on. A loop is always added to attach a tether, in order to prevent loss in orbit. The handles are usually enlarged to make grasping with a spacesuit glove easier and less tiring; indeed, spacesuits are very thick with insulation (to protect from extreme temperatures and micrometeoroids), and the pressure in them means that hands have to work against a restoring force which replaces the gloves in their rest position.

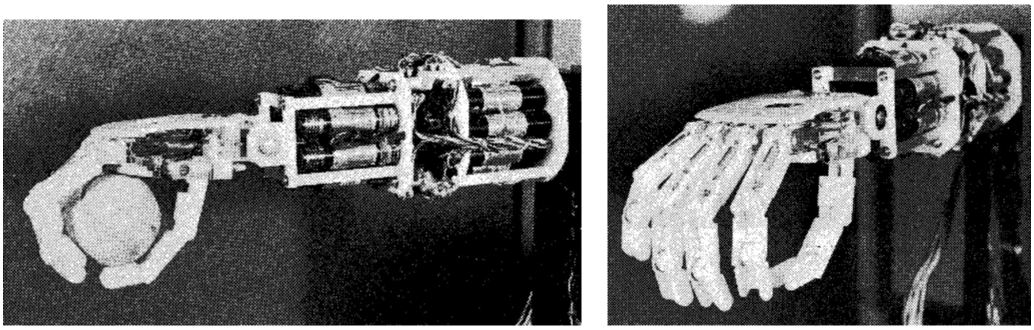
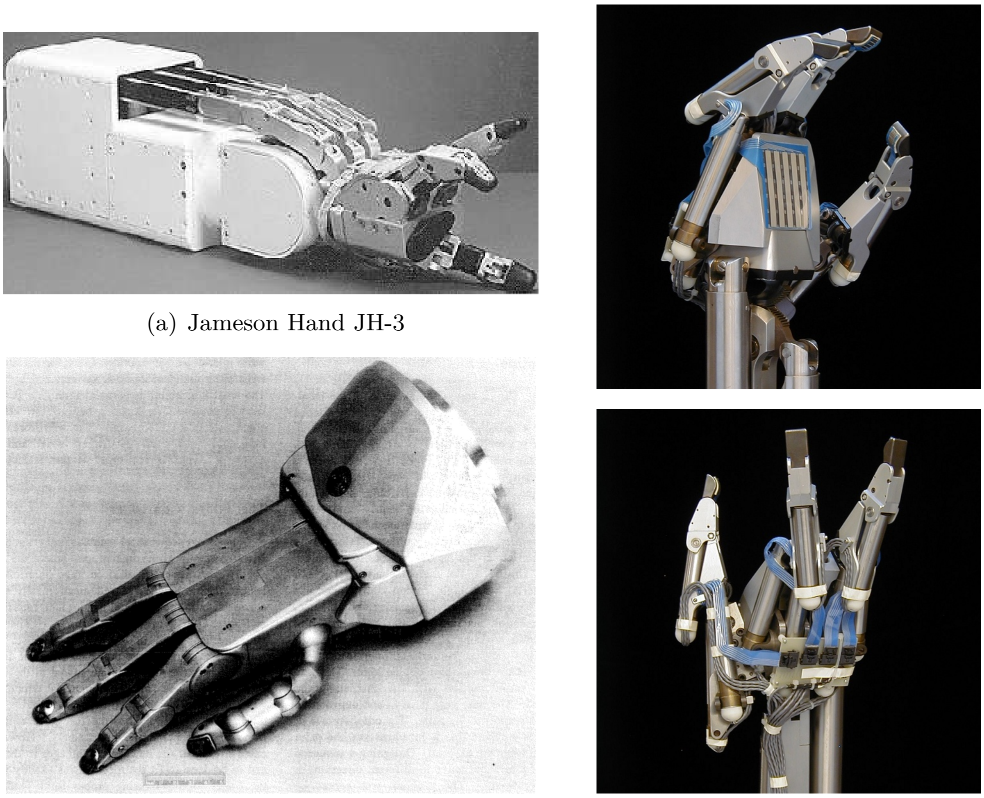


Figure 3.106 – Anthropomorphic hand for teleoperation, by Maeda, Tachi, and Fujikawa (1989). The actuators are arranged around an empty space and the wires which transmit power to the joints pass through this space. The forearm weights 2970 g, of which 2180 g are motors, including reduction gears and encoders. The hand weights only 370 g.

Space agencies have of course an obvious interest in teleoperated dextrous hands. NASA in particular has a long tradition of funding hand-related robotics projects, even when their potential applicability in space telerobotics is not immediate (that is to say, always, when speaking about humanoid dextrous hands). The hands of Robonaut, which was sent to the International Space Station on February 24, 2011 (see figure 3.12 in section 3.1.3), are therefore set in the context of a long-term research activity, conducted in NASA centers and in partner universities and companies since Crossley and Umholtz's three-fingered hand and Skinner's gripper in the 1970s (see figures 3.56 and 3.57 in section 3.3.2). In particular, in the late 1980s and early 1990s, several attempts at dexterity and anthropomorphism were conducted, most notably the Jameson Hands, the Omni Hand, the Jau/JPL Hand, and the Anthrobot.

**Jameson Hands** The Jameson Hands were a series of robotic hands designed at NASA Johnson Space Center in Houston, Texas. There were at least four different versions, labeled JH-1 to JH-4; they got their name from the designer of a previous hand design, John Jameson. The JH-3 Hand is pictured in figure 3.107(a). It is "an integrated hand-wrist-forearm package that approximates the combined size of a human hand, wrist, and forearm", with three identical two-degree-of-freedom digits (Hess and L. Li 1990; Hess, L. Li, Farry, and I. Walker 1994). The six motors of the fingers are located in the forearm, and tendons are routed to the joints through three conduits that protect them from entanglement and damage, but on the bad side also restrict the range of motion of the wrist. This transmission system was abandonned in favor of a few gears in the JH-4 Hand, whose six actuators are located right behind the proximal joints of the digits, making the hand much smaller (Hess, L. Li, Farry, and I. Walker 1994). In any case both JH-3 and JH-4, with only six independent degrees of freedom, are not very dextrous, but Hess and L. Li (1990) made it clear that they were only steps in the evolution of a type of robot "capable of assisting an extra-vehicular activity crewmember", or even "substituted for the human crewmembers for certain hazardous extra-vehicular activity tasks". At that time, the envisioned robot was already pictured as humanoid and autonomous, with two arms and dextrous robotic hand capability.

**Omni Hand** The Omni Hand is a three-fingered hand too, comprising a thumb, an index finger and a middle finger (figure 3.107(c)). It was designed by Mark Rosheim and Hans Trechsel from Ross-Hime Designs, under contract with NASA Marshall Space Flight Center in Huntsville, Alabama (Rosheim and Trechsel 1989, 1993; Rosheim 1994, 1999; Ross-Hime Designs 2011). It has a number of specific features, among which ball-and-socket metacarpophalangeal joints, direct-drive actuation by electric linear motors located on the dorsal side of the hand and proximal phalanges (similarly to the Karlsruhe Dextrous Hand II, see figure 3.94), and a protective glove similar to a spacesuit glove. The digits are modular and interchangeable, a feature which “simplifies servicing and maintenance, which must be done frequently in such complex mechanism” (Rosheim and Trechsel 1993). There are three joints and three independent degrees of freedom per finger: two for the metacarpophalangeal joint, one for the proximal interphalangeal joint, and the distal interphalangeal joint is coupled with the proximal one. The joint motion is comparable in range to the human fingers. Tactile sensing on the palm and fingertips is provided.



(a) Jameson Hand JH-3

(b) Jau/JPL Hand

(c) Omni Hand

Figure 3.107 – Hands for space robotics at the turn of the 1990s

**Jau/JPL Hand** The Jau/JPL Hand was designed and engineered at the NASA Jet Propulsion Laboratory in California Institute of Technology, Pasadena, California. Its designer was called Bruno Jau, hence the name of the device. It was part of a teleoperation system intended for extra-vehicular activity and originally envisioned as a “dexterous front end” to the space shuttle’s and space station’s arm, performing tasks in place of astronauts during the construction of the station (Jau 1989b, see also figure 3.108). It does not seem to have been used though: astronauts have already spent about 1000 hours of extra-vehicular activity to built the International Space Station (NASA 2011a), and their first robotic system with multifingered dextrous capability, Robonaut 2, only arrived on board this year, thirteen years after the start of the construction[57]. The Jau/JPL Hand and the rest of the teleoperation system is thoroughly described by Jau (1989b,a, 1990b,a, 1991, 1992). Evaluations focusing on tool handling and astronaut-equivalent tasks are reported by Jau, A. Lewis, and Bejczy (1995) and Jau (1995a).

As can be seen from figure 3.107(b), the hand has three fingers and a thumb. Each digit has four independent degrees of freedom. The hand component is the size of a human hand, while the wrist and the forearm are much larger and bulkier than those of a human. Indeed, the forearm contains all the actuators (electric motors) and the wrist is enlarged to facilitate the routing of the transmission cables. The system is completed by a motorized exoskeleton-like master controller built on top of a glove worn by the operator, torque and position sensors for each joint of the slave hand and master glove, appropriate control electronics, and of course cameras to monitor the events remotely.

A specific feature separates this hand from other multifingered mechanical hands: "each finger and the wrist has its own active electromechanical compliance system, allowing the joint drive trains to be stiffened or loosened" and therefore joint compliance to be adjusted to any level (Jau 1992). These five mechanisms, which are built into the joints and necessitate five additional motors in the forearm, "[imitate] the human muscle dual function of positioner and stiffness controller". They are described in detail by Jau (1995b). Their presence in a system supposed to achieve high mechanical dexterity is consistent with how important the possibility to adjust finger stiffness is to our own dexterity (see chapter 7). Besides, Jau (1995a) notes that experimental results "reveal that the combination of a [multifingered] hand and active compliance enables unprecedented task executions" in teleoperation.

Operation of the Jau/JPL Hand is user-friendly and natural, according to the designer, because of the exact one-to-one kinematic correspondence between the joints of the master unit and slave hand. This is, as mentioned previously, an advantage of anthropomorphism. Telemanipulation of the Jau/JPL Hand works in hybrid force/position control with automatic compliance control (Jau 1989b): that is to say, the slave hand moves when nothing prevents its motion, and produces a torque in its joints when they are prevented from moving, while at the same time stiffening the internal joint stiffness mechanisms, like our hands do when they apply force. That way, "position and force control are automatically regulated in a human-like fashion without the operator having to switch from one mode to another". To provide the operator a sense of actually operating in the remote environment, the actual joint positions, joint torques, and joint compliances of the slave hand are fed back to the master controller, which is actuated to return this feedback to the user.

Despite this feedback, the good articulation and actuation of the hand, the intuitive force/position control, and the addition of adjustable compliance, Jau (1995a) notes that manipulations with tools, such as "cutting with a scissor or engaging a simple tethering device", remain "surprisingly difficult to perform". He explains this disappointing outcome by the lack of tactile feedback to the user: "not only [...] the locations of contact but also the strengths and directions of the applied forces" are unknown to the operator.

57. The first module of the International Space Station was launched on November 20, 1998, and the last assembly flight is scheduled for May 2012.

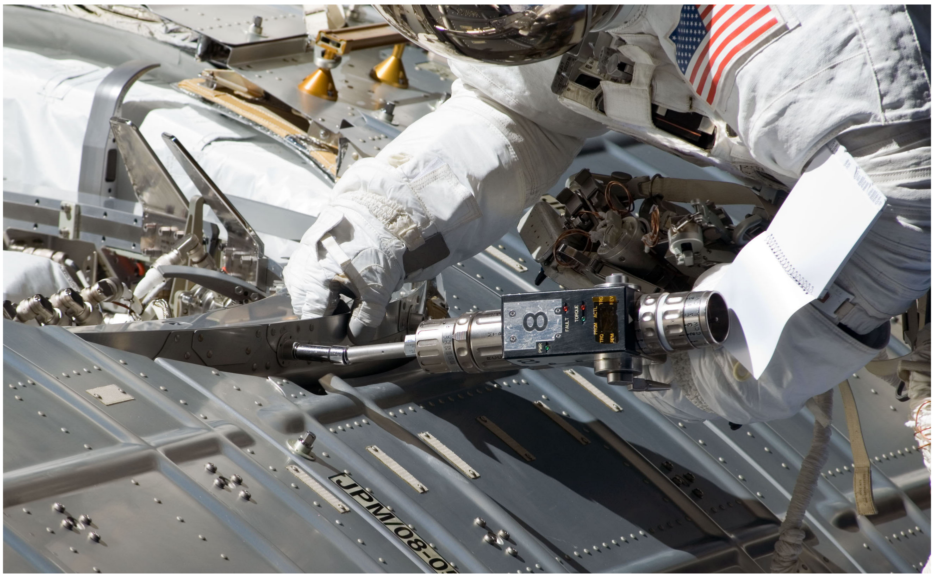


Figure 3.108 – An astronaut tightens a bolt using a power tool, outside the International Space Station in 2008. This an exemple of task that robots should do instead of humans. Note the lateral precision grip at the right hand and the power grip at the left hand.

**Anthrobot** Contrary to what we may think from the name, Anthrobot is not an anthropomorphic robot, but only the hand: a five-fingered humanoid hand, consistent with the anatomical model in "the placement and motion of the thumb, proportions of the link lengths, and shape of the palm" (Ali and Engler 1991). The first version of this hand, Anthrobot-1, was built at Lehigh University in Pennsylvania by Charles Engler Jr. and Mikell Groover (1989). Then Charles Engler worked at NASA Goddard Space Flight Center in Greenbelt, Maryland and developed an improved version of the hand with Michael Ali: Anthrobot-2 (Ali and Engler 1991). Shortly afterwards, the New York State Center for Advanced Technology in Automation and Robotics at Rensselaer Polytechnic Institute, Troy, New York "launched a major effort towards the utilization of the Anthrobot in unstructured environments", that is to say, not only in space (Ali, Kyriakopoulos, and Stephanou 1993). Papers by Michael Ali and his colleagues from Rensselaer report the research they conducted on the "kinematic analysis, sensing, planning and control" of this hand, "with central emphasis on uncertainty" (Van Riper, Ali, Kyriakopoulos, and Stephanou 1992; Ali, Kyriakopoulos, and Stephanou 1993; Zink and Kyriakopoulos 1993; Kyriakopoulos, Van Riper, Zink, and Stephanou 1997). Also, the roboticists built a third version of the hand, Anthrobot-3 (Kyriakopoulos, Van Riper, Zink, and Stephanou 1997); this final version is pictured in figure 3.109.

In each of its versions, the Anthrobot has the same twenty degrees of freedom as our hands, four per digit. The classical compromises on articulation and actuation have been made, namely the two-degree-of-freedom metacarpophalangeal joints of the fingers and carpometacarpal joint of the thumb are implemented via two rotational joints each, and the distal phalanges of the fingers are not independently actuated but mechanically coupled with the middle phalanges, so there are only sixteen independent degrees of freedom. Sixteen servomotors, located in the forearm (more like a base actually), actuate the fingers via a flexor and extensor tendon each: a pulley is mounted on the axis of the motor and another one is mounted in the

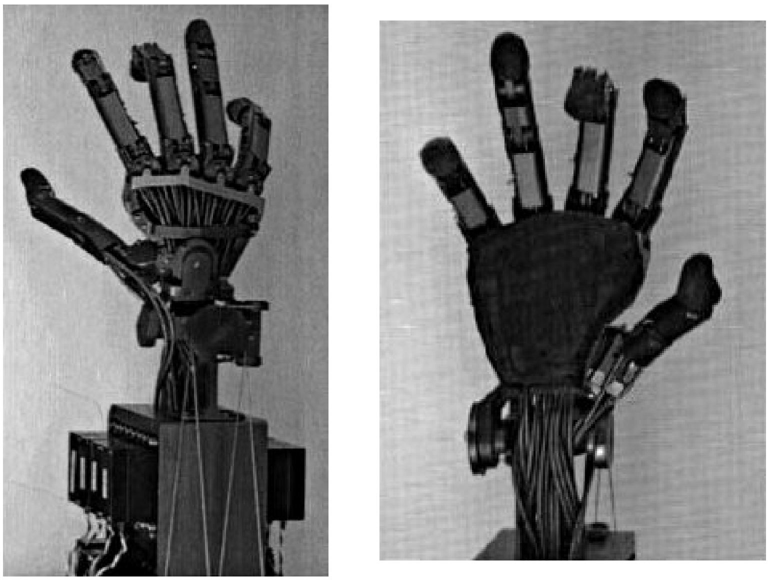


Figure 3.109 – The Anthrobot-3, back and front sides (Kyriakopoulos, Van Riper, Zink, and Stephanou 1997). The sheaths of the tendons are visible in the wrist and in the dorsum of the hand. The black boxes on each side of the base are servomotors.

corresponding joint, and two cables attach to these pulleys, so that clockwise and counter-clockwise rotation of the servomotor provides flexion and extension of the joint. The wrist adds two degrees of freedom and two actuators. The mechanical structure of the hand is made of aluminium, but the palm surface and the fingertips are made of silicone in the Anthrobot-3.

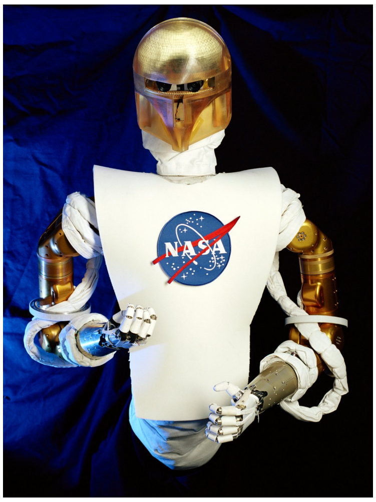
Operation of the Anthrobot is meant to be either autonomous or teleoperated. Unfortunately, the sensorization of the hand is very limited: it includes only potentiometers in the servomotors, for position feedback. So the performance of any control scheme is necessarily limited too. As a matter of fact, Anthrobot-2 was actually controlled in an open-loop fashion to begin with (Ali and Engler 1991). Closure of the loop was provided afterwards, in hybrid force/position control laws developed after the dynamic model of the fingers was identified (Zink and Kyriakopoulos 1993; Kyriakopoulos, Van Riper, Zink, and Stephanou 1997). But tactile sensing capability was never added, and research seems to have halted at this point, when the researchers were considering investigating shared control for teleoperation, rather than pure master/slave control (in shared control, “the computer control system that runs the slave offloads some of the task execution responsibility from the operator” by closing various control loops locally in the slave; for instance, the Southampton Adaptive Manipulation Scheme mentioned in section 3.2.4 is such a control strategy, for prosthesis operation rather than teleoperation though).

**Robonaut** In the second half of the 1990s, following the robot hands presented above, NASA started a long-term research effort to develop a robotic system that can really take the place of an astronaut during extra-vehicular activities. With respect to the International Space Station, whose construction was about to start, the goal of this project was twofold: first, reduce the burden of extra-vehicular activities on the crew and avoid putting astronauts in jeopardy, and second, gain a rapid response capacity on the outside the spacecraft (Lovchik and Diftler 1999). Indeed, extra-vehicular activities are time-consuming, wearying, hazardous, and necessitate planning. They start with a long preparation time, including breathing pure oxygen at spacesuit pressure for hours in order to avoid decompression sickness [58]. Once outside, the astronauts must be extremely cautious to prevent damage to their spacesuits. They are also threatened by micrometeoroids and other orbital debris during the whole duration of their spacewalk, typically seven to eight hours. On top of that, extra-vehicular activities are scientifically uninteresting, since they are mainly "routine inspection and maintenance chores" such as configuring equipment, connecting services, or replacing faulty components (Rehnmark, Bluethmann, Mehling, Ambrose, Diftler, Chu, and Necessary 2005). Having dexterous space robots performing those chores, if possible autonomously, would spare a lot of valuable mission time. Even if autonomy is not possible and astronaut supervision from the inside of the cabin remains necessary, it would still save the risks of spacewalking; in fact, Rehnmark, Bluethmann, Mehling, Ambrose, Diftler, Chu, and Necessary (2005) report that "NASA's vision for space exploration features extra-vehicular teams that combine the information-gathering and problem-solving skills of human astronauts with the survivability and physical capabilities of diverse robot archetypes".

The current robotic system resulting from NASA's effort to fulfill this vision is Robonaut, a dexterous humanoid robot, built and designed at Johnson Space Center in Houston, Texas, in cooperation with the Defense Advanced Research Projects Agency and the aerospace and defense company Lockheed Martin. As can be seen from figure 3.110, it features a torso, a head, two arms and two multifingered dextrous hands. The arm and hand subsystems were introduced first in 1999 and the whole half-humanoid in 2000 (Lovchik and Diftler 1999; Ambrose, Aldridge, Askew, Burridge, Bluethmann, Diftler, Lovchik, Magruder, and Rehnmark 2000). Several lower bodies have been adapted to this upper body, in particular a single seven-degree-of-freedom leg with a special connector at the end, suited to operation outside the International Space Station and illustrated in figure 3.111(a) (Bluethmann, Ambrose, Askew, Goza, Lovchik, Magruder, Diftler, and Rehnmark 2001; Diftler and Ambrose 2001). Wheeled lower bodies, such as the rover pictured on figure 3.111(b), are better suited to planetary surface exploration (Ambrose, Savely, Goza, Strawser, Diftler, Spain, and Radford 2004; Diftler, Ambrose, Goza, Tyree, and Huber 2005; Mehling, Strawser, Bridgwater, Verdeyen, and Rovekamp 2007).

Acknowledging that "the depth and breadth of human performance is beyond the current state of the art in robotics", NASA targeted "the reduced dexterity and performance of a suited astronaut as Robonaut's design goals, specifically using the work envelope, ranges of motion, strength and endurance capabilities of space walking humans" (NASA 2011c). The humanoid design was chosen for three reasons: first, "over the past five decades, space flight hardware has been designed for human servicing"; second, NASA already invested substantialy in human-adapted extra-vehicular tools; and of course, the humanoid design has advantages in teleoperation control. Indeed, Robonaut works under human supervision for now, although it is partially autonomous. More precisely, the robot has three levels of autonomy (Diftler, Culbert, Ambrose, Platt, and Bluethmann 2003; Diftler, Culbert, Ambrose, Huber, and Bluethmann 2003):

58. Decompression sickness, aka "the bends", is the formation of gas bubbles within the body when undergoing rapid depressurization, from gases that were dissolved under higher pressure, mainly, nitrogen. Spacesuit pressurization is indeed lower than the pressurization of the International Space Station. Pre-breathing pure oxygen purges the body of dissolved nitrogen to avoid the risks of decompression sickness.

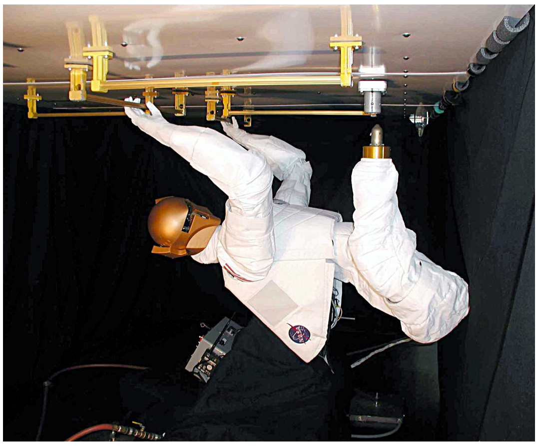



(a) Robonaut 1, without its protective covers (but wearing a vest)


(b) Robonaut 1 engaging a tether in a loop (under teleoperation)

(c) A teleoperated Robonaut 1 participates in a test with an astronaut at NASA Johnson Space Center in 2003, to evaluate human/robot collaborative work. They are assembling an aluminium truss structure.

Figure 3.110 – Robonaut 1 (2000)



(a) Like astronauts, a spacewalking Robonaut would move around the International Space Station using the external handrails and latch onto the station using the same sockets used by astronauts for foot restraint. It is shown here mounted on an air-bearing sled simulating zero-gravity, in 2004.

(b) Robonaut 1 mounted on a Centaur 1 four-wheeled rover, picking up a rock sample during a field test in the Arizona desert in 2006, near Meteor Crater. Such a mobile manipulation system is a good candidate for future exploration missions on Mars and the Moon.

Figure 3.111 – Mobility solutions for Robonaut

**Direct teleoperation** is Robonaut's initial control mode. Actually, the chosen technique is telepresence, "an immersive version of teleoperation" where the human operator uses "a collection of virtual reality gear [to] immerse himself into the robot's environment" (figure 3.112). This equipment consists of a helmet with stereo screens linked to the robot's stereo cameras; headphones and a microphone for communication with the other astronauts, but also with Robonaut itself via voice recognition and synthesis; magnetic-based position and orientation trackers on the arms, neck, chest and waist; data gloves worn on both hands to control the fingers; and small finger-mounted motors for programmable vibratory feedback (Diftler, Jenks, and L. Williams 2002; Diftler, Culbert, Ambrose, Platt, and Bluethmann 2003; Rehnmark, Bluethmann, Mehling, Ambrose, Diftler, Chu, and Necessary 2005). The teleoperator can be either a station crew member or someone on the ground.

**Shared control** between the teleoperator and the robot has been made possible by the development of "low-level skills and functions" resulting from the inclusion of new sensors and new software into the robot during the early 2000s. These skills include, for instance, simple compliance control, pre-programmed grasp patterns, short term memory of where objects are located in the workspace, and real-time visual identification and tracking of tools (Diftler, Culbert, Ambrose, Platt, and Bluethmann 2003; Diftler, Culbert, Ambrose, Huber, and Bluethmann 2003). Having the robot use them autonomously results in a significant reduction of the teleoperator workload and task completion time.

**Supervised autonomy** uses the same basis skills as shared control, and was achieved for the second generation of Robonauts, developed in the late 2000s. In this operational mode, Robonaut is set to pre-defined tasks that have been programmed into it, or that it learned beforehand through teleoperation and machine learning algorithms (Peters, Campbell, Bluethmann, and Huber 2003); then it carries these tasks through "autonomously with periodic status checks"

(NASA 2011b). This shift towards more autonomy anticipates future destinations “in which distance and time delays would make continuous management problematic”. Indeed, communications with the International Space Station or even with the Moon typically have data transmission delays of a few seconds, that teleoperators located on the ground can deal with simply by moving more slowly, or adopting a “move-and-wait” strategy to allow the visual feedback to catch up (Rehnmark, Bluethmann, Mehling, Ambrose, Diftler, Chu, and Necessary 2005). But the one-way communication delay ranges from about three to twenty-two minutes with Mars, depending on the position of the planets on their orbits, and besides, there are communications blackouts of the order of a month when the Sun is directly between Earth and Mars. Therefore, in the event that humanoid robots derived from Robonaut are sent to Mars in preparation of a future manned mission, they will have to do without teleoperation.

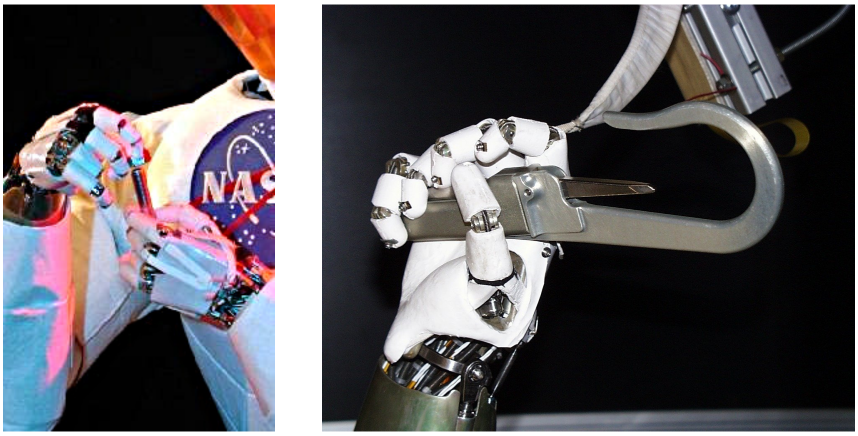
Whichever of these three operational modes is used, the low-level control functions remain the same, namely “joint and cartesian controllers for the forty-three degrees of freedom, sensing, safety functions, and low-level sequencing” (Diftler and Ambrose 2001). These low-level systems operate independently of the higher-level functions that constitute the three control modes above. Both layers are separated in the software implementation of the control architecture, so that the lower layer is “unaware of which higher-level control system is being used”.

Teleoperation from a mobile trailer during a field test next to the Johnson Space Center, in 2006.

Figure 3.112 – Teleoperation gear for Robonaut

Several articles and the Robonaut’s website (NASA 2011c,b) present the various subsystems of the robot: hands, arms, body, and head, but also vision algorithms, control architecture, embedded electronics, telepresence solutions, and mobility systems. For instance, Aldridge, Bluethmann, Ambrose, and Diftler (2000) describe the initial control architecture, Diftler, Culbert, Ambrose, Huber, and Bluethmann (2003) give some details about the capability of the vision system to recognize tools and identify humans, and Diftler, Jenks, and L. Williams (2002) describe the telepresence hardware and software. Articles by Ambrose, Aldridge, Askew, Burridge, Bluethmann, Diftler, Lovchik, Magruder, and Rehnmark (2000), Bluethmann, Ambrose, Diftler, Askew, Huber, Goza, Rehnmark, Lovchik, and Magruder (2003), and Bluethmann, Ambrose, Diftler, Huber, et al. (2004) present the whole robot in a more general fashion. Also, Rehnmark, Bluethmann, Mehling, Ambrose, Diftler, Chu, and Necessary

(2005) list and explain the most significant, long-term technology hurdles encountered by the NASA roboticists. Among them, not surprisingly, shared control, mobile manipulation, sensor feedback, and autonomy: challenges faced by many other robotics researchers around the world.



(a) Two-hand fingertip manipulation: threading a nut onto a bolt

(b) Power grip: grasping a tether hook

Figure 3.113 – Close-up views of Robonaut 1 Hands (1999)

Dextrous manipulation is, of course, central to the Robonaut project. The five-fingered hands of the humanoid, illustrated in figure 3.113, were actually developed and constructed first, in the late 1990s, by Chris Lovchik, Hal Aldridge, and Myron Diftler (Lovchik and Diftler 1999; Lovchik, Aldridge, and Diftler 1999). They have nineteen joints and twelve independent degrees of freedom (not counting the wrist). The actuators are brushless DC motors located in the forearm, which also houses drive electronics consisting of twelve separate circuit boards, and all the wiring for the hand. The hand itself has three characteristic features:

1. The number of degrees of freedom varies through the fingers because they are grouped in two sections (see figure 3.114): the thumb, index and middle fingers constitute "dextrous fingers" that are used for manipulation, while the ring and little fingers form "grasping fingers" that allow the hand to "maintain a stable grasp while manipulating or actuating a given object" (Lovchik and Diftler 1999).

    a) The index and middle fingers have three phalanges and three independent degrees of freedom each: metacarpophalangeal abduction/adduction, metacarpophalangeal flexion/extension, and proximal interphalangeal flexion/extension. The distal interphalangeal joint is not independently actuated, but linked to the proximal one so that both close with equal angles.

       The thumb has two phalanges and three independent degrees of freedom. It is similar in design to the index and middle fingers, but has a wider range of motion. It is also "mounted to the palm at such an angle that the increase in range of motion results in a reasonable emulation of human thumb motion" (Lovchik and Diftler 1999).

    b) The ring and little fingers have three phalanges but only one degree of freedom each: flexion/extension of the whole finger. The phalanges are coupled via linkages so that all three joints close down with approximately equal angles.

2. The palm has a “metacarpal mechanism” at the base of the grasping fingers (see figure 3.114) which provides an additional degree of freedom: a “cupping” or “hollowing” motion of the palm, inspired by the intermetacarpal mobility of the human hand. It enhances the stability of the Robonaut hand during tool grasps (power grasps).

3. The transmission system is not tendon-based, but uses flexible shafts. These devices consist of a rotating wire which is flexible but has some torsional stiffness, so that it can transmit a rotary motion between two objects which are not fixed relative to one another. Here, the rotary motion of the actuator’s reduction gears is transmitted by a stainless steel flexible shaft to a small leadscrew assembly which converts it to linear motion, effectively pulling on a phalanx to close the joint.

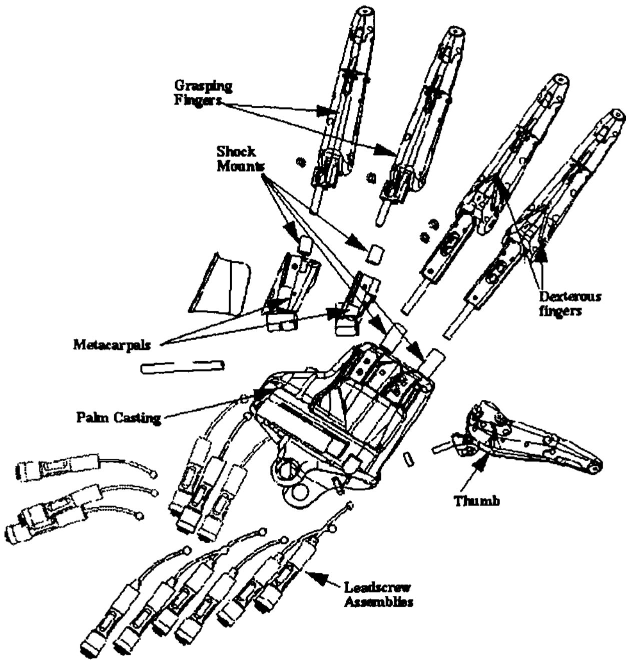



Figure 3.114 – Robonaut 1 Hand (Lovchik and Diftler 1999)

The hand is provided with forty-three sensors, not including tactile sensing: joint position sensors, motor encoders, and strain gauges in the leadscrew assemblies for force feedback. Tactile sensing was incorporated into instrumented gloves rather than directly into the hand (T. Martin, Diftler, Ambrose, Platt, and Butzer 2004; T. Martin, Ambrose, Diftler, Platt, and Butzer 2004, and figure 3.115). The gloves are rugged and have good overall sensor coverage: they add protection to the hand, as well as thirty-three tactile sensors made of pressure-sensitive resistive material [59]. The force data provided by the gloves can be used in control algorithms “to improve dexterous, tool and power grasping primitives”.

59. Namely, force sensing resistors and quantum tunneling composites, respectively invented and manufactured by Interlink Electronics (Santa Barbara, California) and Peratech (Durham, England). Both materials show a decrease in electric resistance when the force applied to their surface increases.

Figure 3.115 – Tactile glove for Robonaut 1 (2004)

NASA's success in developing and demonstrating the capabilities of its humanoid attracted the attention of the automotive company General Motors. The Detroit-based company "approached NASA in 2006 as part of a worldwide review of humanoid robotics, searching for new technologies that would [...] improve product quality and manufacturing assembly processes" (Diftler, Mehling, Abdallah, Radford, et al. 2011). The two organizations teamed up in 2007 to work together on the next generation of Robonaut [60], with common goals despite the different expertises: automating "non-traditional" tasks demanding dexterity, and relieving humans, "be they factory workers or astronauts, from dangerous, ergonomically stressful, or difficult activities" (Diftler 2010; Diftler, Mehling, Abdallah, Radford, et al. 2011).

Robonaut 2 was revealed to the public in February of 2010. It is illustrated in figure 3.116(a) and described in presentations by Diftler (2010) and Ambrose (2011), in an article by Diftler, Mehling, Abdallah, Radford, et al. (2011), and in a website and a fact sheet edited by NASA (2011c,b) [61]. In comparison to its predecessor, the new robot "is capable of speeds more than four times faster, is more compact, is more dexterous, and includes a deeper and wider range of sensing" (NASA 2011c). All subsystems were improved, and wiring was drastically reduced (the more wiring, the more breakdowns). As far as the hands are concerned, the most significant changes affect the thumb and the sensorization:

1. The thumb gains a fourth degree of freedom, achieving "a very human kinematic layout" and an extended range of motion; to add to the anthropomorphism, "the design also provides the thumb with significantly greater strength than the opposing fingers" (Diftler, Mehling, Abdallah, Radford, et al. 2011). On the other hand, the metacarpal mechanism at the base of the ring and little fingers is removed. In spite of that, the additional degree of freedom of the thumb is sufficient to increase a lot the grasping capability of the hand (figure 3.116(b)): the Robonaut 2 hand realizes successful grasps across 90% of Cutkosky's grasp

60. General Motors is not a new player in the field of robotics, if we remember that it was the first manufacturer to use the Unimate, the world's first industrial autonomous robot, in 1961 (Murray, Z. Li, and Sastry 1994, page 3). Today, it employs "over 25 000 robots" in its manufacturing plants worldwide, and "has influenced the industry over the years by leading technical development efforts" in industrial robotics (Diftler, Mehling, Abdallah, Radford, et al. 2011). Its relationship with NASA is also ancient: the two organizations have a long history of working together, "starting in the 1960s with the development of the navigation systems for the Apollo missions", followed by their collaboration on the Apollo Lunar Rover (NASA 2011c).

61. A sign of the times, Robonaut 2 also has a Facebook account (`facebook.com/NASArobonaut`), posts photos on Flickr (`flickr.com/nasarobonaut`), and answers questions on Twitter (`twitter.com/AstroRobonaut`).

(a) General view

(b) Pencil grip

(c) Six-axis force sensor at fingertip

Figure 3.116 – Robonaut 2 (2010)

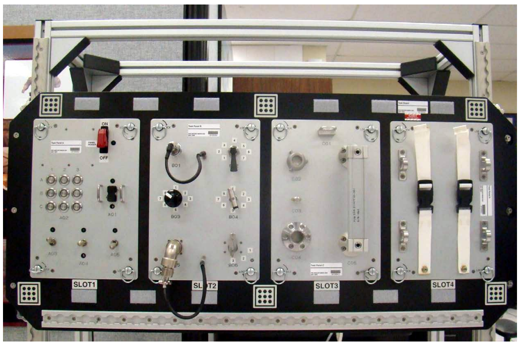
taxonomy (Cutkosky 1989, see also figure 2.38 and section 2.2.2, in chapter 2), while the Robonaut 1 hand can only emulate about 50% of these grasps.

2. Each finger phalanx is designed to accommodate on its palmar side an extremely small custom six-axis load cell (figure 3.116(c)), which comes in addition to the already existing sensing system. These sensors provide fourteen measurement points for all six components of the contact force and torque.

3. The transmission system is also changed for a more classical set of sheathed tendons, in "$n+1$ configuration" (see figure 3.64 and the Stanford/JPL Hand, in section 3.3.2). Since such a configuration works in flexion and extension, coordinated actuation of tendons makes compliance control of the fingers possible.

Robonaut 2 was launched to the International Space Station on space shuttle Discovery's last flight, the STS-133 mission, on February 24, 2011 (figure 3.117(a)). It was not supposed to leave Earth initially, but only serve as another prototype, so it had to be upgraded for space station compatibility and tested for lift-off resistance (flammability requirements, electromagnetic interference, radiation tolerance, noise level, vibration resistance, and so on, see NASA 2011c,b). Once on board, Robonaut was attached to a fixed pedestal, but it wasn't powered up until a first system test with no movement on August 22, 2011, because of the crew's busy schedule. Now the robot is under initial testing, and the first experimental objectives include testing dextrous manipulation in microgravity, see how it differs from manipulation on the ground, and refine the control algorithms accordingly, in particular, adjust the control gains and parameters that need it (Ambrose 2011). To this aim, a taskboard was shipped with the robot, with various switches, buttons, knobs, connectors, loops and straps to manipulate; it is illustrated in figure 3.117(b).

(a) Robonaut 2 and American astronaut Cady Coleman on board the International Space Station, shortly after the robot's arrival. Robonaut keeps its arms in their power-off posture.



(b) The robot's manipulation taskboard has "panels with increasingly difficult tasks" and is modular, so that "new interfaces and experiments will be built up using equipment already on the International Space Station" (Ambrose 2011).

Figure 3.117 – Robonaut 2: first humanoid robot in space (2011)

Future plans for Robonaut include hardware and software upgrades to allow mobile intra-vehicular operations, that is to say moving around the interior of the station and perhaps performing basic low-risk maintenance tasks, "such as vacuuming or cleaning filters" (NASA 2011b). A pair of legs is currently in development to achieve this mobility (one foot would grasp a handrail while the other one would reach for the next handrail, which would free the hands for working) (Ambrose 2011). Further enhancements and modifications could be added afterwards, to allow Robonaut to function outside the station (for instance, Robonaut uses fans at the moment to regulate the temperature of its processors; they would be useless in the vacuum of space) (Ambrose 2011).

**Dextrous hands for robotics manipulation research** The dextrous hands reviewed previously are oriented towards a specific application, telemanipulation, even though only the most recent Robonaut Hand can be considered a success in this field. Most dextrous hands proposed to date, however, are not application-oriented but research-oriented. That is to say, they are built to serve experimental purposes in robotics research, and are not supposed to leave laboratories and be used in specific applications. More precisely, common motivations for building such hands include:

**Experiments in control design** Having a dextrous hand at one's disposal makes it possible to test and compare control algorithms for multifingered grasping and dextrous manipulation. Computer simulations can be used too instead, but in terms of demonstration force, an actual dextrous hand is superior to simulated environments. Besides, robotics is about robots, so a confrontation with reality is eventually necessary. Typical examples of hands used as experimental platforms are the Shadow Hand and DLR Hand II.

**Achievement in mechatronics** Building a dextrous hand is a challenging mechatronics undertaking, which requires significant integration efforts and innovative practical solutions. When successful, it results in a dextrous hand where mechanical design, actuators, sensors, electronics and control strategies are tightly integrated one another to make the best of them: that is to say, there is an optimization of the functionality of the final product. Examples of mechatronics efforts include the UB Hand 2 and the DLR Hands.

**Proof of concept** Some dextrous hands are built to demonstrate the feasability of some new idea or new technology in mechanical design, actuation, or sensing. They may not be used a lot for dextrous manipulation, because they are primarily proof-of-concept prototypes. The best example is probably the Karlsruhe Ultralight Hand, but the UB Hand 3 and the hands with shape-memory-alloy-based actuators are good examples too.

Whereas the dextrous hands for teleoperation that we have presented previously are the work of NASA and its American partners, those that we are going to review now are mostly European constructions, with a few American and Asian ones. In particular, several research centers in Italy and Germany have become reputed in the last two decades for their experience in the construction of dextrous hands.

**UB Hands** Work on the first European dextrous hand started in 1986 at the University of Bologna, in Italy. Two years later, in 1988, a three-fingered articulated hand was available at the laboratory, mounted on a test frame; it was latter installed on a gantry robot in the beginning of 1989. This hand was called the University of Bologna Hand, Version 1; UB Hand 1 or UBH 1 for short (Bonivento, Caselli, Faldella, Melchiorri, and Tonielli 1988; Bologni, Caselli, and Melchiorri 1988).

As illustrated in figure 3.118 (see also figure 3.10 in section 3.1.2), the UB Hand 1 has two identical three-phalanx fingers, a two-phalanx thumb in opposition, and a non-anthropomorphic palm between them. There is a total of eleven degrees of freedom, four for each of the upper fingers and three for the thumb. The fingers feature one-axis force sensors. Gabriele Vassura and Antonio Bicchi (1993) state that most of the experimental work that was carried out with this hand consisted in "examining the reliability of the proposed device and evaluating its effectiveness in dextrous manipulation tasks, with particular reference to grasping". The experiments were conclusive, and led to the development of a second version of the hand.

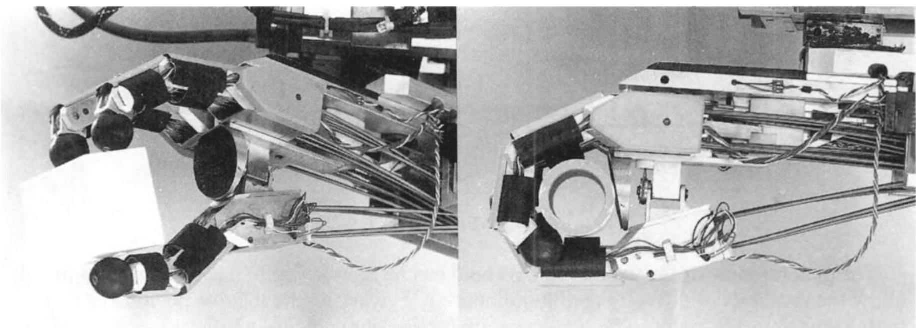


Figure 3.118 – A fingertip precision grip and a whole-hand power grip performed by the UB Hand 1 (1988)

The UB Hand 2 was ready in 1992, and subsequently presented at several conferences (Bonivento, Faldella, and Vassura 1991; Fantuzzi, Rossi, Tonielli, and Vassura 1992;

Bonivento and Melchiorri 1993; Vassura and Bicchi 1993; Melchiorri and Vassura 1992, 1993, 1994; Eusebi, Fantuzzi, Melchiorri, Sandri, and Tonielli 1994). As illustrated in figure 3.119, the hand's kinematic configuration is very close to that of the UB Hand 1, with the same fingers and degrees of freedom. The hand is characterized by its integration with the Puma robotic arm it is installed on: both the hand and the arm subsystems are tightly integrated at the design level and coordinated at the control level, that is to say, there is structural and functional integration of the subsystems into a consolidated manipulation system. The actuators for the hand are located in the forearm of this system, and their motion is transmitted to the joints through tendons routed mainly by pulleys and by sheaths in some places. All the joints are independently actuated, so that makes a total of eleven gear-reduced electric motors (and two additional motors for the wrist). A classical three-level control structure is in charge of the hand-arm system operation: the highest level, implemented on a separate computer, is for planning and task programming; the middle level, implemented on a separate electronic board, is a real-time hand-arm controller which computes the control strategies and generates the setpoints for the servo loops, at a frequency of about 50 Hz; and the lowest level, implemented on an electronic board hosted in the robot's forearm, runs the servo loops and manages the input/output functions (input from the sensors, output to the actuators), at a frequency of about 1 kHz.

The sensorial equipment of the UB Hand 2 is better than that of its predecessor. Indeed, in addition to the usual motor encoders and joint position sensors, a six-axis force sensor is located inside each phalanx, and another lies under the surface of the palm. These sensors, based on strain gauges, measure the contact forces from within the inside of the hand's segments, and by elaboration of the information they provide, combined with the knowledge of the geometry of the surface of the segments, it is also possible to deduce the position of the contact points (provided there is no more than one contact point per segment). This sensorization makes a total of nine "active" surfaces that provide feedback for control and can therefore be involved in the grasping process: the eight phalanges and the palm. So the hand can interact with objects in a controlled manner with all its surfaces, not only with its fingertips, a characteristic that separates the UB Hand 2 from similar hands of that time.

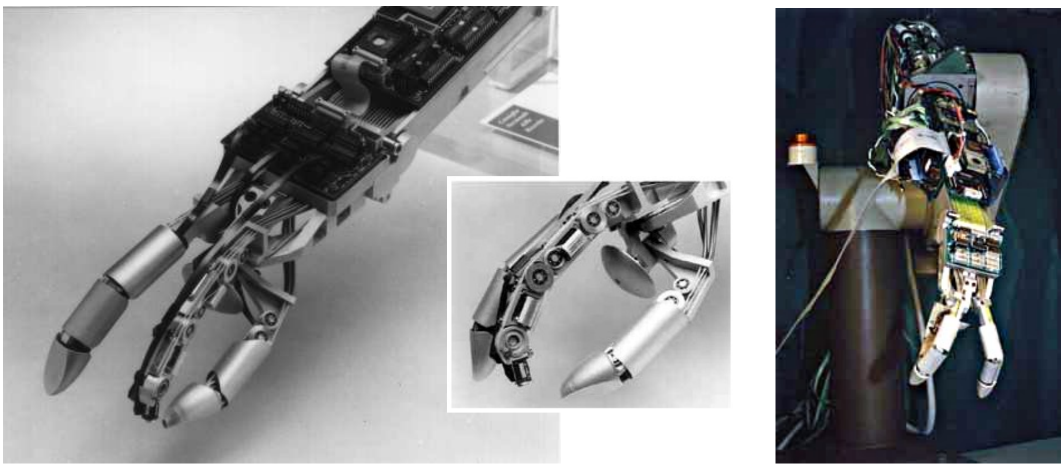


Figure 3.119 – Various views of the UB Hand 2 (1992). The covers of one of the upper fingers are removed to show the inside.

The following version of the University of Bologna Hand, the UB Hand 3, was made much later and is completely different. With five fingers and an anthropomorphic shape, it is "based on an endoskeleton made of rigid links connected with elastic hinges, actuated by sheath-routed tendons and covered by continuous compliant pulps" (Lotti, Tiezzi, Vassura, Biagiotti, Palli, and Melchiorri 2005). The result is shown in figure 3.120.

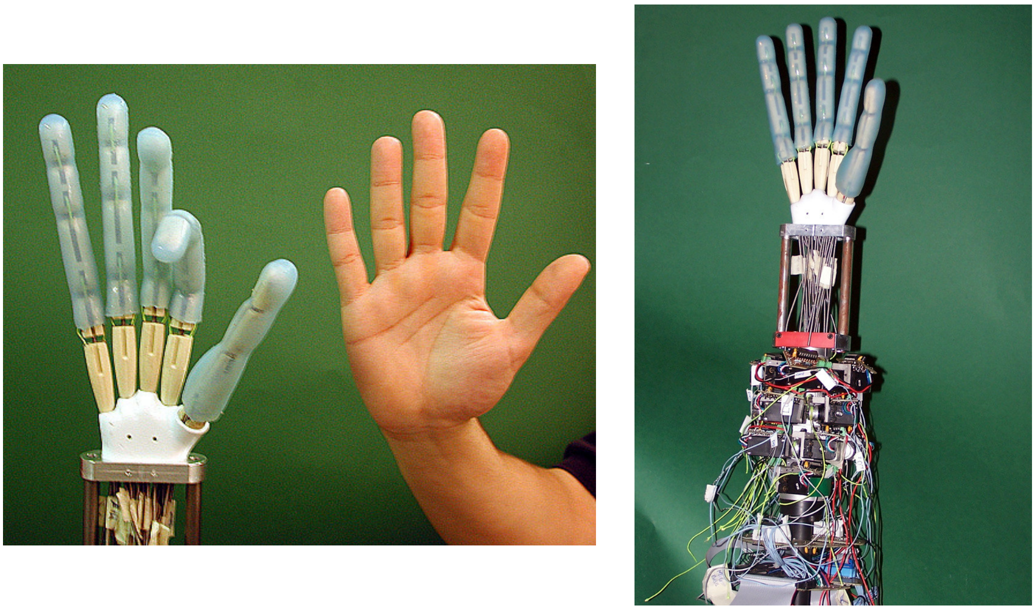


Figure 3.120 – The UB Hand 3 (2005). To keep the hand simple, the four fingers are identical, hence the oversized little finger.

The mechanical structure of this hand is innovative in that it utilizes compliance effects, "considered in the past as a defect to be mechanically eliminated", to produce the desired properties of the device (Biagiotti, Lotti, Melchiorri, and Vassura 2003). It moves from the classical concept of stiff structures, often precise but complex to assemble from many different parts, to the concept of flexible mechanisms, realized with less assembly and a reduced number of parts, some of them able to bend to allow relative motion. The perspective of high mechanical simplification through flexibility has the benefits of reliability enhancement (fewer parts liable to fail or get loose) and cost reduction (fewer parts and also cheaper parts), and therefore a possible larger diffusion of humanoid robotics, that is to say not only in academic or research institutions.

The flexibility in question refers to the joints, which are deformable elements instead of classical revolute pairs based on pin-and-bearing design. In the first prototype of the hand (Lotti and Vassura 2002; Biagiotti, Lotti, Melchiorri, and Vassura 2003), the fingers were made all in one piece from a single polymeric material, and the joints were flexures in this material [62]. Phalanges, joints, and tendons were therefore a single item, milled in a plate of polytetrafluoroethylene, aka PTFE or teflon (figure 3.121). The final UB Hand 3 (Lotti, Tiezzi, Vassura, Biagiotti, and Melchiorri 2004; Lotti, Tiezzi, Vassura, Biagiotti, Melchiorri, and Palli 2004; Lotti, Tiezzi, Vassura, Biagiotti, Palli, and Melchiorri 2005) adopts different materials for the joint hinges, the phalanges and

62. As a side note, this idea of joints being elastic flexures in a one-piece finger can be found in the subsequent SDM Hand, from Harvard University (figure 3.84).

the tendons. The inner structure of each finger is a continuous framework obtained by plastic molding, with inclusion of close-wound steel spiral coils as the elastic elements that form the hinges (figure 3.122). These spiral coils, interestingly, work at the same time as sheaths for tendon routing (figure 3.122(b)).

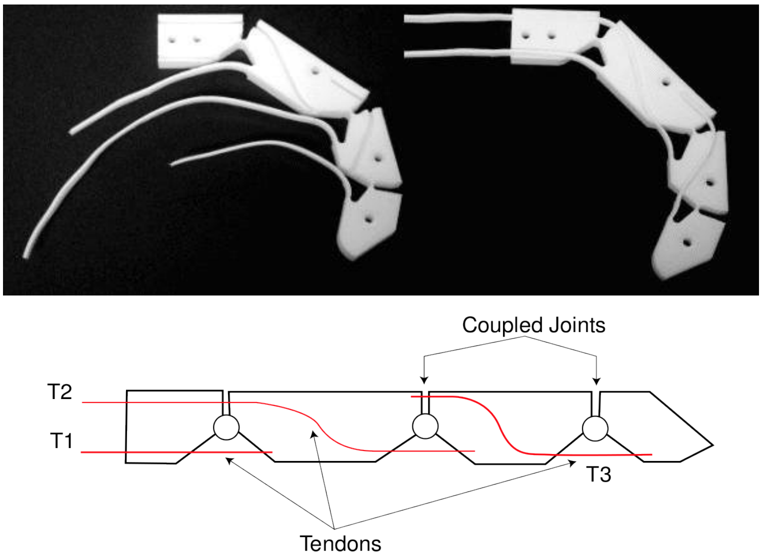
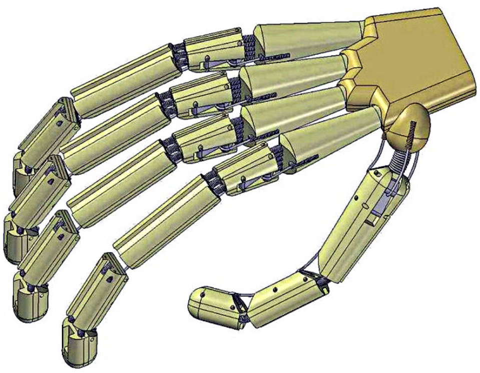
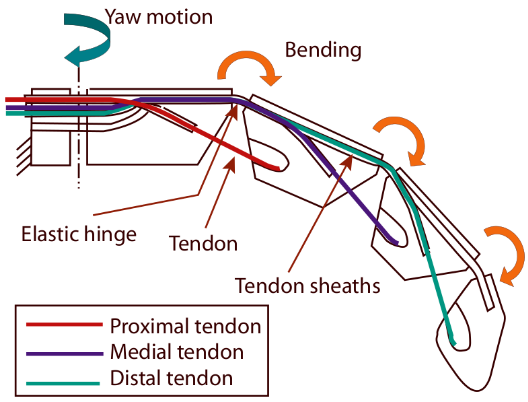



Figure 3.121 – A UB Hand 3 finger prototype (2002) as it comes out of the milling machine (left) and with the tendons put in place (right). Several routing paths have been tried out; here there are two motor tendons and one internal tendon coupling the two distal joints.



(a) UB Hand 3 computer model




(b) Tendon routing inside the index or middle finger (independently actuated joints)

The four fingers have four joints each, but not all the joints are independently actuated: it depends on the finger. All digits together, there is a total of 14 actuated joints, 3 coupled joints and 2 locked joints. The base joint of the thumb is a two-degree-of-freedom joint (actuated by three tendons), so that makes a total of 15 independent degrees of freedom.

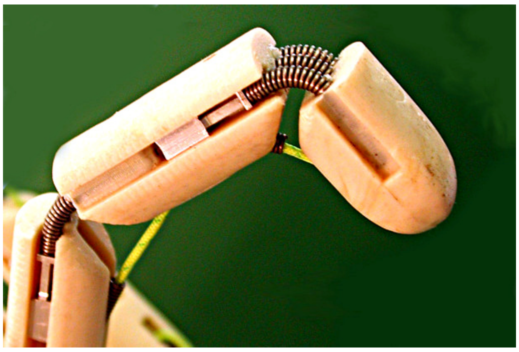
Figure 3.122 – Endoskeleton and tendon routing of the UB Hand 3

Compared with traditional robotic designs, for instance the UB Hand 2, the internal articulated frame of the UB Hand 3 is much more space-efficient. In particular, pulleys are avoided: in traditional design solutions, they "help overcome many problems related to tendon transmission but introduce severe design restrictions, because their diameter cannot be too small and they occupy most of the finger cross section" (Lotti and Vassura 2002). As a result it is often difficult "to host the other necessary things like sensors, wires and skin pads" (Lotti and Vassura 2002). In particular, "in most cases [the robotic hands] are covered with thin layers of elastomeric material, capable to provide high surface friction but not enough thick to actually work as real compliant pads" (Lotti, Tiezzi, Vassura, Biagiotti, Palli, and Melchiorri 2005). All these problems are avoided with the UB Hand 3, whose endoskeleton provides a reduced cross section, leaving enough space for sensors and their wires, and very suitable to be covered with a thick external layer of soft material reproducing the role of the soft tissues of the human hand (Lotti, Tiezzi, Vassura, Biagiotti, and Melchiorri 2004).

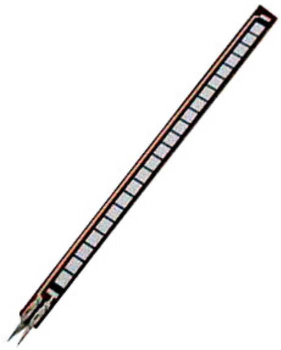
This compliant cover is particular in that it is a continuous external shell covering the whole finger, not just the phalanges as is often the case. It is made of a polyurethane gel, rather than the more common rubbers and silicone rubbers, and it is about 3 mm thick on the phalanges, thinner on the joints. The mechanical properties of this material are investigated by Tiezzi, Lotti, and Vassura (2003), Biagiotti, Tiezzi, Vassura, and Melchiorri (2004), and Biagiotti, Melchiorri, Tiezzi, and Vassura (2005): it exhibits "a softness not far from that a biological tissue", and "a remarkable viscoelastic behaviour, very appreciable for grasp stabilization", besides, it can "sustain without breakage very high strain [...], and is therefore compatible with large shape variations of the covered objects, so that it can be easily used also for covering articulated joints, providing a continuous flesh-like cover of the whole finger". The indentation-depth-versus-normal-load characteristic of the covered fingertip is found to be quite similar to the power-law defined by Xydas and Kao (1999), making the fingers of the UB Hand 3 "soft fingers" (see section 5.1.4 in chapter 5).

Several solutions were tried out for sensing and actuation. Indeed, "the non-conventional structure of the hand imposes the design of ad-hoc force and position sensors" (Lotti, Tiezzi, Vassura, Biagiotti, Palli, and Melchiorri 2005), in particular because their is no clearly identified, fixed center of rotation between the phalanges, so classical joint position sensors such as potentiometers or Hall-effect transducers prove difficult to put in place. On the contrary, any kind of actuator is conceivable, because they are in any case remotely located in the forearm and pull on tendons. Linear synchronous motors, pneumatic muscles, and actuators based on a rotative motor and a ball screw were successively tried out (Biagiotti, Lotti, Melchiorri, and Vassura 2003; Lotti, Tiezzi, Vassura, Biagiotti, and Melchiorri 2004), and the last version of the UB Hand 3 simply uses sixteen low-cost DC electric brushed motors, each equipped with a position sensor and a tendon force sensor. The fingers include other position sensors: a miniature load cell with two strain gauges is located at the basis of one of the springs composing each hinge (figure 3.123(a)). Prior to this joint position sensing solution, flex sensors based on piezoresistive effect were used, just like in data gloves (figure 3.123(b)) (Lotti, Tiezzi, Vassura, Biagiotti, and Melchiorri 2004). As for exteroceptive sensing, tactile sensor arrays were tried out, but the presence of the gel layer reduces their sensitivity, and above all makes their dynamic very slow, because "after the initial application of the external force, [the polyurethane gel] changes its configuration, distributing the external pressure on the overall underlying surface", which makes the force distribution measured by the sensor totally unrepresentative of the reality at the surface of the gel (Lotti, Tiezzi, Vassura, Biagiotti, and Melchiorri 2004). Strain-gauge based intrinsic tactile sensors, directly built on the finger frame, are preferable, because since they measure only the resultant force, not the force distribution, they are unaffected by the filtering effect of the gel.

More information about the UB Hand 3 can be found in the papers by Lotti, Tiezzi, Vassura, and Zucchelli (2002), Lotti and Vassura (2002), and Biagiotti, Lotti, Melchiorri, and Vassura (2003) for the prototype with flexure joints; Lotti, Tiezzi, Vassura, Biagiotti, and Melchiorri (2004), Lotti, Tiezzi, Vassura, Biagiotti, Melchiorri, and Palli (2004), and Lotti, Tiezzi, Vassura, Biagiotti, Palli, and Melchiorri (2005) for the version with spring joints. The laboratory's website hosts videos of the hand moving under teleoperation, and performing a few enveloping grasps and fingertip manipulations (object reorientations), seemingly under teleoperation too (University of Bologna, Laboratory of Automation and Robotics 2011).



(a) Load cell used in the final version of the hand (at the basis of the spring). It has one strain gauge on each side.



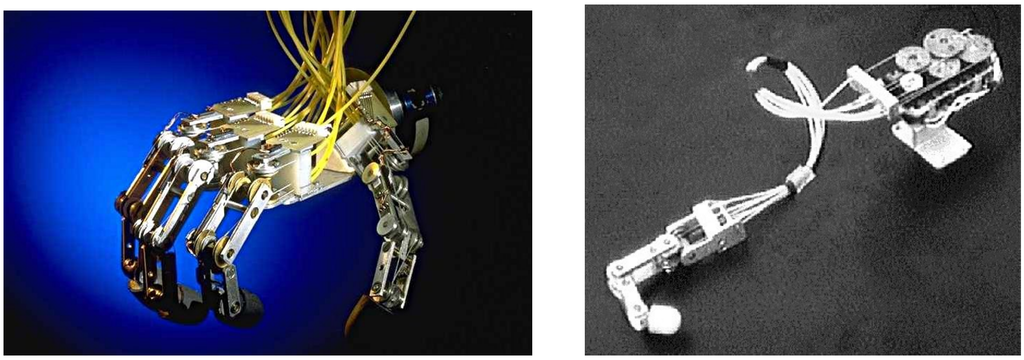
(b) Flex sensor used in the prototype version of the hand

Figure 3.123 – Joint position sensors of the UB Hand 3

**DIST Hand** Another notable Italian robotic hand is the DIST Hand, built at the University of Genoa at the end of the 1990s by Andrea Caffaz, Giorgio Cannata, Giuseppe Casalino and their colleagues (Caffaz, Bernieri, Cannata, and Casalino 1997; Caffaz and Cannata 1998; Caffaz, Cannata, Panin, and Reto 1998; Caffaz, Casalino, Cannata, Panin, and Massucco 2000). It is a four-fingered tendon-driven mechanism with sixteen degrees of freedom and anthropomorphic kinematics, illustrated in figure 3.124. The fingers are identical, the thumb being a finger mounted at an angle on the palm, in opposition to the other fingers. The whole device is human-sized and lightweight, so it can be easily installed on various existing robots, even on small manipulators as illustrated by figure 3.125. DIST stands for the name of the laboratory's department (Dipartimento di Informatica, Sistemistica e Telematica, i.e. Department of Communication, Computer and System Sciences).

Each finger of the DIST Hand has four rotational degrees of freedom and is actuated through six tendons: two tendons fixed on the same motor move the abduction/adduction joint, and four tendons driven by four other motors move the three flexion/extension joints in a "$n + 1$ design" (see figure 3.64 in section 3.3.2). Pulleys are used inside the fingers, and a characteristic feature of the DIST Hand is that the routing of the tendons and the dimensioning of the pulleys have been optimally determined, by an analytical study, to make the mapping between joint torques and tendon tensions as regular as possible, that is to say, avoid sudden changes in joint torques in response to small changes of tendon tensions.

The sensorization of the hand consists of Hall-effect position sensors in the joints, intrinsic three-axis strain-gauge force sensors in the fingertips, and extrinsic tactile



(a) The bare exoskeleton design makes the hand quite unfit to whole-hand grasping. It is more adapted to fingertip manipulation.

(b) A finger with its six tendons and five actuators (sheathed polyester cables, DC electric motors with reduction gears)

Figure 3.124 – The DIST Hand (1997)

sensors based on conductive rubber at the surface of the fingertips (the conductive rubber used is a silicon rubber drugged with silver and graphite; its electrical resistance decreases when it is compressed, making it a pressure transducer). By integrating the information coming from these sensors, it is possible to realize position and force control loops for fine manipulation tasks. The control architecture that was developed consists of a hierarchical two-level closed-loop trajectory tracking control strategy for the motion of the object, with a complementary force control for the contact interactions. Caffaz, Giorgi, Panin, and Casalino (2001) and Casalino, Cannata, Panin, and Caffaz (2001) give the full details of this control.

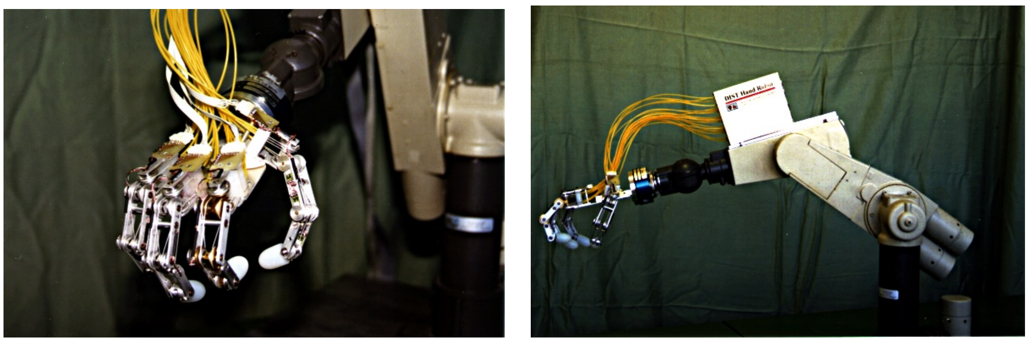


Figure 3.125 – The DIST Hand and its actuator pack mounted on the forearm of a small PUMA manipulator (Panin 2002)

**DLR Hands** The dextrous hands developed by the roboticists at the Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center) in Oberpfaffenhofen, Germany, and later in cooperation with the Harbin Institute of Technology in Harbin, China, are famous for being extremely integrated hands: all their actuators and much of their electronics are located inside them, and virtually every millimeter is occupied by some component – even the power converters for the actuators are integrated in the hand. That way, the hands achieve maximum modularity, that is to say that they are standalone devices which may be mounted on any robot arm with minimal adaptation, a bit like the Barrett Hand: only wires for power and signal come out of them, no tendons or other transmission systems.

The first DLR Hand, conveniently named DLR Hand I, was introduced in 1997, after a first three-fingered gripper-like prototype (H. Liu, Meusel, and Hirzinger 1995). It is a four-fingered construction where all the fingers are identical. It is illustrated in figure 3.126 and was developed by Gerhard Hirzinger, Jörg Butterfass, Stefan Knoch, and Hong Liu (Hirzinger, Butterfass, Knoch, and H. Liu 1998b,a; Butterfass, Hirzinger, Knoch, and H. Liu 1998). Each finger has three joints and three independent degrees of freedom:

- The base joint is realized by a cardan-like mechanism providing the two independent degrees of freedom of a metacarpophalangeal joint, abduction/adduction and flexion/extension, with intersecting axes. It is driven by two miniaturized linear actuators located in the palm.
- A third miniaturized linear actuator is located in the proximal phalanx and drives the proximal interphalangeal joint directly by a short tendon, and the distal interphalangeal joint passively by elaborate coupling via a spring.

The linear actuators in question have been specially designed by the DLR to offer a good compromise between compactness and power. They consist in brushless DC motors whose rotor is a hollow shaft hosting a roller screw to translate directly the rotational motion into linear motion. Their small size (21 mm in diameter, 33 mm in length) makes their integration into the hand possible, although they cause it to be larger than a human hand (approximately 1.5 times), and also heavy (1.8 kg).


Figure 3.126 – The DLR Hand I (1997)

The sensorization of the DLR Hand I is rich: each finger and its three motors integrate 28 sensors, in particular joint angle sensors, joint torque sensors, rotor position sensors, extrinsic tactile sensors, temperature sensors, and a laser diode in the fingertip “to simplify image processing for the tiny stereo camera system integrated in the hand’s palm” (Butterfass, Hirzinger, Knoch, and H. Liu 1998). Preprocessing electronics and analog-to-digital converters are also included into the hand, as close as possible to the sensors in order to keep noise induction low. Thanks to this sensory equipment, several feedback control schemes can be implemented, using the following hardware and software control architecture:

1. A task-level programming environment including a grasp planner, support for model-based manipulation, and support for telemanipulation. A data glove is used for teleoperated execution of fine manipulations and for skill-transfer purposes, that is to say machine learning by demonstration (in order to build autonomous grasping and manipulation abilities).
2. A real-time control environment consisting of a (global) hand controller and a (local, joint-level) finger controller:
    a) The global hand controller runs on a computer running a real-time operating system. It is responsible for collision avoidance, kinematics calculation, cartesian stiffness calculation, and trajectory interpolation.
    b) The local finger controller runs on four printed circuit boards, one per finger, located in a separate box (these electronics are too large to be integrated into the hand). It is responsible for managing the hand's input/output and executing each finger's servo loops.

Joint control strategies for the DLR Hand I are presented by Hong Liu, Jörg Butterfass, Stefan Knoch, Peter Meusel, and Gerhard Hirzinger (H. Liu, Meusel, Butterfass, and Hirzinger 1998; H. Liu, Butterfass, Knoch, Meusel, and Hirzinger 1999).


Figure 3.127 – The DLR Hand II (2000)

The following hand, the DLR Hand II (figure 3.127), was ready in 2000 (Hirzinger, Butterfass, M. Fischer, Grebenstein, Hähnle, H. Liu, Schäfer, and Sporer 2000; Hirzinger, Butterfass, M. Fischer, Grebenstein, Hähnle, H. Liu, Schäfer, Sporer, Schedl, and Köppe 2001; H. Liu, Butterfass, Grebenstein, and Hirzinger 2001; Butterfass, Grebenstein, H. Liu, and Hirzinger 2001; DLR 2010). It demonstrates better manipulation abilities and an even higher degree of integration, in particular by the massive reduction of the wiring going in and out of the hand. It is still larger than a human hand and weights the same as the DLR Hand I, 1.8 kg.

The development of the Hand II is of course based on the results of the use of the Hand I. The main design targets for the new version were better performance in grasping and manipulation, increase of the velocity and force of the fingers, and easier manufacturing, assembly and maintenance (Hirzinger, Butterfass, M. Fischer, Grebenstein, Hähnle, H. Liu, Schäfer, and Sporer 2000). The main differences from the previous version are summarized below:

**Endoskeletal design** To facilitate access to the components of the fingers and make their maintenance easier, an endoskeleton and removable shell covers are preferred to the former cylindrical exoskeleton.

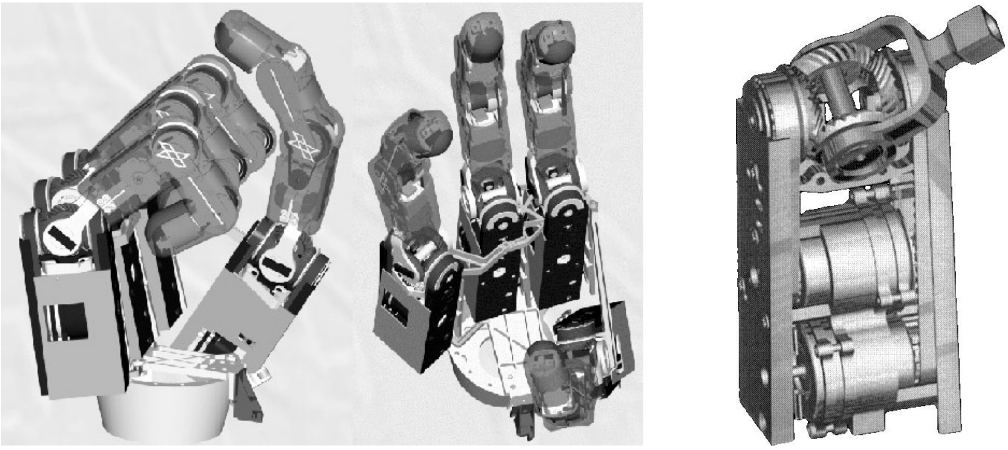
**Configurations for power grasp and precision grasp** Hirzinger, Butterfass, M. Fischer, Grebenstein, Hähnle, H. Liu, Schäfer, and Sporer (2000) note that "the results gained in simulation and practical usage showed that the position of the four fingers of Hand I are not yet optimal for doing fine manipulation nor for doing power grasps". Therefore, Hand II was designed with an additional degree of freedom that switches the hand between a power grasp configuration and a precision grasp configuration: in the power grasp configuration, the second, third and fourth fingers are nearly parallel, whereas in the precision grasp, the fourth finger and the thumb are brought closer and in better opposition (figure 3.128(a)). Strictly speaking, it would rather be a prismatic grasp configuration and a circular grasp configuration in fact, because both can be used for power grasping as well as precision grasping (see section 2.2 in chapter 2 on that matter).

**New base joint and better actuation** Instead of a cardan-like mechanism actuated by two linear actuators, the new base joint is a differential bevel gear driven by two rotational actuators (figure 3.128(b)). This has a significant advantage. In Hand I, each degree of freedom of the joint has its own actuator, which means that motion according to one degree of freedom does not utilize the actuator of the other degree of freedom. In Hand II, "the torque and power of both actuators is used for manipulation without respect of the desired direction of actuation" Hirzinger, Butterfass, M. Fischer, Grebenstein, Hähnle, H. Liu, Schäfer, and Sporer (2000). For flexion/extension, "the motors apply a synchronous motion to the bevel gears using the torque of both motors". For abduction/adduction, "the motors turn in contrary directions, [...] again using the torque of both motors". The consequence is that the maximum force produced on the fingertip is doubled, while using identical motors.

**Force/torque fingertip sensor** A few sensors are changed for better ones in the new hand, but the most important novelty is a custom-designed six-axis force/torque sensor, 20 mm in diameter and 16 mm in height, developed for the fingertips. It is, of course, strain-gauge based.

**Electronics, communication, and wiring** There are around 400 cables coming out of the DLR Hand I, to bring power to the actuators, sensors, electronics, and fetch sensor values for control. This is of course extremely cumbersome. In the new hand, through better integration of electronics and a brand new, high-speed communication architecture, wiring is reduced to 12 cables: a four line power supply and an eight line communication interface (Butterfass, Grebenstein, H. Liu, and Hirzinger 2001). This reinforces the modular nature of the hand, making it extremely easy to don and doff. Haidacher, Butterfass, M. Fischer, Grebenstein, Jöhl, Kunze, Nickl, N. Seitz, and Hirzinger (2003) present the new communication architecture, and more generally the hardware and software architecture for the whole information processing (data collection, sampling and preprocessing; communication layer; low level control and high level control).

A lot of research on manipulation and grasping has been conducted at the DLR with the help of the DLR Hand II. In particular, this system helped research on cartesian impedance control approaches; see, for instance, Biagiotti, H. Liu, Hirzinger, and



(a) Power and precision configurations. This minor degree of freedom is realized with just one motor (a small, slow brushed DC motor) which moves both the thumb unit and the ring finger unit. It simulates the intermetacarpal mobility we have in our hands.

(b) The base joint of the fingers. Each actuator is made of a brushless DC motor and a small harmonic drive gear, and drives one wheel of the differential bevel gear.

Figure 3.128 – Mechanical details of the DLR Hand II

Melchiorri (2003) and Wimböck, Ott, and Hirzinger (2006, 2008). Recently, two-hand grasping and manipulation have been experimented too, with DLR's half-humanoid robot Justin, an upper body system which uses two DLR Hands II (figure 3.129) (Ott, Eiberger, Friedl, Bäuml, et al. 2006; Borst, Ott, Wimböck, Brunner, Zacharias, Bäuml, Hillenbrand, Haddadin, Albu-Schäffer, and Hirzinger 2007; Wimböck, Ott, and Hirzinger 2007).

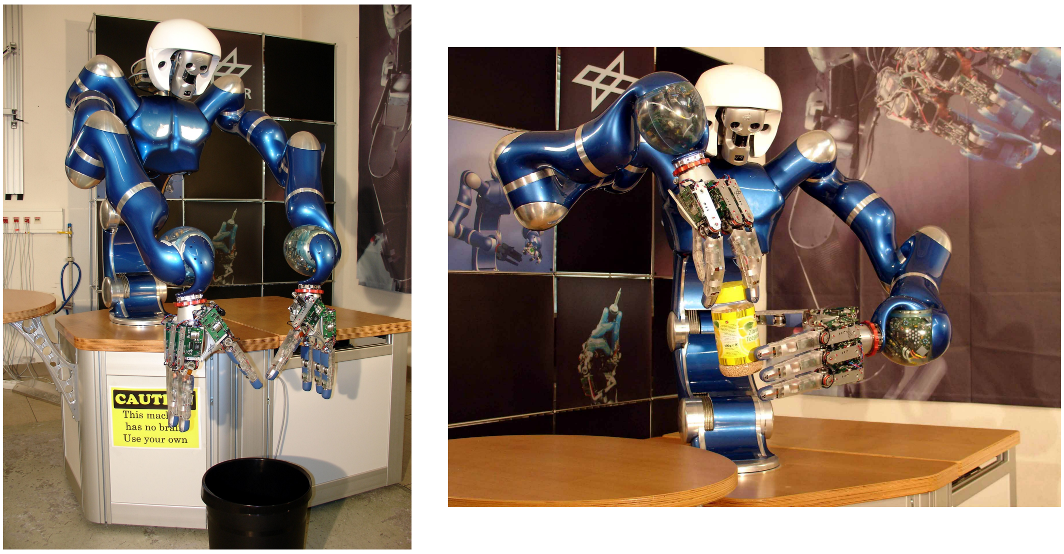


Figure 3.129 – DLR's Justin, so called because it was finished "just in time" for the 2006 Automatica fair in Munich. The half-humanoid combines two of DLR's most well-known realizations: the Lightweight Robot Arm III and the Hand II.

**Gifu Hands and KH Hands** The dextrous hands developed at Gifu University, in Japan, share with the DLR Hands the characteristic of actuators being located directly inside the hand. This makes them modular, like the DLR Hands (that is to say easily adapted to any kind of robot manipulator). Tactile sensitivity is the other distinctive feature of these hands: the palm and the palmar side of the phalanges are entirely covered by a distributed tactile sensor comprising several hundreds sensing points. Even though these sensing points are far from measuring up to the mechanoreceptors of our hands, be it in terms of number, density, sensitivity or frequency response range (see section 2.1.5 in chapter 2 for a description of human tactition), they still provide the Gifu Hands with a tactile sensing capability superior to that of most robot hands.

There have been three Gifu Hands and two KH Hands developed and built at Gifu University: the Gifu Hand I, the Gifu Hand II, the Gifu Hand III, the KH Hand, and the KH Hand type S (Gifu University, Kawasaki/Mouri Laboratory 2010). The first model, the Gifu Hand I, was developed in the late 1990s and introduced in 1997, something else in common with the DLR Hands. The last models of each line, that is to say the Gifu Hand III and the KH Hand type S, are sold today by the company Dainichi (2010) as experimental platforms for research projects. All five models are very close to each other in design and appearance, but they have several important differences too.

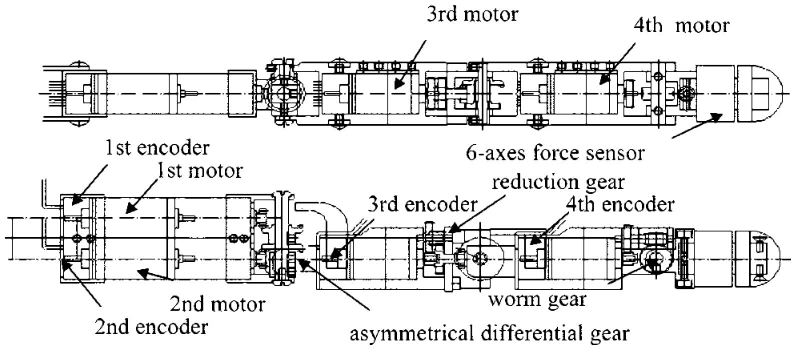
The Gifu Hands and the KH Hands are all five-fingered anthropomorphic constructions, actuated by servomotors built in the palm and fingers. Because of the integrated actuation, they are slightly larger than an average human hand (the Gifu Hand III is about 1.5 times larger, like the DLR Hands). They are also relatively heavy: the Gifu Hands weight about 1.4 kg. However the KH Hand is slimmed down to 1.1 kg, and the KH Hand type S to 620 g.

All the digits have three joints and four degrees of freedom: the base joint provides both abduction/adduction and flexion/extension, with orthogonal axes as in the human hand and in the DLR Hands. The main difference between the thumb and the fingers is shown in figure 3.130: the last joint of the thumb is actuated by its own servomotor, located in the second link (proximal phalanx), whereas the last joint of each finger is coupled with the preceding joint by a planar four-bar linkage mechanism, so these two joints share the same servomotor, located in the first link (proximal phalanx). As a result, there are sixteen independent degrees of freedom, and the thumb is more dexterous and more powerful than the fingers. The KH Hand type S is different however: its thumb doesn't have the additional degree of freedom and all its digits are identical.

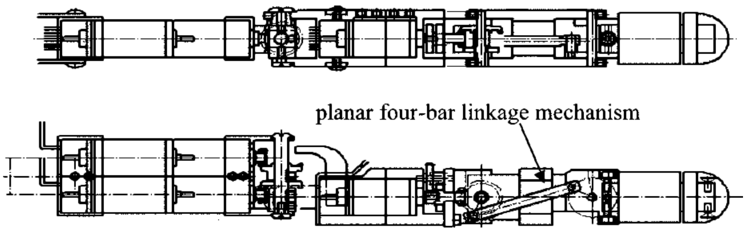
The differences between the models of the Gifu Hand and KH Hand series concern mainly tactile sensing and some improvements in the mechanical design:

**Gifu Hand I** The first Gifu Hand didn't have any tactile sensing ability at all, it was just an early prototype build to get the mechanical design right (H. Kawasaki, Komatsu, Masanori, and K. Uchiyama 1998; H. Kawasaki and Komatsu 1999).

**Gifu Hand II** The second Gifu Hand however was covered with a custom-developed distributed tactile sensor, comprising 624 sensing points: 312 on the palm, 72 on the thumb, and 60 on each finger. The fingertips were also equipped with six-axes force/torque sensors. The base joints were re-designed to reduce backlash, and the motors and reduction ratios were changed to increase the output torque. The Gifu Hand II is illustrated in figure 3.131 and documented by H. Kawasaki, Komatsu, K. Uchiyama, and Kurimoto (1999), H. Kawasaki, Shimomura, and Shimizu (2001), and H. Kawasaki, Komatsu, and K. Uchiyama (2002).

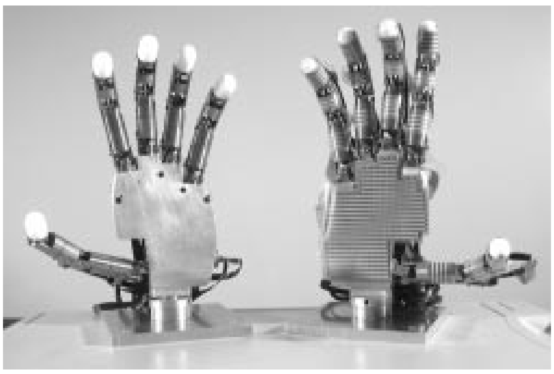



(a) Thumb

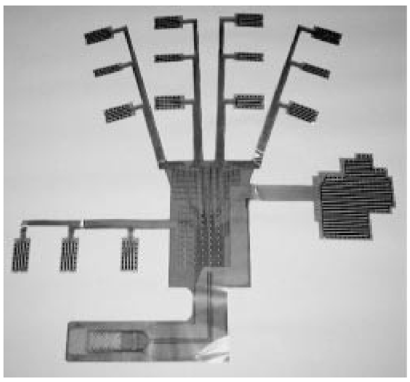



(b) Finger

Figure 3.130 – Mechanical design of the digits of the Gifu Hand II. They are built as exoskeletons, and the thumb is slightly longer. All the servomotors use DC motors and reduction gears, and include magnetic position encoders. The transmission to the joints is gear-based and does not include tendons.



(a) The hand on the right is covered with the tactile sensor.



(b) The sensor has grid pattern electrodes and uses conductive ink whose electric resistance changes in proportion to pressure.

Figure 3.131 – The Gifu Hand II and its distributed tactile sensor (1999)

**Gifu Hand III** The third and current Gifu Hand, shown in figure 3.132, has better tactile abilities than the Gifu Hand II, with 859 detecting points in the sensor: 313 on the palm, 126 on the thumb, and 105 on each finger (Mouri, H. Kawasaki, K. Yoshikawa, Takai, and S. Ito 2002). The base joints were improved again to further reduce backlash, and the fingers were slightly moved to enhance thumb opposability (figure 3.133). It is important to reduce backlash to a negligible amount because there are no position sensors in the joints, contrary to the majority of robotic hands. Position sensing depends solely on the motor encoders, and backlash in the gear transmission makes it impossible to get a reliable measurement of joint angle from motor angle.

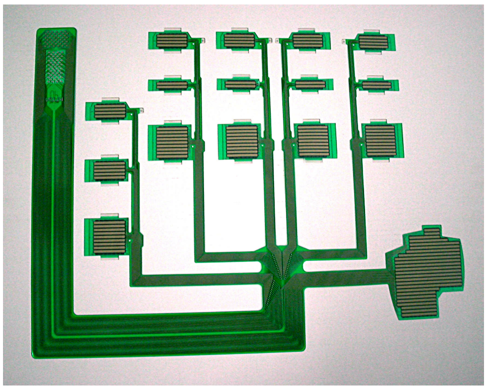
**KH Hand** The KH Hand, or Kinetic Humanoid Hand, is mainly a downsized Gifu Hand III (see size comparison in figure 3.134). Two factors contribute to a length reduced to 88% of that of the Hand III (H. Kawasaki, Mouri, and S. Ito 2004). First, the hand uses smaller, custom-developed prototype motors, with a diameter changed from 13 mm to 12 mm and a length reduced to 90% of that of the commercial motors used in the Hand III. But most importantly, the major factor is the reduction of wiring, which clutters the frame of the Hand III. Indeed, six wires are required to bring ground, power, and signal to each actuator (meaning motor, encoder, and control circuit). So that makes a total of 96 wires for all the actuators, not counting the lines for the fingertip force sensors and the distributed tactile sensor. In order to save space, a high-speed serial system was investigated for the KH Hand, which transmits high-voltage power, low-voltage power, control signals, sensor signals, and synchronization signals for the whole hand overlaid in only two wires (H. Kawasaki, Mouri, and S. Ito 2004). This system was also implemented on the Gifu Hand III.

Despite the size reduction of the hand, the number of detecting points in the tactile sensor could be slightly augmented by reducing the size of the electrodes and the space between them. There is now a total of 895 sensing points: 321 on the palm, 126 on the thumb, and 112 on each finger.

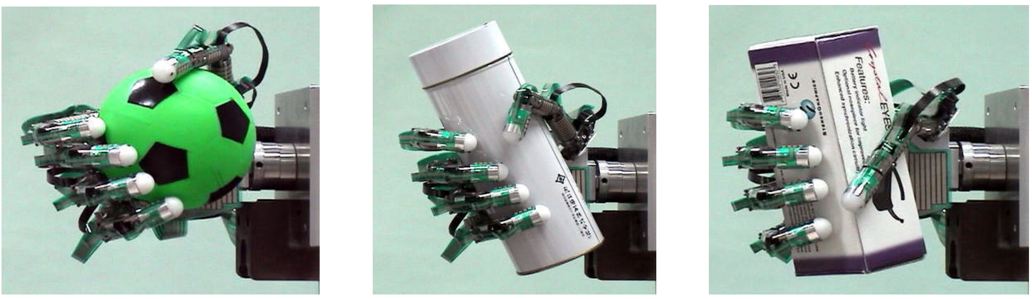
**KH Hand type S** This last hand differs from the KH Hand mainly by the loss of the thumb's additional degree of freedom, the change from a titanium frame to a lighter plastic frame, and the use of commercial motors again instead of the prototype motors. Indeed, even though the prototype motors of the KH Hand are small, their drivers are large and difficult to miniaturize. The commercial motors used in this hand are even smaller (10 mm in diameter) but they are also much weaker (Mouri, H. Kawasaki, and Umebayashi 2005; Mouri and H. Kawasaki 2007).

The roboticists at Gifu University study not only the mechanical structure of robot hands, but also control methods for grasping and dextrous manipulation. They have therefore used the Gifu Hands and the KH Hands as experimental platforms in their work during the whole last decade, in particular to validate adaptive control laws, investigate machine learning by demonstration, and experiment with telemanipulation approaches. The knowledge of robotics technology that they acquired with these hands also inspired other systems, in particular a five-fingered haptic interface and a virtual-reality-based hand rehabilitation system. Mouri, Endo, and H. Kawasaki (2011) recently wrote a retrospective review of this decade of research with robot hands at their laboratory, from the manufacturing to the applications.

(a) The hand on the left is covered with the tactile sensor.



(b) Conductive-ink-based tactile sensor



(c) Various power grasps

Figure 3.132 – The Gifu Hand III and its distributed tactile sensor (2002)

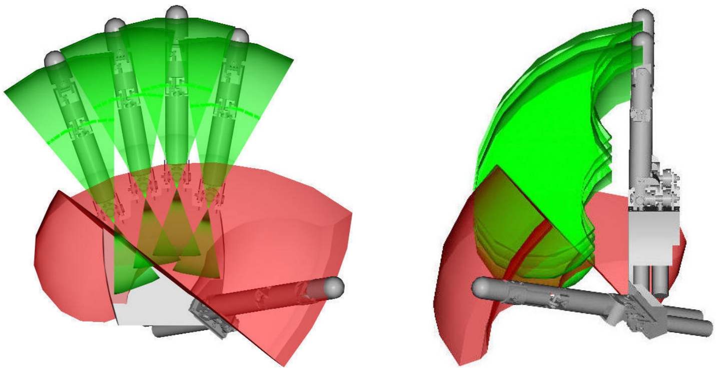


Figure 3.133 – Workspace of the fingertips of the Gifu Hand III

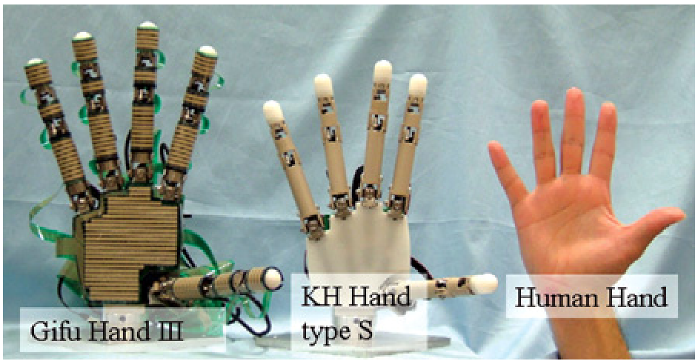



Figure 3.134 – Size comparison between Gifu Hand III, KH Hand type S, and human hand. All the wires in the robotic hands run along the back, so as not to hinder finger motion.

**Shadow Dextrous Hand** For several reasons, electric actuation is the actuation of choice for most dextrous hands. Electric motors are common, diverse, inexpensive, low-maintenance, well-known, and easy to control. Electric energy can be acquired very simply from a power socket and an adequate transformer. In comparison, hydraulic and pneumatic actuators are subjects to leaks and require specialized sources of energy, namely liquid tanks and gas cylinders, in addition to electric energy for pumps and valves and their associated electronics.

So it comes as no surprise that the previous dextrous hands are all driven by electric motors. However, hydraulic and pneumatic actuators have their own advantages, among which inherent compliance, less noisy operation, and a much higher power-to-weight ratio than electric actuators (several hundreds to one instead of a few dozens to one). So there exist a few non-electrically actuated dextrous hands. The Shadow Dextrous Hand is no doubt the most well-known.

The Shadow Dextrous Hand is a relatively recent creation of a small robotics company located in London, United Kingdom, and employing a dozen persons: the Shadow Robot Company. Originally, this company was a group of robot enthusiasts set up in 1987 by Richard Greenhill, a professional photographer and amateur roboticist [63] (R. Walker 1996; Shadow Robot Group 1997; Grossman 2009; Sims 2010). The group met weekly to work on the development of a household humanoid robot [64]: an optimistic goal given their lack of specialized knowledge and the little funding of the project (money initially came from the photographic library business Richard Greenhill and his wife Sally owned). Over the course of the 1990s, they build several robotic systems, in particular a bio-inspired two-leg prototype named the Shadow Biped or the Shadow Walker (figure 3.135) (R. Walker 1996; Shadow Robot Group 1997). They also developed and implemented a basic balance control scheme that would make this robot stand up straight and "remain in this position, under its own control, for periods of fifteen or more minutes" (Shadow Robot Group 1997; Shadow Robot Company 2005). The biped even staggered two steps once, but it was accidental. All of this hardware and software development remained relatively

63. He is described in a newspaper as the "archetypal eccentric British hobbyist" (Grossman 2009).
64. This goal seems to be the origin of the name for the group and the company: Richard Greenhill's manifesto for the Shadow Project, written in October 1986, is a long and simplistically optimistic description of how our lives would be better if "our Shadows" did all the chores of our daily lives for us (see Shadow Robot Group 1997).

primitive, but it helped the members of the Shadow Robot Group to gain knowledge in robotics technology and experience with pneumatic muscles (figure 3.135), which are the actuators of all its past robots and the basis for the Shadow Dextrous Hand.

The Shadow Robot Company was established in 1998 by a small team of the original developers, to sell air muscles, build air-muscle-based robots on demand, and work on the development of a bio-inspired robot hand rather than keep working on the biped. Indeed, following the lauch of the "Humanoid Robotics Project" in Japan by the Ministry of Economy, Trade and Industry, and the visit of Hirochika Inoue, professor at the University of Tokyo and leader of the project, to Shadow in London (Shadow Robot Company 2011), the robotics team decided to leave it to the Japanese to keep working on humanoids, and "moved on" [65] (Sims 2010). Besides, they had realized that even if a robot has legs and can move around human environments, it is still going to need hands in order to be useful in these environments (Sims 2010). So in keeping with the "household humanoid robot" objective from the starts of the Shadow Robot Group, it was logical to investigate not only locomotion but also manipulation abilities.

The first prototypes of the Shadow Dextrous Hand, called Hand A and Hand B (figure 3.136), were developed at the start of the 2000s (Tuffield and Elias 2003; Shadow Robot Company 2003). They were followed by Hand C, which is now in its sixth version, that is to say, Hand C6, and is the current Shadow Dextrous Hand (Reichel and Shadow Robot Company 2004; Shadow Robot Company 2011).

In its current version, the Shadow Dextrous Hand is a five-fingered humanoid robot hand, similar in size and articulation to the human hand, and built with a combination of metals and plastics (Shadow Robot Company 2009, 2010, 2011). It is driven through sheathed tendons by actuators located in a forearm. The hand shows a high degree of bioinspiration, if not biomimetics, and has a total of twenty-four degrees of freedom, twenty of them being independently actuated (figure 3.137):

- The wrist has two independent degrees of freedom, flexion/extension and radio-ulnar deviation. Prono-supination is absent, although it can still be realized by rotating the whole forearm. The situation is actually similar to the human model: in our hands, prono-supination is not realized by the condyloid radiocarpal joint but by the relative motion of the ulna and radius (see section 2.1.1 in chapter 2 for more on the human model). The forearm of the Shadow Dextrous Hand only has one central "bone" though.
- The hand itself has twenty-two degrees of freedom, eighteen of them independent: as in our hands and in most robot hands, the four distal interphalangeal joints of the fingers are coupled to the proximal interphalangeal joints. All the degrees of freedom of our hands are closely imitated, even the intermetacarpal mobility (there is an additional joint below the little finger to provide the hand with a "cupping" or "hollowing" motion of the palm) and the slight abduction/adduction of the thumb metacarpophalangeal joint (it is a two-degree-of-freedom joint, and the Shadow Hand is the only robot hand which reproduces it).

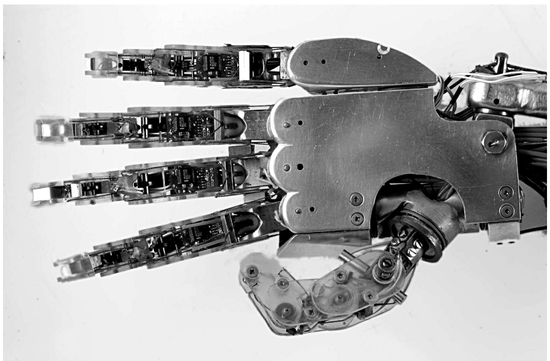
65. This was the right decision, considering that Japanese robotics already had a strong focus on humanoids, that Honda was developing an army of humanoid robots which eventually led to Asimo in 2000, that the roboticists involved in the Humanoid Robotics Project quickly developed a series of state-of-the art human-like robots, the HRP robots, and that in the end the 2000s established Japan as the world leader in humanoid robotics. See figure 3.90 for a few details and references on Asimo and the HRP robots.


The biped is build around a wooden skeletal frame (maple). There is a total of eight joints, enabling twelve degrees of freedom. Twenty-eight air muscles are mounted as antagonist pairs, in accordance with the bio-mimetic approach. The upper body consists of the control valves, the pressure sensor gauges, the control electronics and the various computer interfaces. The whole robot stands 160 cm tall. The control of the biped's balance is pretty basic and based on joint position measurements. Each joint has a center position, and deviations from this position are corrected by filling and emptying the appropriate muscles according to two simple rules: if the deviation is in a certain direction, fill agonist muscle and empty antagonist muscle, and if the deviation is in the other direction, empty agonist muscle and fill antagonist muscle (Shadow Robot Group 1997; Shadow Robot Company 2005).

The air muscles operate on compressed air at low pressure. They consist of a rubber tube wrapped in a tough plastic weave which shortens in length when pulled out. So when the tube fills with air, it expands and pulls out the plastic weave, which shortens the whole muscle (Shadow Robot Company 2005).

Figure 3.135 – The Shadow Biped, or "Arnie" as it was nicknamed, and its actuator the Shadow Air Muscle

(a) Hand A. The skeletal frame has individualized metacarpals, and it is made of wood (maple).



(b) Hand B. The little finger has a separate mounting to provide an extra degree of freedom.

Figure 3.136 – Shadow Dextrous Hands A and B (prototypes, early 2000s) (Shadow Robot Company 2003)

Hall-effect sensors are installed at each joint to sense the position of all these degrees of freedom. For exteroception, tactile sensor arrays can be installed on the fingertips (34 tactels each) (Reichel and Shadow Robot Company 2004; Shadow Robot Company 2011).

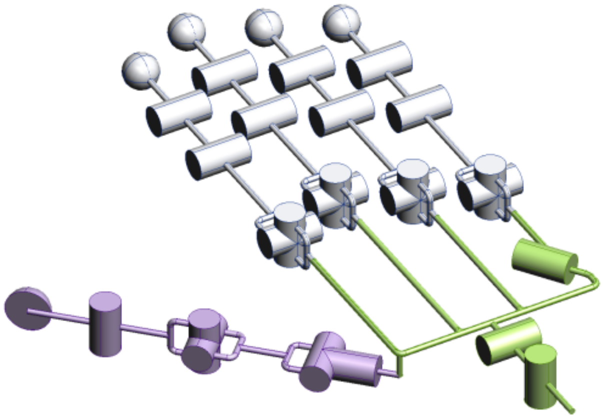


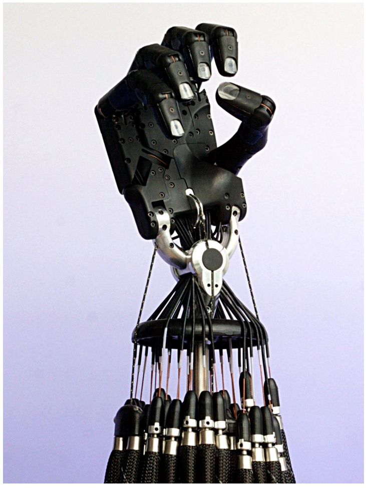
Figure 3.137 – Kinematic structure of the Shadow Dextrous Hand C6

In the original, pneumatic version or the Shadow Dextrous Hand, the actuators are air muscles (figure 3.138; Shadow Robot Company 2010; Greenhill, Elias, R. Walker, and Godden 2007, 2010). However, an electric model of the Shadow Dextrous Hand has been released recently, and it uses high-efficiency rare-earth motors (figure 3.139; Shadow Robot Company 2009; Rosa Tames, R. Walker, Goldsmith, Elias, Godden, and Greenhill 2011). The pneumatic model is called the "Dextrous Air Muscle Hand" and is identified by the C6P version number, while the electric model is called the "Smart Motor Hand" and is identified by the C6M version number. The hand itself remains the same, only the actuation system changes.

**Shadow Dextrous Hand C6P** In the pneumatic model, forty air muscles located in the forearm work in antagonist pairs to drive the twenty independent degrees of freedom. In addition, the forearm contains eighty control valves, two per muscle: air input and air output. Air pressure sensors and integrated electronics to manage sensor feedback and drive the valves accordingly are also present. To accomodate all this hardware, the forearm is much wider than a normal human forearm. The control boards implement proportional-integral-derivative control of individual valves, permitting control of joint position and muscle pressure.

**Shadow Dextrous Hand C6M** In the electric model, twenty electric actuators are coupled to the twenty independent joints via two antagonist tendons each. The forearm also contains tendon force sensors and integrated electronics to manage sensor feedback and drive the motors. In comparison with the pneumatic model, the forearm is shorter, but it is still much wider than a human forearm. The control boards implement proportional-integral-derivative control of joint position and joint torque (two nested servo loops, inner force and outer position).

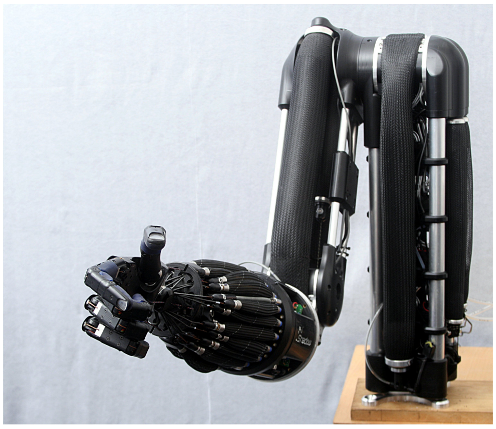
In both cases, the whole system weights around 4 kg, its force output is limited to that of the human hand for safety reasons, and its maximum speed is on average about half the maximum speed of the human hand. A controller area network bus interfaces the hand to the outside world, namely a standard x86-compatible computer running Debian GNU/Linux with the Real-Time Application Interface kernel extension and various open-source software written by Shadow. This computer is the offboard controller, on which high-level control strategies can be programmed. It has full access to all the hardware of the robot; for instance it can read the sensor values, change the gains and the setpoints of the onboard proportional-integral-derivative controllers, or even deactivate them completely (Shadow Robot Company 2009, 2010, 2011).



Nails add to the biomimetics.

Side view of the hand.

For compliant grasping, polyurethane pads are installed on the fingers (blue).



Hand and forearm mounted on a biomorphic arm. The arm uses air muscles too.

Figure 3.138 – Shadow Dextrous Hand C5P (2006)

The Shadow Robot Company does not investigate applications and high-level control issues for its product, preferring to focus on the hardware and concentrate on “making the best hand [they] can” (Shadow Robot Company 2011). However several of its customers have acquired hands to work on these issues, and many others have bought air muscles and the associated low-level control hardware to support their own research. The first customer to order a whole hand was the neuroinformatics group at the University of Bielefeld, Germany, in 2004 (Kochan 2005; Shadow Robot Company 2011). They used the hand in their research on artificial intelligence for vision-based grasping (see e.g. Ritter, Haschke, Koiva, Röthling, and Steil 2005; Röthling, Haschke,

Figure 3.139 – Shadow Dextrous Hand C6M (2009)

Steil, and Ritter 2007). NASA also bought a Shadow Hand during the development of its Robonaut, and it was used as a source of inspiration and to experiment with grasping and manipulation algorithms. Other customers who needed the whole hand too were the Carnegie Mellon University in Pittsburgh, Pennsylvania, and recently the University Pierre and Marie Curie in Paris, France (Shadow Robot Company 2011).

**Dextrous hands for humanoid robots** In the previous pages, we have reviewed many dextrous hands. Few of them are actually mounted on humanoid robots: the only examples are the hands of Robonaut and Justin (figures 3.110 to 3.117 and figure 3.129). Instead, attachment on a manipulator arm is much more common, and also much easier, mainly because space and weight constraints aren't as restrictive as they are for a humanoid robot.

As a matter of fact, the hands of humanoid robots are more frequently adaptive than dextrous. That is to say, most humanoid robots use underactuated hands capable of whole-hand adaptive grasping of objects, rather than fully actuated hands able to perform dextrous manipulations too. Examples of humanoids robots with adaptive hands can be found easily in Japanese and Korean robotics: a lot of their humanoid robots have such hands (some of them are illustrated in figures 3.89 to 3.91).

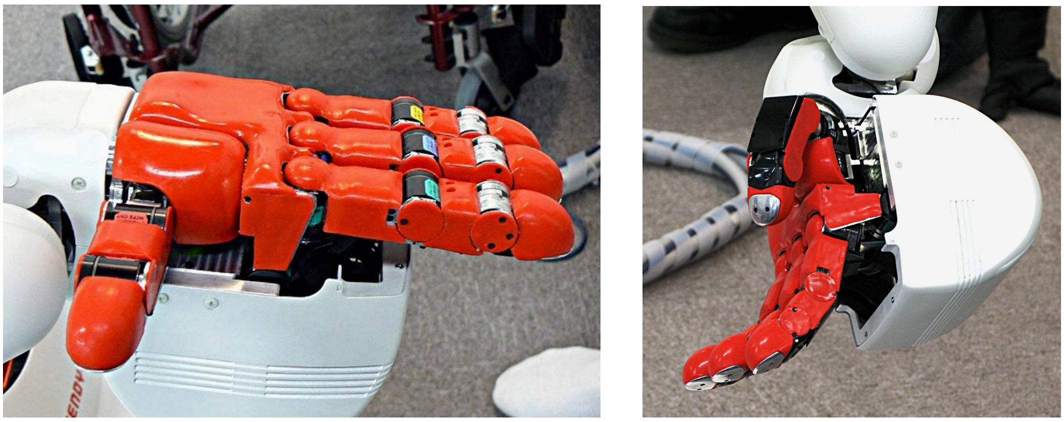
To conclude this chapter on robot hands, we report here on three dextrous hands actually used by a few recent humanoid robots: Twendy-One, Reem-B, and iCub. Together with Robonaut and Justin, they make up the few humanoids (or at least half-humanoids[66]) having hands articulated and actuated enough to exhibit a certain in-hand manipulation ability. As far as I know, there aren't any others at the moment.

66. Robonaut and Justin are upper bodies only and Twendy-One has wheels instead of legs.

**Twendy-One** The robot Twendy-One has been developed at Waseda University in Tokyo, Japan. It is the follow-up to the university's previous humanoid robot, Wendy (figure 3.89). As such, it is a wheeled humanoid too.

The new robot was introduced in November 2007 as a potential daily life support robot for the elderly. Therefore safety, dependability, and human-friendliness have been emphasized in the design, described by Iwata and Sugano (2009b) and the Waseda University Twendy Team's website (2011). The key feature of the robot is the combination of high output actuators with passive elements located in the joints and on the outer shell: namely, passive impedance mechanisms similar to springs and dampers (Sugaiwa, Iwata, and Sugano 2008a), and a soft shock-absorbent silicone rubber skin covering much of the robot (Sugaiwa, Iwata, and Sugano 2008b). That way, the robot is strong enough to help an old person stand up or sit down, and compliant enough for safe physical contact with humans.

Extra care has been given to the hands and their control, so that the robot is able to handle a lot of objects found in our daily lives (Iwata and Sugano 2009a). As a matter of fact, these hands represent a fair attempt at anthropomorphism in form (figure 3.140) and function (figure 3.141). Each hand has three fingers, a thumb, and thirteen independent degrees of freedom: four for the thumb and three for each finger (the distal interphalangeal joint is coupled to the proximal interphalangeal joint). The actuators are directly embedded in the joints they drive, so they are not very powerful and the hand is bigger than a human hand. The side and palmar parts of the fingers and palm are covered with compliant material. They are also equipped with distributed tactile sensors based on capacitive technology and comprising 241 pressure-sensing points. The fingertips have a curved, human-like shape and include a six-axis force/torque sensor. Hard nails are provided to help the robot pick up small and flat objects (for instance coins fallen on the floor, which old people may find difficult to reach).

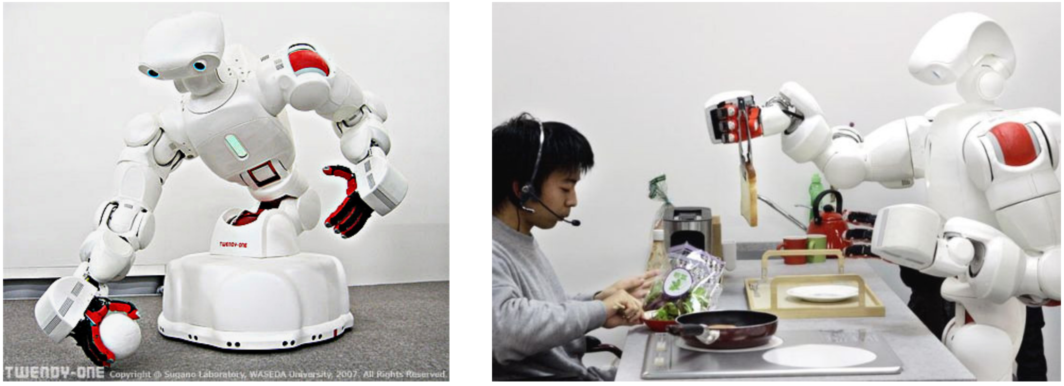


(a) Right hand, palmar view. The motors are visible in the joints except the distal joints of the three fingers.

(b) Left hand, side view. Most of the red material is a compliant artificial skin.

Figure 3.140 – The hands of the humanoid robot Twendy-One

Thanks to the important articulation, good motorization, extensive sensorization, and adequate control algorithms (Sugaiwa, Yamaguchi, Iwata, and Sugano 2009; Sugaiwa, Nezumiya, Iwata, and Sugano 2010; Sugaiwa, K. Iwamoto, Iwata, and Sugano 2010; Sugaiwa, Fujii, Iwata, and Sugano 2010), the hands of Twendy-One can perform nineteen grasp types in both whole-hand power and fingertip precision categories, and they do not crush or drop the grasped object. A certain degree of dextrous manipulation can be achieved too, but only one particular demonstration, albeit an impressive one, has been publicized: picking up a straw and manipulating it among the fingertips (figure 3.142) (Waseda University Twendy Team 2011). So dextrous manipulation with Twendy-One remains to be generalized.




(a) The robot picks up an object fallen on the floor (spherical power grasp).

(b) The robot picks up a toast from a toaster and places it on a plate (prismatic precision grasp of the tongs) while a student prepares a salad, during a demonstration at Waseda University in 2007.

Figure 3.141 – Twendy-One (2007)

Despite its undeniable achievements, Twendy-One needs improvements in many respects before it can become a useful service robot. Its battery life is too short (15 min), it is too heavy (111 kg for 147 cm), its expected price is too high (around US $ 200 000), it is extremely noisy, and of course speed and control are always in need of improvements, especially for manipulation tasks. A practical model is supposed to be ready for release by 2015.

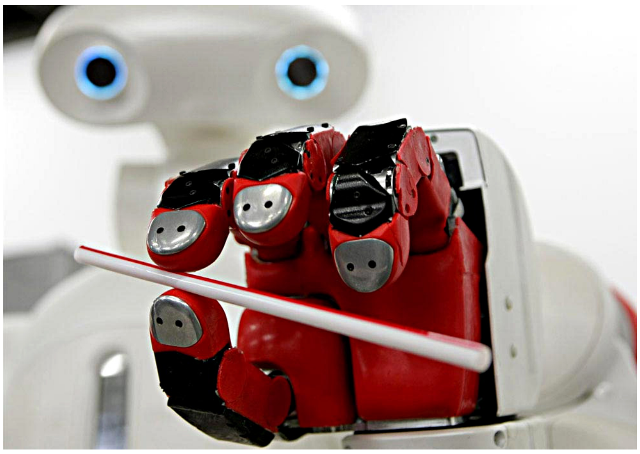


Figure 3.142 – Twendy-One's manipulation abilities have been demonstrated with a straw: the robot is able to switch between several opposition patterns without dropping it (thumb against index finger, against middle finger, against index and ring fingers, and so on). A video of this demonstration is available on the robot's website (Waseda University Twendy Team 2011).

**Reem-B** Reem-B is the second humanoid robot developed by PAL Robotics, a small Spanish company founded in 2004 and based in Barcelona, but supported by investors in the United Arab Emirates (it is part of the Royal Group, a conglomerate of sixty companies based in Abu Dhabi) (PAL Robotics 2011a,b). Released in 2008, the robot, illustrated in figure 3.143, is a prototype and a research platform that is not commercially sold. It was preceded by a first prototype, Reem-A, and followed by another prototype, Reem-H, before the recent release of the company's first commercial product, simply called Reem. Contrary to Reem-A and Reem-B, which are legged humanoids, the robots Reem-H and Reem are wheeled humanoids. The purpose of this series of robots is to commercialize a service robot for public places, for instance "hotels, trade shows, entertainment parks, shopping malls, holiday resorts, museums, airports, hospitals, and so on" (PAL Robotics 2011a). As for the name "reem", it comes from Arabic and means "antelope" or "gazelle"; it is also a female name in the Arab world [67].

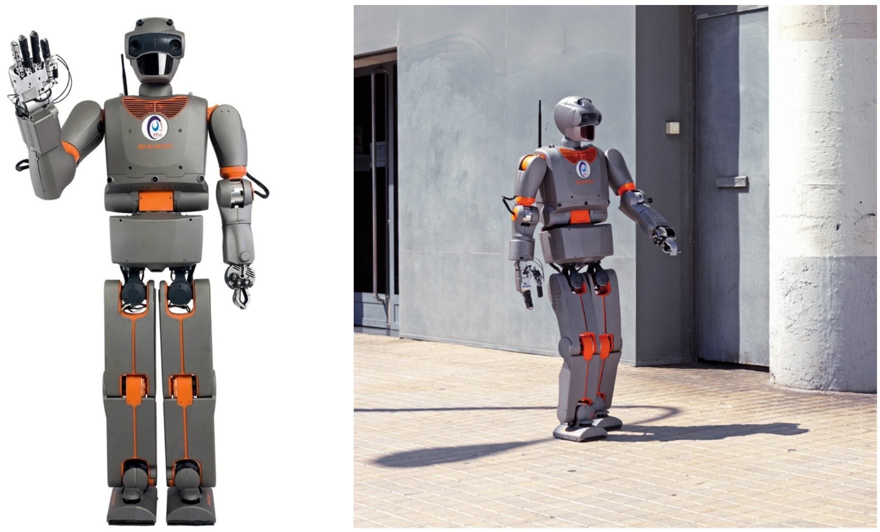


Figure 3.143 – Reem-B (2008). The humanoid is 147 cm tall and weights 60 kg. Its left hand is a two-degree-of-freedom gripper that can grasp heavy objects like bottles or books, whereas its right hand can grasp smaller objects in fingertip precision grips. The previous prototype Reem-A had only grippers, and the following Reem-H and Reem have three-fingered gripper hands.

Reem-B comes with one multifingered hand only, the other hand being a gripper. The multifingered hand, illustrated in figure 3.144, has one thumb, three fingers, and a total of eleven degrees of freedom. It features tendons, ten motors, infrared and pressure sensors on each digit, and with the visual feedback of the robot's stereo camera system it has been reported to "pick up small objects, such as chess pieces", and "[grasp] cans and bottles" (PAL Robotics 2011b; Tellez, Ferro, Garcia, Gomez, et al. 2008). Other than that, nothing more is known about it, since the focus of the robot is not really grasping, let alone manipulation, but rather autonomous navigation

67. There is also an island named Reem Island 600 m off the coast of Abu Dhabi island. Coincidentally, and unrelated to the robot or the Arabic language, "reem" is also a British English slang term meaning nice, good-looking, attractive, beautiful, cool, great, sexy, fit, hot, top-class, and so on (as in, "my hair is looking reem", or, "this robot is reem"). A somewhat forgotten word, it is enjoying some new-found popularity today following its use by a character in a popular (and reportedly terrible) British reality TV show, *The Only Way Is Essex*.

and human/robot interaction, so these aspects are much better documented (the robot can map indoor spaces, locate itself in these spaces, move around while avoiding obstacles, and detect, memorize, and recognize faces; another notable feature is that it is able to carry heavy objects, up to 20% of its own weight).

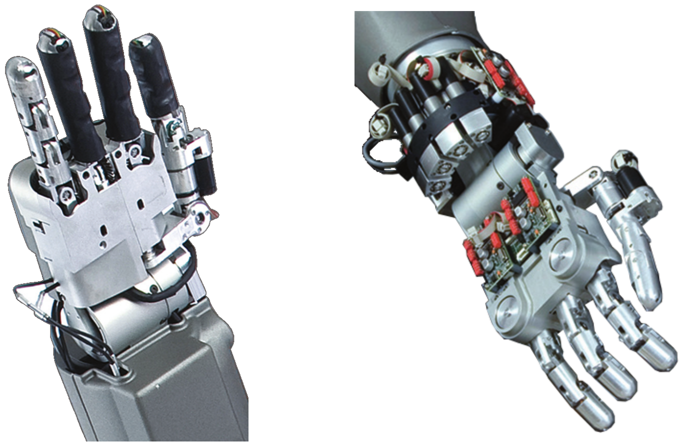


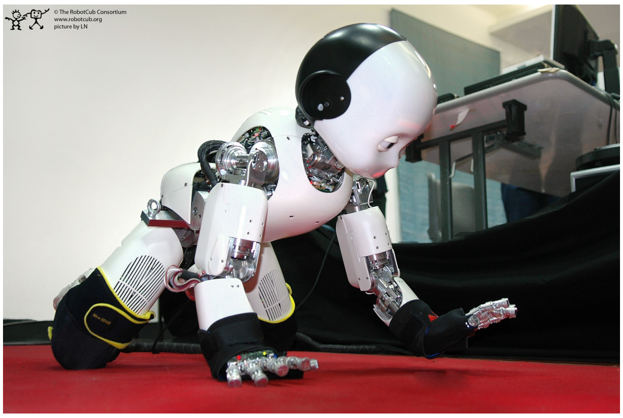
Figure 3.144 – The multifingered hand of Reem-B, palmar and dorsal views (from PAL Robotics 2011b)

**iCub** Last but not least, iCub is probably one of the most anthropomorphic robots of the last decade. It is a small, child-size humanoid robot, built as a platform for research into cognition and artificial intelligence. It is illustrated in figure 3.145.

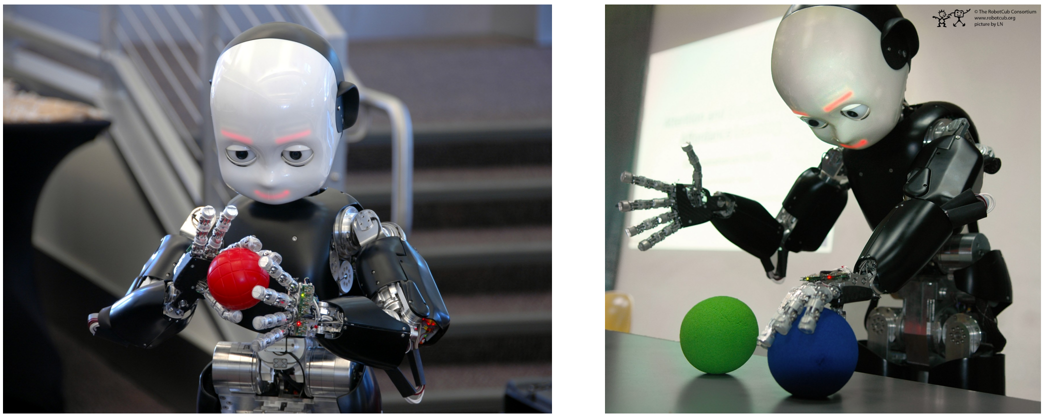
iCub was designed as part of RobotCub, a European research project which started in September 2004 and ended in January 2010. The project associated many European universities and research institutions located in Italy, Switzerland, the United Kingdom, Sweden, and Portugal, as well as a few non-European partners in Japan and the United States (RobotCub 2010). By the diversity of their expertises, the participants in the project were a glaring example of the multidisciplinary background that constitutes and characterizes robotics: computer science, mechatronics, artificial intelligence, computer vision, developmental psychology, neurophysiology, motor control in humans and robots, all those skills and domains of competence were represented and needed (RobotCub 2010).

The main goal of the RobotCub project was to advance our understanding of cognition and of its development, through the realization and the exploitation of a particular embodied cognitive system: a humanoid robot the size of a three or four year old child (RobotCub 2010; iCub 2011). The motivation behind the humanoid design is the embodied cognition theory, a philosophical idea and a theory of cognition that emphasizes the reciprocal link between the human mind and the human body. In broad outline, this theory states that just as our mind influences our bodily actions, our motor system influences our mental processes (information processing, attention, remembering, producing and understanding language, solving problems, making decisions, and so on). It postulates that our mind is largely determined by our body, and that in the development of our cognitive abilities (our mental processes) during childhood, interaction with the world, in particular exploration through grasping and manipulation with the hands, plays a fundamental role.

The strong mind-body relationship postulated by embodied cognition (and which is absent from other theories of cognition) has consequences in psychology, neurobiology,



(a) Crawling like a young toddler is iCub's main locomotion mode (it is also able to walk).



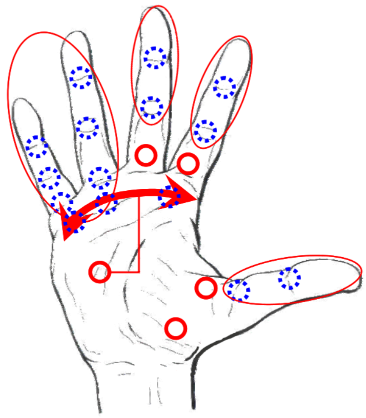
(b) iCub grasps (and learns) various spheres.

Figure 3.145 – iCub (as of 2009 and 2010)

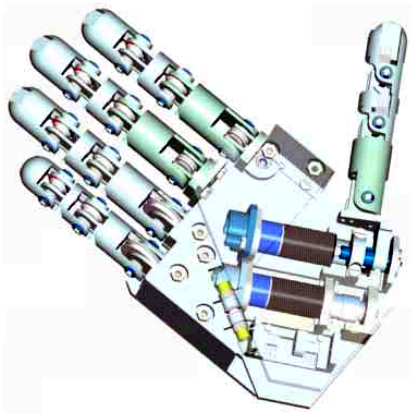
linguistics, and artificial intelligence. In this last area, embodied cognition implies that true artificial intelligence can only be achieved by machines that have sensorimotor skills, that is to say machines that have an artificial body to establish a relationship with. In contrast, software-only artificial intelligence systems are bound to fail, because they cannot relate to the world and therefore cannot develop cognitive abilities comparable to those developed by beings with a body.

RobotCub aimed at testing and developing this paradigm of embodied cognition (Metta, Sandini, Vernon, Natale, and Nori 2008). To this aim, it was necessary to create an artificial intelligence system with an artificial body and artificial sensorimotor skills: iCub, where "Cub" stands for "cognitive universal body". The robot was designed by imitating a human child in shape, motor skills, and perceptual systems, as much as possible, so that it could interact with the world in the same way that a child does. Therefore, it has a motor system of fifty-three actuators that move the head, the arms, the hands, the waist and the legs, and it has a sensory system comprising vision, hearing, proprioception (encoders on all joints), movement perception (accelerometers and gyroscopes), and tactition (force/torque sensors, touch sensors on the palms and fingertips) (iCub 2011). The resulting system is convincing at behaving like a child: it crawls on its arms and legs and grasps objects such as balls and toys, learning about the world and hopefully forming its cognitive capabilities as it goes (figure 3.145).

iCub is open-source and open-hardware, in the sense that the hardware design, the developed software, and the documentation have all been released under open-source licenses (RobotCub 2010; iCub 2011). There are now nineteen iCubs in various laboratories around Europe and one in the United States; they are used by scientists studying embodied cognition in artificial systems. Even though the European project is over, the Cognitive Humanoids Laboratory at the Italian Institute of Technology (2011), one of the main participant in the original project, has taken over further development of the robot platform, and a second version of iCub is now underway.



(a) Red indicates independent degrees of freedom, blue indicates underactuated degrees of freedom.



(b) Design of the palm: the two intrinsic actuators and the metacarpal degree of freedom for the "hollowing" of the palm are clearly visible.

Figure 3.146 – Degrees of freedom and degrees of actuation in iCub's hands

Given how important exploration through grasping and manipulation is to embodied cognition, the hands of iCub have been particularly taken care of. They are both very anthropomorphic, five-fingered, and small-sized enough to fit with the rest of the child-sized humanoid. Papers by Stellin, Cappiello, Roccella, Carrozza, Dario, Metta, Sandini, and Becchi (2006), Stellin, Cappiello, Zaccone, Cipriani, Carrozza, and Dario (2007), and Stellin, Cipriani, Zaccone, Carrozza, Laschi, and Dario (2008) describe the hands in full detail. Also, Schmitz, Maggiali, Natale, and Metta (2010) recently described a touch sensor system for these hands.

The little available space for the actuators is of course a huge problem in such a small form factor (iCub is 104 cm tall, for a weight of about 22 kg). Stellin, Cappiello, Zaccone, Cipriani, Carrozza, and Dario (2007) note that "a trade-off between the accomplishment of high-level manipulation tasks and the dimensional limitations is mandatory", and they explain that a "mixed implementation" of driven joints and underactuated joints has been chosen, with most of the actuators (DC electric motors) located in the forearm, as in the human hand. As a result, there is a total of nine motors for twenty degrees of freedom, and so the hands amount to eighteen of the fifty-three actuated degrees of freedom of the whole robot (that is, a third of them). The degrees of freedom of the hand are illustrated in figure 3.146 and described below (Stellin, Cappiello, Zaccone, Cipriani, Carrozza, and Dario 2007):

**Extrinsic actuation** Fifteen phalanx flexions are driven by seven actuators located in the forearm. The transmission uses sheathed flexor tendons pulling against torsion spring returns, except in the case of the metacarpophalangeal joints of the thumb, index finger and middle finger, where two antagonist flexor/extensor tendons are used.

1. Flexion/extension of the metacarpophalangeal joints of the thumb, index finger and middle finger: they constitute three independent degrees of freedom.

2. Flexion/extension of the interphalangeal joints of the thumb, index finger and middle finger: the proximal and distal interphalangeal joints are coupled by an underactuation mechanism which makes the phalanges exhibit an adaptive behavior, i.e. they automatically wrap around the object according to its shape. There is a total of six degrees of freedom, but three independent.

3. Flexion/extension of all the joints of the ring and little fingers: these joints are coupled by an underactuation mechanism, the fingers are coupled by a differential mechanism in the palm, and the whole set is driven by a single actuator. So the ring and little fingers have an adaptive behavior even more pronounced than the other fingers, with a total of six degrees of freedom, but only one independent.

   Stellin, Cappiello, Zaccone, Cipriani, Carrozza, and Dario (2007) point out that this situation reminds of the Robonaut's hand (see figure 3.114), where the ring and little fingers form a "grasping set", a lot less actuated than the "dextrous set" formed by the thumb, index finger and middle finger.

**Intrinsic actuation** Five degrees of freedom are driven by two actuators located directly in the palm (figure 3.146).

1. Opposition/retroposition of the thumb is direct-driven by one actuator.

2. Abduction/adduction of the index finger, ring finger and little finger, as well as an additional degree of freedom in the palm under the ring and little fingers for "hollowing" of the palm (figure 3.146), are all driven together by the last actuator. Palm hollowing is coupled with finger abduction, so this last degree of freedom switches between a neutral posture and a spherical grasp.

All the extrinsic actuators have their own encoder for position control, and the intrisic actuators use smaller optical angle sensors instead. Joint angles can also be measured using custom-designed Hall-effect sensors, and there are also three torque sensors in the "dextrous" fingers (thumb, index, middle). In addition to this basic sensory system, five custom-designed tendon tension sensors based on strain gauges are located in the fingertips (Stellin, Cappiello, Zaccone, Cipriani, Carrozza, and Dario 2007). Last but not least, a capacitive pressure sensor system with 108 sensing points has been developed (Schmitz, Maggiali, Natale, and Metta 2010). In this sensor, "the palm has 48 taxels and each of the five fingertips has 12 taxels", and the sensor also "incorporates silicone foam and is therefore compliant". Using this system, it is possibe to determine "where and (although to a lesser extent) how much" pressure is applied on the hand and the fingertips by the contacts with an object.

In the end, the hands of iCub feature sufficient articulation, actuation and sensing to be considered dextrous systems. Indeed, although the whole point of underactuation is to decrease the number of active, controllable degrees of freedom (for size and simplicity reasons), there remain fourteen degrees of freedom and eight degrees of actuation in the thumb, index and middle, and this is “enough for manipulation, if well controlled” (Stellin, Cappiello, Zaccone, Cipriani, Carrozza, and Dario 2007). Yet only whole-hand grasping and whole-hand manipulation as in figure 3.145(b) have been reported since iCub has been finished. Dextrous, in-hand manipulations seem to have been left aside. This is most likely just because despite its good hands, iCub is not meant to study dexterity but cognition. Besides, it must be acknowledged that whole-hand grasping and whole-hand manipulation are typical of young children, whose fine manipulation abilities are not yet fully formed (see figure 1.3 in chapter 1 and also the references in section 2.4.2 of chapter 2). So in this respect iCub is right in favoring whole-hand manipulation over dexterity.

The fact that they don’t make the most of their hands’ dexterity is actually a point shared by the three humanoids Twendy-One, Reem-B, and iCub. With respectively thirteen, ten, and nine actuated degrees of freedom, their hands are potentially at least fairly dextrous. Yet they are used mainly for adaptive grasping at the moment. Still, in spite of that, these hands differ a lot from the more common adaptive hands, with only a few actuated degrees of freedom, that are found on the majority of present-day humanoid robots. They bring in the possibility of in-hand dexterity, in addition to versatile grasping and whole-hand manipulation. In this respect, they hopefully set a trend for the future of humanoid robotics.

# 4

# Mathematics and mechanics for robot modeling

## Contents



Robotics research usually requires a certain understanding of rigid body mechanics. This is because many robots can be described, as a first approximation at least, as a set of rigid bodies articulated one another. This is especially the case for humanoid robots: most often, their limbs have hard plastic or metal outer coverings and are connected by revolute joints. Rigid body mechanics is therefore the primary framework for their modeling.

Rigid body mechanics is, of course, a very classical topic. It has a century-old history. It is the subject of a dedicated chapter or appendix in virtually any textbook on robotics. Everyone is supposed to be fluent in rigid body mechanics nowadays. Yet the truth is that this matter is regrettably overlooked by some. In fact, the careful description and understanding of rigid body motion may be subtle, and can lead very far, to the abstract formalism of differential geometry. Partial understanding of rigid body mechanics and/or lack of rigor in its use is one of the most effective ways to produce unclear and inaccurate reasonings, and in the end, erroneous proofs of wrong results.

In this chapter, we provide an overview of the concepts and results of rigid body mechanics that we use to model humanoid robot hands. Although the subject is classical, the mathematics we use is modern, based on a matrix formulation of screw theory described in detail by Richard Murray, Zexiang Li, and Shankar Sastry (1994).

If the reader is familiar with it, they will only skim through this chapter to get used to the notations we have chosen.

After a short introduction about rigid body mechanics and its history, we provide basic reminders on the geometric description of rigid bodies and rigid motions, in section 4.1. Then sections 4.2 and 4.3 deal with rigid body kinematics and dynamics, respectively.

## 4.1 Geometric description of rigid bodies

### 4.1.1 Rigid body mechanics and screw theory

#### General presentation

The tools and concepts of rigid body mechanics enable us to describe how the various parts of a humanoid robot are arranged with respect to each other and its environment, how they move relatively to each other and the environment, and what are the interactions between them, or between them and the environment. That is to say, respectively, they enable the description of the robot's geometry (translations and rotations), kinematics (velocities and angular velocities), and dynamics (accelerations and angular accelerations, forces and moments). In our case, the humanoid robot is limited to a hand, and the environment is an object supposed to be manipulated by this hand.

Now, rigid body mechanics is not the definitive answer to robot modeling, of course. The limitations of the rigid-body assumption are well-known. Most importantly, it does not describe contact interactions very well. In the rigid body model, a contact between two parts is typically a point, whereas in the real world, it is a surface, because there is always a certain amount of deformation between the parts in contact. This is especially true if one of them, or both, is not so rigid: for instance, robot fingers are often covered with a soft, compliant material in order to increase friction and improve the grip. In spite of its shortcomings, rigid body mechanics remains an interesting framework for the modeling of humanoid robots: it describes them fairly well with relatively simple mathematics. And besides, any model is an approximation of reality.

#### History overview

Rigid body mechanics is as old as mechanics itself, with roots in the knowledges of several ancient civilizations. But it really became a science, in the modern sense of the word, with the works of Galileo Galilei in Italy in the sixteenth and seventeenth centuries, followed by those of Isaac Newton in England in the seventeenth and eighteenth centuries. Both laid the foundations of what we call now classical mechanics.

Another early and prominent contributor to mechanics, at the turn of the eighteenth century, was Pierre Varignon, a French mathematician with a marked interest in statics. He worked on force and moment relationships, especially on the static equilibrium of objects subjected to forces and moments. He also gave formal definitions to the concepts of instantaneous velocity and acceleration, using the recent theory of infinitesimal calculus developed by Isaac Newton and Gottfried Leibniz: he was a friend of both of them, and an early adopter and fierce advocate of their infinitesimal calculus. Still using infinitesimal calculus, he showed that the acceleration of a body could be obtained from its instantaneous velocity by differentiation.

The development of classical mechanics kept going during the eightteenth and nineteenth centuries, led by scientists such as Leonhard Euler, Jean le Rond d'Alembert, Joseph-Louis Lagrange, Gaspard-Gustave Coriolis, and William Hamilton. Important contributions to rigid body mechanics were made by French mathematicians Michel Chasles and Louis Poinsot in the early nineteenth century. Michel Chasles proved that any movement of a rigid body consists of a rotation around a straight line followed by a translation along that line: a *screw motion* in modern terms. The infinitesimal version of a screw motion describes the instantaneous motion of the rigid body, in terms of its linear and angular instantaneous velocities; it is called a *twist*. Louis Poinsot proved that any system of forces acting on a rigid body is equivalent to a single force applied along a straight line, combined with a moment around that same line; the set of both these linear and angular actions is called a *wrench*.

With these two fundamental theorems as a starting point, Irish astronomer and mathematician Robert Ball developed a mathematical, abstract formulation of rigid body mechanics, at the end of the nineteenth century: screw theory (Ball 1900). This formalism has become nowadays an important and practical tool in robotics, mechanical design, and multibody dynamics.

Figure 4.1 – Caricature of Sir Robert Stawell Ball, astronomer and founder of screw theory (Leslie Ward, 1905)

### 4.1.2 Basic geometry concepts

#### Rigid bodies and rigid motions

In this chapter, the notations $S_1$ and $S_2$ designate two *rigid bodies*. A rigid body is a body such that the distance between any two points of it remains fixed, regardless of any motion of the body or any force acting on the body [1].

1. The notation $S$ is for *solid*.

Similarly, a motion of a body such that the distance between any two points of the body remains fixed at all times is called a *rigid motion* (or, sometimes, a rigid body motion). By definition, any motion of a rigid body is a rigid motion; however, rigid motions are not limited to rigid bodies: deformable bodies may have rigid motions too.

The net movement of a body from one location to another via a rigid motion is called a *rigid displacement*. The rigid motion is the continuous succession of the locations of the rigid body over time, whereas the rigid displacement is the geometric relation between the initial and final configurations of the body, or more generally between any two of its configurations.

**Frames and bases**

In this chapter, the notations $a$ and $b$ designate two *direct orthonormal frames* of the three-dimensional space $\mathbb{R}^3$. These frames consist of an origin and a direct orthonormal basis each. The origins of $a$ and $b$ are noted $A$ and $B$, and their bases are noted $a$ and $b$ like the frames. Confusion is unlikely since the context always makes it clear if $a$ or $b$ is a frame or a basis. Hence we can write: $a = (A, a)$ and $b = (B, b)$.

In the formulation of screw theory developed by Murray, Z. Li, and Sastry (1994), the frames $a$ and $b$ are specific: $a$ is a fixed or inertial frame, called the *space* frame (and often noted $s$), whereas $b$, called the *body* frame, is a frame rigidly linked to a rigid body whose motion relative to $a$ is being studied. In this chapter, and more generally in all this thesis, it is not the case: unless otherwise stated, the frames $a$ and $b$ are not supposed to be rigidly linked to any of the rigid bodies $S_1$ and $S_2$.

When we write a quantity $q$ with a frame or a basis as a superscript to the right, like this: $q^a$, that means that the quantity is written (expressed) in the frame or the basis in question. This applies to any quantity $q$ anywhere in this document, be it a vector, a point, a velocity, a force, a twist, a wrench, or anything else. For instance, if $u$ is a vector, then $u^a$ is the same vector written in $a$ coordinates, that is to say written in the basis $a$, and $u^b$ is the same vector again but in $b$ coordinates.

Bodies and frames will remain generic in this chapter, but in the next ones they will have a meaning relative to a humanoid hand. For instance, for now $\omega^a_{S_2/S_1}$ is the angular velocity of $S_2$ relative to $S_1$, written in $a$ coordinates. In the following chapters, that could be $\omega^{obj}_{obj/dp_1}$, the angular velocity of a grasped object relative to the first distal phalanx of the hand, written in the basis of a frame rigidly linked to the object. Or $\omega^{ref}_{obj/dp_1}$, the same angular velocity but written in the basis of a fixed or inertial reference frame. And so on.

We try to always make it clear in which frame or basis such or such quantity is written, in order to avoid any confusion or vagueness in the mathematical developments. However, it happens at times that we drop the top-right frame indication, for brevity of the expressions. When unspecified, a frame is the most "natural" frame for the quantity; or it could be that the quantity is not written in coordinates, but intrinsically. That is the difference between $q$ (the quantity), $q^a$ (the quantity written in $a$ coordinates), and $q$ (the quantity written in the coordinates of the most natural frame, hence not specified).

As a rule of thumb, the most natural frame is frequently the "body frame", in the terms of Murray, Z. Li, and Sastry (1994). The body frame is a particular frame rigidly linked to the rigid body whose motion is being studied. For instance, $\omega_{obj/dp_1}$ would most likely be $\omega^{obj}_{obj/dp_1}$, the angular velocity of the object relative to the first distal phalanx of the hand, written in the object's body frame. But it could be something else, depending on which frame the context makes the most natural for this angular velocity. In any case, when there is a risk of confusion, we do not omit the frame specification.

**Vectors and points**

Let $u$ denote a vector, $u^a$ its coordinates in the basis $a$. Let also $P$ denote a point, $P^a$ its coordinates in the frame $a$. These respective coordinates are column vectors of 3 (standard coordinates) or 4 (homogeneous coordinates) elements:

$$u^a = \begin{pmatrix} x \\ y \\ z \end{pmatrix} \quad u^a = \begin{pmatrix} x \\ y \\ z \\ 0 \end{pmatrix} \qquad\qquad P^a = \begin{pmatrix} x \\ y \\ z \end{pmatrix} \quad P^a = \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

The coordinates of a point in a frame are nothing else than the coordinates, in the basis of this frame, of the vector between the origin of the frame and the point. That is to say, $P^a = \overrightarrow{AP}^a$ (modulo the terminal coefficient in homogeneous coordinates).

Vectors are the elements of the euclidean vector space $\mathbb{R}^3$ over the field $\mathbb{R}$, and points are the elements of the associated affine space $\mathbb{R}^3$ over the field $\mathbb{R}$.

### 4.1.3 Rotations and rigid transformations

**Rotations and rotation matrices**

In the vector space $\mathbb{R}^3$, any two direct orthonormal bases $a$ and $b$ differ by a rotation only, that is to say, the three vectors of the basis $b$ can be obtained from the three vectors of the basis $a$ by the same rotation of a certain angle around a certain axis (and vice-versa).

This rotation may be represented by a $(3, 3)$ matrix whose column vectors are the coordinates in the basis $a$ of the vectors of the basis $b$. This is the *rotation matrix* of the basis $b$ with respect to the basis $a$, noted ${}^aR_b$. That is to say, if we note $b = (b_1, b_2, b_3)$ the three vectors of the basis $b$, and $(b_1^a, b_2^a, b_3^a)$ the coordinates in $a$ of these three vectors, then:

$${}^aR_b = \begin{pmatrix} b_1^a & b_2^a & b_3^a \end{pmatrix}$$

A rotation matrix is *orthogonal*, that is to say that its columns are orthogonal unit vectors, and so are its rows too. Equivalently, it means that it is always invertible and that its inverse is equal to its transpose:

$${}^aR_b {}^aR_b^T = {}^aR_b^T {}^aR_b = I_3 \qquad {}^aR_b^{-1} = {}^aR_b^T$$

A rotation matrix is actually *special orthogonal*, or *direct orthogonal*, that is to say that it is orthogonal and its columns form a direct basis of $\mathbb{R}^3$, and so do its rows too. Equivalently, it means that it is orthogonal and its determinant is $+1$ (the other possible determinant for an orthogonal matrix is $-1$, for indirect orthogonal matrices).

We also have the following property:

$$ {}^aR_b^{-1} = {}^aR_b^T = {}^bR_a $$

The set of $(3,3)$ special orthogonal matrices, that is to say the set of spatial rotations, forms a *group* for matrix multiplication. This group is noted $SO_3(\mathbb{R})$ and called the *special orthogonal group* of degree 3 over the field $\mathbb{R}$.

It is a subgroup of $O_3(\mathbb{R})$, the orthogonal group of degree 3 over the field $\mathbb{R}$, which is the set of all $(3,3)$ orthogonal matrices (direct and indirect). This group $O_3(\mathbb{R})$ is itself a subgroup of $GL_3(\mathbb{R})$, the general linear group of degree 3 over the field $\mathbb{R}$, which is the set of all $(3,3)$ invertible matrices.

#### Rigid transformations and homogeneous matrices

In the affine space $\mathbb{R}^3$, any two direct orthonormal frames $a$ and $b$ differ by a rigid transformation only. A rigid transformation, also called a rigid body transformation, is a transformation from $\mathbb{R}^3$ to itself that preserves distances between every pair of points (isometry) and orientation of angles between vectors (direct isometry). Rigid transformations include rotations, translations, and their combinations; they are used to represent the rigid displacement of a body.

The rigid transformation from $a$ to $b$ may be represented by a $(4,4)$ matrix which features the contributions of both the rotation (of $b$ with respect to $a$) and the translation (from $A$ to $B$) in the rigid transformation. This is the *homogeneous matrix* of the frame $b$ with respect to the frame $a$, noted ${}^aH_b$. Its definition is:

$$ {}^aH_b = \begin{pmatrix} {}^aR_b & r^a_{a,b} \\ 0_{1,3} & 1 \end{pmatrix} \tag{4.1} $$

where $r_{a,b} = \overrightarrow{AB}$ is the vector between the origins of the frames $a$ and $b$, and $r^a_{a,b} = \overrightarrow{AB}^a$ is its coordinates in $a$. Pure rotations have a homogeneous matrix where the translation part is null: $r_{a,b} = 0_{3,1}$. Pure translations have a homogeneous matrix where the rotation part is the identity: ${}^aR_b = I_3$.

A homogeneous matrix has certain properties, that must not be mistaken for those of the rotation matrices.

First of all, it is always invertible, but its inverse is not its transpose (which is not a homogeneous matrix):

$$ {}^aH_b^{-1} \neq {}^aH_b^T \qquad {}^aH_b^{-1} = \begin{pmatrix} {}^aR_b^T & -{}^aR_b^T r^a_{a,b} \\ 0_{1,3} & 1 \end{pmatrix} = \begin{pmatrix} {}^bR_a & -{}^bR_a r^a_{a,b} \\ 0_{1,3} & 1 \end{pmatrix} \tag{4.2} $$

and since $-{}^bR_a r^a_{a,b} = -r^b_{a,b} = r^b_{b,a}$ by a change of expression basis for the vector $r_{a,b}$ (see further, section 4.1.4) followed by an inversion of direction for the same vector, we have:

$$ {}^aH_b^{-1} = \begin{pmatrix} {}^bR_a & r^b_{b,a} \\ 0_{1,3} & 1 \end{pmatrix} = {}^bH_a \tag{4.3} $$

The determinant of a homogeneous matrix is $+1$, like that of a special orthogonal matrix.

Last but not least, the set of homogeneous matrices forms a *Lie group*, noted $SE_3(\mathbb{R})$ and called the *special euclidean group* of degree 3 over the field $\mathbb{R}$. It is the set of the spatial direct isometries, or rigid transformations of the three-dimensional space.

It is a subgroup of the Lie group $E_3(\mathbb{R})$, the euclidean group, which is the set of all spatial isometries (direct and indirect): rotations, translations, line reflections, and their combinations. This group $E_3(\mathbb{R})$ is itself a subgroup of the Lie group $A\!f\!f_3(\mathbb{R})$, the general affine group, which is the set of the spatial invertible affine transformations (or affinities), that is to say, the set of the combinations of an invertible linear application (i.e. one of $GL_3(\mathbb{R})$) followed by a translation.

### 4.1.4 Change of frame formulas for vectors and points

When a vector is written in the coordinates of some basis, it is practical to know how to obtain their coordinates in some other basis. This operation is called a change of expression basis, or change of basis for short.

Similarly, it is practical to know how to obtain the coordinates in some frame of a point written in the coordinates of some other frame: a change of expression frame, or just change of frame.

#### Change of basis

Let $u$ denote a vector and $u^a$, $u^b$ its (standard) coordinates in the bases $a$, $b$. The rotation matrix of $b$ with respect to $a$, ${}^aR_b$, is the change of basis matrix between $a$ and $b$:

$$\boxed{u^a = {}^aR_b u^b} \tag{4.4}$$

#### Change of frame

Let $P$ denote a point and $P^a$, $P^b$ its (homogeneous) coordinates in the frames $a$, $b$. The homogeneous matrix of $b$ with respect to $a$, ${}^aH_b$, is the change of frame matrix between $a$ and $b$:

$$\boxed{P^a = {}^aH_b P^b} \tag{4.5}$$

## 4.2 Kinematics of rigid bodies

### 4.2.1 Twists

We let $V^a_{S_2/S_1}$ denote the *twist* of the motion of the rigid body $S_2$ relative to the rigid body $S_1$, written in the frame $a$, that is to say [2]:

$$\boxed{V^a_{S_2/S_1} = \begin{pmatrix} v^a_{A\in S_2/S_1} \\ \omega^a_{S_2/S_1} \end{pmatrix}} \tag{4.6}$$

where $\omega^a_{S_2/S_1}$ is the angular velocity of the rigid body $S_2$ relative to the rigid body $S_1$, written in $a$ coordinates, and $v^a_{A\in S_2/S_1}$ is the velocity of the point $A$ considered as a point of the rigid body $S_2$ (i.e. rigidly linked to $S_2$), relative to the rigid body $S_1$, written in $a$ coordinates.

2. The notation $V$ is for *velocity*.

### Vocabulary

The two components of a twist have special names: the one that is not a function of the *twist expression point* ($A$) is called the *resultant* of the twist, and the one that is a function of this point is called the *moment* of the twist at the point of expression. Hence the resultant is the angular velocity and the moment is the linear velocity.

Twists are sometimes called *generalized velocities*. The angular velocity $\omega^a_{S_2/S_1}$ may also be called the rotational velocity, and the velocity $v^a_{A\in S_2/S_1}$ may be called the linear velocity, to separate it from the angular velocity. All these velocities are instantaneous velocities of course.

### Remarks

The twist expression point $A$ is not necessarily a point of the rigid body $S_2$, it is only considered as such. However, it is often the case, and it is very common that this point is in fact the center of gravity of the rigid body. It is also common that the associated basis $a$ is a specific basis of the rigid body $S_2$, rigidly linked to it. For instance, it may be the basis of its principal axes of inertia, especially if the twist expression point $A$ is the center of gravity.

As for the rigid body $S_1$, it is very common that it is the "reference" rigid body, the "world". When it is the case, it is often omitted in the expression of the twist: $V^a_{S_2}$.

When both cases happen, i.e. when $S_1$ is the reference rigid body and when $a = (A, a)$ is a specific frame of the rigid body $S_2$, then the twist $V^a_{S_2/S_1}$ is the twist of the *absolute* motion of the rigid body $S_2$ (i.e. relative to the world), written in its own frame (the specific frame of $S_2$). We often omit the world and/or the specific frame from the expression of the twist, and write for short: $V_{S_2}$.

### Important remark

It is important to understand that the point $A$ in a twist is not just the point $A$, but rather the point $A$ considered as a point of the rigid body $S_2$ (i.e. rigidly linked to $S_2$). In other words, it is *a point rigidly linked to $S_2$ that coincides with $A$ at the current given time*, or *a (possibly imaginary) point of the rigid body $S_2$ which is traveling through the point $A$ at the current given time*. Hence the notation $A \in S_2$ rather than just $A$: both points are not the same, even though they are at the same place.

The distinction is important because although both points are at the same location in space, they are not necessarily there with the same velocity. That is to say, the velocity $v_{A\in S_2/S_1}$ is *not* necessarily equal to the velocity $v_{A/S_1}$. For instance, when the frame $a$ is not rigidly linked to $S_2$, its motion relative to $S_1$ may be totally different from the motion of $S_2$ relative to $S_1$. Consequently, the instantaneous velocity $v_{A/S_1}$ of its origin $A$ may have nothing in common with the instantaneous velocity $v_{A\in S_2/S_1}$ of the point rigidly linked to $S_2$ that travels through $A$ at the time in question.

Another example is when $a$ is a contact frame on the surface of $S_2$, moving on this surface according to the evolution of the contact. In this case, the velocity $v_{A\in S_2/S_1}$ represents the instantaneous velocity of $S_2$ relative to $S_1$, measured at the current time in the point of $S_2$ that coincides with the contact point $A$. On the contrary, the velocity $v_{A/S_1}$ represents the instantaneous velocity of the contact point $A$ itself.

However, when the point $A$ is fixed relatively to $S_2$ (i.e. motionless), for instance when it is the center of gravity of $S_2$ or any other point rigidly linked to $S_2$, then the two velocities $v_{A\in S_2/S_1}$ and $v_{A/S_1}$ are equal, because there is no difference between the point $A$ and a point rigidly linked to $S_2$ that coincides with $A$ at the given time: it really is the same point.

To sum it up, two cases may happen: either $A$ is rigidly linked to $S_2$, in which case the two points $A$ and $A \in S_2$ are (really) the same, either $A$ is not rigidly linked to $S_2$, in which case these two points are at the same place at any given time, but with different velocities.

#### Varignon's relationship

The resultant and the moment of a twist are related through *Varignon's relationship*:

$$v_{B\in S_2/S_1} = v_{A\in S_2/S_1} + \omega_{S_2/S_1} \times \overrightarrow{AB} \tag{4.7}$$

where $\times$ is the usual vector cross-product. When this relationship is written in coordinates, all the vectors must be written in the same basis of course.

This relationship is also called the *moment displacement relationship*, since it enables to write the moment of a twist in another point. It is a property used in the more general change of frame of the twist, which consists of a moment displacement and a change of expression basis for both the moment and the resultant (see section 4.2.3).

#### Mathematical remark

Given the fact that the two components of a twist are related (not independent), we cannot state that a twist is a mere element of $\mathbb{R}^6$, even though it has the adequate size.

The set of the twists is in fact a *Lie algebra* of the special euclidean group $SE_3(\mathbb{R})$, an algebra which is actually the tangent space at the identity of $SE_3(\mathbb{R})$. It is noted $se_3(\mathbb{R})$.

### 4.2.2 Adjoint matrices

The *adjoint matrix* ${}^a\!Ad_b$ of the rigid body transformation ${}^aH_b$ is a $(6,6)$ square matrix defined as follows:

$${}^aH_b = \begin{pmatrix} {}^aR_b & r^a_{a,b} \\ 0_{1,3} & 1 \end{pmatrix} \qquad {}^a\!Ad_b = \begin{pmatrix} {}^aR_b & \hat{r}^a_{a,b}\,{}^aR_b \\ 0_{3,3} & {}^aR_b \end{pmatrix} \tag{4.8}$$

where $\hat{r}^a_{a,b}$ is a $(3,3)$ skew-symmetric matrix embedding the operation of left-wise cross-product by the vector $r^a_{a,b}$, in $a$ coordinates:

$$r^a_{a,b} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} \quad \mapsto \quad \hat{r}^a_{a,b} = \begin{pmatrix} 0 & -z & y \\ z & 0 & -x \\ -y & x & 0 \end{pmatrix}$$

$$\text{this matrix meets: } \forall\, u \in \mathbb{R}^3,\ \hat{r}^a_{a,b} u^a = r^a_{a,b} \times u^a$$

For that reason, we call $\hat{r}^a_{a,b}$ a *cross-product matrix*.

An adjoint matrix has some noticeable properties. First of all, it is always invertible, has a determinant equal to +1, and its inverse may be written as follows:

$$ {}^{a}Ad_{b}^{-1} = \begin{pmatrix} {}^{a}R_{b}^{T} & (\hat{r}_{a,b}^{a}\,{}^{a}R_{b})^{T} \\ 0_{3,3} & {}^{a}R_{b}^{T} \end{pmatrix} = \begin{pmatrix} {}^{a}R_{b}^{T} & {}^{a}R_{b}^{T}(\hat{r}_{a,b}^{a})^{T} \\ 0_{3,3} & {}^{a}R_{b}^{T} \end{pmatrix} = \begin{pmatrix} {}^{b}R_{a} & -{}^{b}R_{a}\hat{r}_{a,b}^{a} \\ 0_{3,3} & {}^{b}R_{a} \end{pmatrix} \tag{4.9} $$

and since $-{}^{b}R_{a}\hat{r}_{a,b}^{a} = -\hat{r}_{a,b}^{b}\,{}^{b}R_{a} = \hat{r}_{b,a}^{b}\,{}^{b}R_{a}$ by a change of expression basis for the cross-product matrix $\hat{r}_{a,b}$ (see further, appendix 4.A) followed by an inversion of direction for the vector of this matrix, we have:

$$ {}^{a}Ad_{b}^{-1} = \begin{pmatrix} {}^{b}R_{a} & \hat{r}_{b,a}^{b}\,{}^{b}R_{a} \\ 0_{3,3} & {}^{b}R_{a} \end{pmatrix} = {}^{b}Ad_{a} \tag{4.10} $$

### 4.2.3 Change of frame formula for twists

Let $V_{S_2/S_1}$ denote a twist and $V_{S_2/S_1}^{a}$, $V_{S_2/S_1}^{b}$ its expressions in the frames $a$, $b$. The adjoint matrix ${}^{a}Ad_{b}$ of the homogeneous matrix ${}^{a}H_{b}$ is the change of frame matrix between $a$ and $b$ for the twists:

$$ \boxed{V_{S_2/S_1}^{a} = {}^{a}Ad_{b}V_{S_2/S_1}^{b}} \tag{4.11} $$

It is clear from the expression of ${}^{a}Ad_{b}$ that it embeds a change of expression point (moment displacement, see Varignon's relationship) and a change of expression basis (for both the moment and the resultant of the twist).

## 4.3 Dynamics of rigid bodies

### 4.3.1 Wrenches

We let $W_{S_1\to S_2}^{a}$ denote the *wrench* of the actions exerted by the rigid body $S_1$ on the rigid body $S_2$, written in the frame $a$, that is to say:

$$ \boxed{W_{S_1\to S_2}^{a} = \begin{pmatrix} f_{S_1\to S_2}^{a} \\ m_{A,S_1\to S_2}^{a} \end{pmatrix}} \tag{4.12} $$

where $f_{S_1\to S_2}^{a}$ is the force applied by the rigid body $S_1$ on the rigid body $S_2$, written in $a$ coordinates, and $m_{A,S_1\to S_2}^{a}$ is the moment in $A$ applied by the rigid body $S_1$ on the rigid body $S_2$, written in $a$ coordinates.

#### Vocabulary

The two components of a wrench have the same special names as the two components of a twist: the one that is not a function of the *wrench expression point* ($A$) is called the *resultant* of the wrench, and the one that is a function of this point is called the *moment* of the wrench at the point of expression. Hence the resultant is the force and the moment is, precisely, the moment.

Wrenches are sometimes called *generalized forces*. The moment $m_{A,S_1\to S_2}^{a}$ may also be called the couple or the torque, although strictly speaking these three words have slightly different meanings. A common opinion is that a moment is the point-dependent component of a wrench, whereas a couple is a wrench whose resultant is null[3], and a torque is the moment of a couple. That being said, there is a great deal of confusion between these terms, since they all represent angular forces. As a matter of fact, the most commonly accepted terminology is different between physics and mechanical engineering, as well as between American English and British English, so there is no need to worry about precision here, it is bound to fail.

### Remarks

As in the case of twists, the wrench expression point $A$ is not necessarily a point of the rigid body $S_2$. It is also worth noting that the expression point of the moment and the application point of the force are in no way necessarily related, therefore the wrench expression point has nothing to do with the application point of its force. That being said, these points may nonetheless happen to be the same. The wrench expression point may also happen to be a characteristic point of the rigid body, for instance its center of gravity, or a point located on an axis of rotation of the body.

Sometimes, $S_1$ is not a rigid body in contact with $S_2$: for instance, in the gravity wrench. Some other times, $S_1$ is not one rigid body, but represents all the rigid bodies exerting an action on $S_2$: its environment. In this case, the wrench is the sum of all the wrenches applied to $S_2$ (wrenches can be added one another to make a total resultant wrench, as long as they are all written at the same point and in the same basis).

Wrenches need less mental caution regarding the expression point than twists: to evaluate the moment applied by $S_1$ on $S_2$, using the point $A$ yields exactly the same result as using a point rigidly linked to any of the rigid bodies and traveling through $A$ at the current given time.

### Varignon's relationship

As in the case of twists, the resultant and the moment of a wrench are related through *Varignon's relationship*:

$$m_{B,S_1\rightarrow S_2} = m_{A,S_1\rightarrow S_2} + f_{S_1\rightarrow S_2} \times \overrightarrow{AB} \tag{4.13}$$

where $\times$ is the usual vector cross-product. When this relationship is written in coordinates, all the vectors must be written in the same basis of course.

This relationship is also called the *moment displacement relationship*, since it enables to write the moment of a wrench in another point. It is a property used in the more general change of frame of the wrench, which consists of a moment displacement and a change of expression basis for both the moment and the resultant (see section 4.3.3).

### Mathematical remark

As in the case of twists, the relation between the two components of a wrench prevents us from stating that a wrench is a mere element of $\mathbb{R}^6$.

As a matter of fact, the set of the wrenches is a *one-form* of the special euclidean group $SE_3(\mathbb{R})$, one-form which is also the dual of the twist space $se_3(\mathbb{R})$. This dual space is noted $se_3^*(\mathbb{R})$.

3. Another term for a couple is "pure moment", to add to the confusion.

### 4.3.2 Co-adjoint matrices

The *co-adjoint matrix* ${}^aAd_b^{-T}$ of the rigid body transformation ${}^aH_b$ is a $(6,6)$ square matrix which is nothing else than the transinverse [4] of the adjoint matrix ${}^aAd_b$, as stated by its notation:

$$ {}^aAd_b^{-T} = ({}^aAd_b^{-1})^T = ({}^aAd_b^T)^{-1} = \begin{pmatrix} {}^aR_b & 0_{3,3} \\ \hat{r}^a_{a,b}\,{}^aR_b & {}^aR_b \end{pmatrix} \tag{4.14} $$

### 4.3.3 Change of frame formula for wrenches

Let $W_{S_1\to S_2}$ denote a wrench and $W^a_{S_1\to S_2}$, $W^b_{S_1\to S_2}$ its expressions in the frames $a$, $b$. The co-adjoint matrix ${}^aAd_b^{-T}$ of the homogeneous matrix ${}^aH_b$ is the change of frame matrix between $a$ and $b$ for the wrenches:

$$ \boxed{W^a_{S_1\to S_2} = {}^aAd_b^{-T} W^b_{S_1\to S_2}} \tag{4.15} $$

As the adjoint matrix, the co-adjoint matrix embeds a change of expression point (moment displacement, see Varignon's relationship) and a change of expression basis (for both the moment and the resultant of the wrench).

## 4.A Change of basis formula for a cross-product matrix

We have already introduced the cross-product matrix $\hat{r}$ associated with any vector $r$ (section 4.2.2). In $a$ coordinates:

$$ r^a = \begin{pmatrix} x \\ y \\ z \end{pmatrix} \quad \mapsto \quad \hat{r}^a = \begin{pmatrix} 0 & -z & y \\ z & 0 & -x \\ -y & x & 0 \end{pmatrix} \tag{4.16} $$
$$ \text{this matrix meets: } \forall\, u \in \mathbb{R}^3,\ \hat{r}^a u^a = r^a \times u^a $$

The change of basis formula is the same as that of any other matrix:

$$ \boxed{r^a = {}^aR_b r^b} \qquad \boxed{\hat{r}^a = {}^aR_b \hat{r}^{b\,b}R_a} \tag{4.17} $$

Basically, this means that $\hat{r}^a$ and $\hat{r}^b$ are the matrices of the same endomorphism in two different bases, $a$ and $b$. We could note $\hat{r}$ this endomorphism.

A fast proof of this result consists in showing that $\forall\, u \in \mathbb{R}^3$, $\hat{r}^a u^a = {}^aR_b \hat{r}^{b\,b}R_a u^a$. For this, let us define $v = r \times u$, we have $v^a = {}^aR_b v^b$ and as a consequence $\hat{r}^a u^a = r^a \times u^a = v^a = {}^aR_b v^b = {}^aR_b(r^b \times u^b) = {}^aR_b \hat{r}^b u^b = {}^aR_b \hat{r}^{b\,b}R_a u^a$.

Other obvious properties:

$$ R(r \times s) = (Rr) \times (Rs) \qquad \widehat{Rr} = R\hat{r}R^T $$

4. Matrix transposition and matrix inversion are commutative: $(M^{-1})^T = (M^T)^{-1}$, hence the shortened notation $M^{-T}$. This is a general property of all (invertible) matrices.

5

# Dynamic optimization-based control of dextrous manipulation

## Contents



In the previous chapters, we have emphasized on multiple occasions the importance of control to get the best out of multifingered hands. For instance, we explained in section 3.2.3 that if current commercially-available prosthetic myoelectric hands underperform, it is in a large part because of their primitive control, and we reviewed in section 3.2.4 the various attempts at improving this control, be it by making the prosthesis more autonomous or by extracting more control information from the user's nervous system. We also stressed the complexity of the control of our hands by our brains in sections 2.3.1 and 2.4.2, and how difficult it is to emulate such an advanced control in artificial systems. Also, we remarked in section 3.1.3

that autonomous robots operating in human-adapted environments will have a very wide variety of manipulation tasks to perform, requiring a considerable amount of dexterity: this, too, underlines the need for efficient, reliable, and versatile control schemes for both grasping and manipulating with artificial multifingered hands.

In this chapter, we present a new control method for dextrous manipulation by a multifingered robot hand. This new control is intended for autonomous manipulation, that is to say non human-supervised manipulation tasks. For this reason it is primarily adapted to autonomous humanoid robots, or computer animation of virtual manipulation. However, nothing seems to prevent a potential adaptation to semi-autonomous cases, such as manipulation tasks in virtual reality, telemanipulation, or prosthesis control (in the event that dextrous manipulation of in-hand objects eventually becomes a function of prosthetic hands). In these three cases, the proposed control method could constitute the low-level part of a hierarchical shared user/hand control scheme (see section 3.2.4 in chapter 3). The high-level part would come from the amputee, the operator of the telemanipulation system, or the person immersed in the virtual environment.

The peculiarity of this new control method is that it is based on an optimization problem, aka a mathematical program (both terms mean the same). Generally speaking, putting a control problem into mathematical programming terms is a good way to get a control that satisfies multiple requirements, something that may be called “multi-objective control”. Indeed, by definition, optimization problems are about maximizing or minimizing a certain function over a certain domain, and to put it simply, the domain models *constraints* that the solution must meet, and the function represents *objectives* that it should satisfy as much as possible (this function is as a matter of fact called the objective function). The solution of an optimization problem is therefore the value which fits the objectives as well as possible while complying with the constraints. Now, in the case where the optimization problem comes from a robot control problem, then the solution is the robot control which fits the control objectives as well as possible while complying with the control constraints. Here lies the multi-objective nature of optimization-based control: some of the control objectives must be met at all costs, they are called constraints and form the domain of the mathematical program; others should be satisfied as much as possible, they are called objectives (or desired values) and make up the objective function of the mathematical program.

Now, which control objective is a constraint and which other is a desired value depends entirely on the control problem, and is ultimately up to the roboticist who designs the control. In our case, the problem is the control of multifingered dextrous manipulation by a humanoid robot hand. Obviously, its control objectives include the motion of the in-hand object and the different contact forces applied by the fingers on the object. Other control objectives may be related to the motor power used by the hand, the limits of the joints, the maximal tension loading of the tendons, the management of the redundancy of the finger kinematic chains, the avoidance of collisions between the fingers, the capability of the grasp to withstand force disturbances, and so on: the list of control objectives may be long. Depending on their importance and how incompatible they are with each other, we divide them into two groups: the constraints and the objectives of an optimization problem. The solution of this optimization problem is the best possible control of dextrous manipulation, with respect to the chosen objectives, which complies with the chosen constraints.

This chapter is based on an article presented at the IFAC Symposium on Robot Control in 2009, which introduced this new control of multifingered dextrous manipulation (Michalec and Micaelli 2009a). We begin this chapter by modeling the hand/object system we want to control, in section 5.1, and by reviewing in broad outline the field of robotic manipulation control (manipulators and hands), in section 5.2. Then, we give the details of our optimization-based control scheme in section 5.3. Its validity is demonstrated by simulation results in section 5.4, and section 5.5 concludes the chapter.

## 5.1 Models of the hand and the object

### 5.1.1 Introduction

#### Description of the models

We model an artificial multifingered humanoid hand as a set of rigid bodies, articulated one another and arranged in a human-like way: a palm and a certain number of anthropomorphic fingers, usually three to five. We model the object as a single rigid body.

In accordance with the human anatomy, each finger of our model is made of three phalanges and three joints. The proximal joint has two degrees of freedom: a first one for abduction/adduction and a second one for flexion/extension. All the joints are independently torque-driven, in other words the degree of actuation of our model is equal to its degree of freedom. This is an idealized abstraction of the various actuation methods used in actual artificial hands (see chapter 3 for a review).

This relatively generic hand model was implemented as a computer model, for simulation purposes. A computer-generated image of this model is given in figure 5.1.

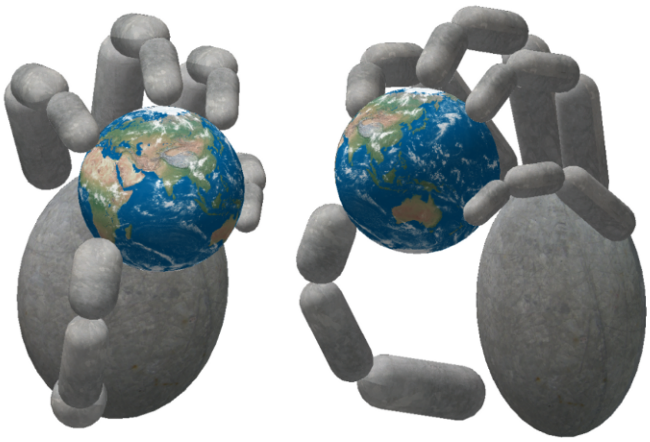


Figure 5.1 – A computer-simulated model of a five-fingered robot hand (front and side views). The phalanges are pill-shaped and the palm is simply a flat ellipsoid: from a control perspective, their geometry doesn't count as much as their dynamics, as long as the contacts between the hand and the object are limited to a few point contacts.

### Dextrous, in-hand, fingertip manipulation

The segments of the hand form a tree structure whose root is the palm. In our model, this root body is free, that is to say that it can move. For instance, it may be attached to the arm of a humanoid robot, which would move it here and there to grasp and manipulate objects. However, in the computer simulations of our model, this root body is fixed and cannot move. That is to say, the attachment of the hand to a robot has not been tested in simulation, and manipulation control has only been tested with a motionless palm for now.

This type of manipulation of an object within one hand and without any motion contribution of the palm is called "in-hand manipulation" or "internal manipulation": it is the "controlled motion of the grasped object in the hand workspace, with the constraint configuration changing with time" (Melchiorri and M. Kaneko 2008).

The term "dextrous manipulation" has mostly the same meaning but stresses the dexterity of the manipulation, that is to say the capability of the device and its control to "change the configuration of the manipulated object from an initial configuration to a final one, arbitrarily chosen within the device workspace" (Melchiorri and M. Kaneko 2008), as opposed to industrial manipulation for instance, which would merely mean grasping of workpieces and moving them to another location by a whole-arm motion of the robot.

Dextrous manipulation is most often performed with a fingertip precision grasp (see section 2.2 in chapter 2 for more about grasps), hence another possible synonym: "fingertip manipulation". This term applies to our case too: even though contacts between the fingers and the object are not restricted to the fingertips in the mathematical description of our model, for now the computer simulations have been conducted in cases of fingertip precision grasps only, such as the one illustrated on figure 5.1.

### Computer simulation

The computer implementations of the hand model and of its control, and the simulation of the resulting motion, were done with Arboris, a physical engine for articulated rigid body mechanics developed at CEA/LIST [1] and UPMC/ISIR [2] (Micaelli and Barthélémy 2006–2010). Arboris is written in Matlab programming language, as an object-oriented toolbox for Matlab itself. It is freely available and open-source.

The Arboris physical engine enables the control and simulation of articulated systems with numerous non-permanent contacts, especially virtual humans (Collette and Micaelli 2007a,b). It simulates three possible rigid body dynamics:

1. In zero-order dynamics, the forces don't produce any motion. Rigid bodies move if and only if their successive positions in space are explicitely specified, for instance by a human animator or by the input of motion capture data.
2. In first-order dynamics, the forces produce velocities. Unconstrained rigid bodies move when subjected to forces, and stop when the forces stop.

1. *Commissariat à l'Énergie Atomique, Laboratoire d'Intégration des Systèmes et des Technologies*: French Atomic Energy Commission, Systems and Technologies Integration Laboratory (Fontenay-aux-Roses, south of Paris, France).

2. *Université Pierre et Marie Curie, Institut des Systèmes Intelligents et de Robotique*: Pierre and Marie Curie University, Institute for Intelligent Systems and Robotics (Paris, France).

3. In second-order dynamics, the forces produce accelerations. Unconstrained rigid bodies move when subjected to forces, and keep moving after the forces stop.

Second-order dynamics is what happens in the real world; lower-order dynamics do not correspond to physical realities. It doesn't mean that they are worthless though; they are used for certain purposes. As a matter of fact, first-order dynamics simulation is common in video games and computer animation, where visual realism is more important than physical realism, and world consistency is not as much an issue as in robot design, industrial prototyping, operator training in virtual reality, and other real-world physical simulation problems. In our case, since we are designing a control that may potentially be used in an actual robot hand, second-order dynamics simulation is the best choice for testing it; as a result we used only this side of Arboris's physical simulation capabilities.

Arboris was written with simplicity and ease-of-use in mind, at least as much as possible for a physical engine (dynamics simulation is a difficult matter and physical engines are accordingly complex software). It is primarily targeted at rapid prototyping and benchmarking of robots and controls, and may also serve to human motion analysis and as an educational tool in robotics studies. On the other hand, computer-animated graphics is not a goal of Arboris, and as a result the simulations it produces look a bit like rough drafts; figure 5.1 is a good example. However, elaborate skinning of the skeletal animations it produces may be done with dedicated software.

In the rest of this section, we present the details of the kinematics and dynamics of the hand/object system. Section 5.1.2 defines the notations we use, and sections 5.1.3 to 5.1.6 give the model equations.

### 5.1.2 Basic notations and definitions

#### Fingers, phalanges, degrees of freedom

We let $n_f \geq 2$ denote the number of fingers, $n_b = 3n_f$ the number of rigid bodies except the root body (that is to say, the number of phalanges), and $n_{dof} = 4n_f$ the number of degrees of freedom. $i$ and $k$ denote respectively the indexes of a finger and a segment: $i \in [|1, n_f|]$, $k \in [|0, n_b|]$ [3]. The index $k = 0$ is for the palm, the indexes $k \geq 1$ are for the phalanges.

#### Frames

Each body in the hand comes with its own frame attached at its centre of mass. These frames are enumerated on figure 5.2: *ref* is an inertial reference frame, *root* is the frame of the palm, $dp_i$ is the frame of the $i$-th distal phalanx, and *obj* is the frame of the object being manipulated. $c_i$ denotes both the contact point between the object and the $i$-th distal phalanx and the contact frame $(t_i^1, t_i^2, n_i)$, with the vector $n_i$ outward and normal to the object's surface, as pictured on figure 5.2.

The orientation of the body frames is totally arbitrary and doesn't change over time: the body frames are rigidly linked to their respective bodies. The orientation of the contact frames is also arbitrary, except for the third vector which is always the outward-pointing normal to the object. Also, the orientation of the contact frames

3. This notation is for an integer interval: $[|1, n|] = \{1, \dots, n\}$.

does change over time since the contact frames are not rigidly linked to a body, they move with the contact points.

All those frames are direct orthonormal of course.

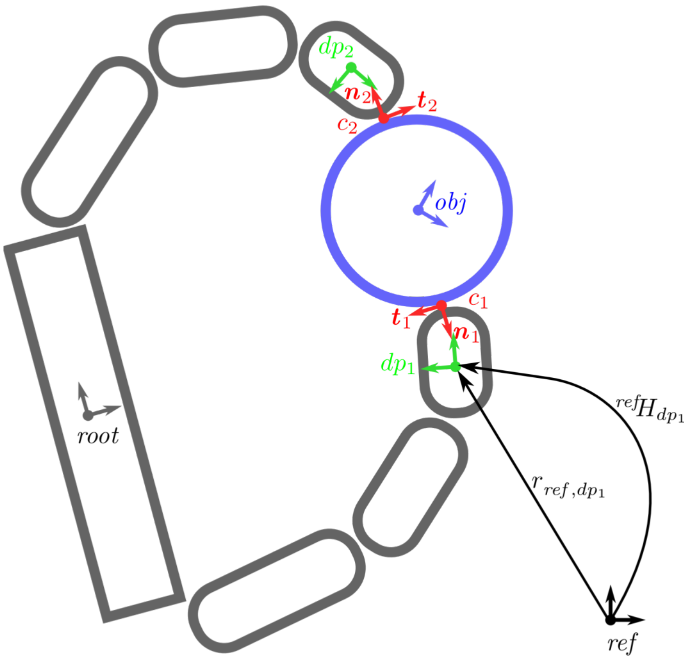



Figure 5.2 – Reference frames, body frames, contact frames, and rigid transformations between these frames

Since the modeling framework is that of rigid body mechanics, all the concepts, definitions and notations of chapter 4 are valid: rigid transformations, twists, wrenches, adjoint and co-adjoint matrices, and so on. We remind that rigid transformations locate frames relatively to each other; since body frames are rigidly linked to rigid bodies, they also locate rigid bodies relatively to each other. Homogeneous matrices are used to represent rigid transformations, for instance:

$$ {}^{ref}H_{dp_i} = \begin{pmatrix} {}^{ref}R_{dp_i} & r^{ref}_{ref,dp_i} \\ 0_{1,3} & 1 \end{pmatrix} \in SE_3(\mathbb{R}) $$

locates the $i$-th distal phalanx relatively to $ref$ through the rotation ${}^{ref}R_{dp_i} \in SO_3(\mathbb{R})$ between the bases of the frames and the translation $r^{ref}_{ref,dp_i} \in \mathbb{R}^3$ from the origin of $ref$ to the origin of $dp_i$, this vector being written in $ref$ coordinates (figure 5.2).

### Mass and inertia

The mass and inertia of the body $k$ are arranged into the body's generalized mass matrix, written in the body's own frame as follows:

$$ M_k = \begin{pmatrix} m_k I_3 & 0_{3,3} \\ 0_{3,3} & [I]_k \end{pmatrix} \qquad \forall\, k \in [|0, n_b|] $$

where $m_k$ is the mass of the body $k$ and $[I]_k$ is its inertia tensor written in the body's own frame.

#### Joints and torques

Last but not least, $q$ denotes the column vector of the hand's articular coordinates and $\tau$ denotes the column vector of its driving torques:

$$q = \begin{pmatrix} q_1 \\ \vdots \\ q_{n_{dof}} \end{pmatrix} \qquad \dot{q} = \begin{pmatrix} \dot{q}_1 \\ \vdots \\ \dot{q}_{n_{dof}} \end{pmatrix} \qquad \ddot{q} = \begin{pmatrix} \ddot{q}_1 \\ \vdots \\ \ddot{q}_{n_{dof}} \end{pmatrix} \qquad \tau = \begin{pmatrix} \tau_1 \\ \vdots \\ \tau_{n_{dof}} \end{pmatrix}$$

$\dot{q}$ and $\ddot{q}$ are the hand's articular velocities and accelerations, respectively.

### 5.1.3 Hand kinematics

#### Twists of the bodies of the hand

We let $V_k$ denote the twist of the absolute motion of the $k$-th body, written in the own frame of this body. That is to say:

$$V_k = V^k_{k/ref} = \begin{pmatrix} v_k = v^k_{K\in k/ref} \\ \omega_k = \omega^k_{k/ref} \end{pmatrix} \qquad \forall\, k \in [|0, n_b|] \tag{5.1}$$

with $v_k$ the velocity of the center of mass $K$ of the body $k$ and $\omega_k$ the angular velocity of the body $k$, both relative to the reference frame $ref$ and written in the frame of the body $k$. See section 4.2 in chapter 4 for more background about twists.

Most velocities from now on are absolute (i.e. relative to the reference frame), but written in the adequate body frame (not in the reference frame). That is to say that except otherwise stated, a missing frame of reference for a velocity is the reference frame $ref$, and a missing frame of expression is the body frame, in short: $V_k = V^k_{k/ref}$.

#### Direct geometric models of the bodies of the hand

Let us consider the kinematic chain between the root body (the palm, $k = 0$) and the $k$-th body (a phalanx, $k \geq 1$). A certain number of joints are involved in this chain, not all the joints of the hand. We let $\tilde{q}_k$ denote the appropriate subset of the articular coordinates $q$, for this particular kinematic chain to the body $k$. We also let $n_{dof,k}$ denote the number of degrees of freedom in this kinematic chain: $\tilde{q}_k \in \mathbb{R}^{n_{dof,k}}$.

The direct geometric model of the kinematic chain to the body $k$ is the function that maps the articular coordinates of the chain into the cartesian position of the last body of the chain. Let $f_k$ denote this function. The articular coordinates are $\tilde{q}_k$, and the cartesian position of the last body can be represented by six degrees of freedom: three linear parameters and three angular parameters between the root body and the $k$-th body. Consequently, $f_k$ is a function from $\mathbb{R}^{n_{dof,k}}$ to $\mathbb{R}^6$.

Traditionally, the linear parameters are the coordinates in a certain basis of the translation vector $r_{0,k}$ between the origins of the frames *root* and $k$, and the angular parameters are three successive rotation angles between the bases of the frames *root* and $k$ (such as Euler angles, Cardan angles, or other roll-pitch-yaw angles). Let $r^k_{0,k} = ((r^k_{0,k})_1, (r^k_{0,k})_2, (r^k_{0,k})_3)$ denote those three linear parameters, written in the basis $k$, and let also $\theta_{0,k} = ((\theta_{0,k})_1, (\theta_{0,k})_2, (\theta_{0,k})_3)$ denote the three angular parameters. These parameters define the six component functions of the direct geometric model $f_k$, in $k$ coordinates:

$$r^k_{0,k} = \begin{pmatrix} (r^k_{0,k})_1 \\ (r^k_{0,k})_2 \\ (r^k_{0,k})_3 \end{pmatrix} \stackrel{\text{def}}{=} \begin{pmatrix} f_{k,1} \\ f_{k,2} \\ f_{k,3} \end{pmatrix} \qquad \theta_{0,k} = \begin{pmatrix} (\theta_{0,k})_1 \\ (\theta_{0,k})_2 \\ (\theta_{0,k})_3 \end{pmatrix} \stackrel{\text{def}}{=} \begin{pmatrix} f_{k,4} \\ f_{k,5} \\ f_{k,6} \end{pmatrix}$$

Since $f_k$ is a function from $\mathbb{R}^{n_{dof,k}}$ to $\mathbb{R}^6$, each component function $(f_{k,p})_{p\in[|1,6|]}$ is a function from $\mathbb{R}^{n_{dof,k}}$ to $\mathbb{R}$:

$$\begin{aligned} f_k : \tilde{q}_k \in \mathbb{R}^{n_{dof,k}} &\mapsto (r_{0,k}, \theta_{0,k}) \in \mathbb{R}^6 \\ f_{k,p} : \tilde{q}_k \in \mathbb{R}^{n_{dof,k}} &\mapsto f_{k,p}(\tilde{q}_k) \in \mathbb{R} \quad \forall p \in [|1,6|] \end{aligned}$$

### Direct kinematic models of the bodies of the hand

We still consider the kinematic chain to the body $k \geq 1$, and its direct geometric model $f_k$, with six component functions $(f_{k,p})_{p\in[|1,6|]}$ in $k$ coordinates.

The derivative of the function $f_k$ is given in coordinates by the jacobian matrix of the function $f_k$, which is the matrix of all its first-order partial derivatives:

$$\tilde{J}_k = \left(\frac{\partial f_{k,p}}{\partial \tilde{q}_{k,l}}\right)_{\substack{p\in[|1,6|] \\ l\in[|1,n_{dof,k}|]}} = \begin{pmatrix} \dfrac{\partial f_{k,1}}{\partial \tilde{q}_{k,1}} & \cdots & \dfrac{\partial f_{k,1}}{\partial \tilde{q}_{k,n_{dof,k}}} \\ \vdots & \ddots & \vdots \\ \dfrac{\partial f_{k,6}}{\partial \tilde{q}_{k,1}} & \cdots & \dfrac{\partial f_{k,6}}{\partial \tilde{q}_{k,n_{dof,k}}} \end{pmatrix}$$

Since the components functions are defined in $k$ coordinates, this jacobian matrix $\tilde{J}_k$ is defined in $k$ coordinates too.

The jacobian matrix of a function represents the best linear approximation to this function near a given point:

$$f_k(\tilde{q}_k + d\tilde{q}_k) = f_k(\tilde{q}_k) + \tilde{J}_k(\tilde{q}_k)\, d\tilde{q}_k + o(\|d\tilde{q}_k\|)$$

When the infinitesimal articular displacement $d\tilde{q}_k$ in this equation is realized over an infinitesimal duration $dt$, the variation $f_k(\tilde{q}_k + d\tilde{q}_k) - f_k(\tilde{q}_k)$ represents the corresponding infinitesimal cartesian displacement of the $k$-th body during $dt$. Loosely speaking, we can write:

$$\frac{f_k(\tilde{q}_k + d\tilde{q}_k) - f_k(\tilde{q}_k)}{dt} = \tilde{J}_k(\tilde{q}_k)\,\frac{d\tilde{q}_k}{dt} + o\left(\left\|\frac{d\tilde{q}_k}{dt}\right\|\right)$$

and since $f_k$ represents the cartesian position of the $k$-th body, the left-hand side of this equation, when $dt$ goes to zero, represents the cartesian velocity of the $k$-th body, in $k$ coordinates since $\tilde{J}_k(\tilde{q}_k)$ is in $k$ coordinates. This is how we get the direct kinematic model of the kinematic chain between the root body and the $k$-th body:

$$V^k_{k/root} = \tilde{J}_k(\tilde{q}_k)\,\dot{\tilde{q}}_k$$

Traditionally in robotics, the jacobian matrix of the direct geometric model of a kinematic chain is just called the jacobian of this chain. The value of this jacobian at the current point, $\tilde{J}_k(\tilde{q}_k)$, is also just denoted $\tilde{J}_k$, even though the latter is strictly speaking a function (from $\mathbb{R}^{n_{dof,k}}$ to $\mathbb{R}^{6\times n_{dof,k}}$). Hence the following usual expression of the direct kinematic model of the kinematic chain between the root body and the $k$-th body (see e.g. Prattichizzo and Trinkle 2008, or any robotics textbook):

$$V^k_{k/root} = V^k_{k/0} = \tilde{J}_k\,\dot{\tilde{q}}_k \qquad \forall\, k \in [|1, n_b|] \tag{5.2}$$

Now we can also write:

$$V^k_{k/root} = V^k_{k/0} = J_k\,\dot{q} \qquad \forall\, k \in [|1, n_b|] \tag{5.3}$$

with $J_k$ being obtained from $\tilde{J}_k$ by padding with zeros where appropriate. For instance:

$k = 1$ The first body is the proximal phalanx of the first finger. One joint with two degrees of freedom separates it from the root body, hence the kinematic model of this very basic kinematic chain is:

$$V^1_{1/0} = \tilde{J}_1 \begin{pmatrix} \dot{q}_1 \\ \dot{q}_2 \end{pmatrix} = J_1\,\dot{q} \qquad \text{with } J_1 = \begin{pmatrix} \tilde{J}_1 & 0_{6,n_{dof}-2} \end{pmatrix}$$

$k = 3$ The third body is the distal phalanx of the first finger. Four degrees of freedom separate it from the root body, hence the kinematic model of the first finger is:

$$V^3_{3/0} = \tilde{J}_3 \begin{pmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \end{pmatrix} = J_3\,\dot{q} \qquad \text{with } J_3 = \begin{pmatrix} \tilde{J}_3 & 0_{6,n_{dof}-4} \end{pmatrix}$$

$k = 6$ The sixth body is the distal phalanx of the second finger. Four degrees of freedom separate it from the root body, hence the kinematic model of the second finger is:

$$V^6_{6/0} = \tilde{J}_6 \begin{pmatrix} \dot{q}_5 \\ \dot{q}_6 \\ \dot{q}_7 \\ \dot{q}_8 \end{pmatrix} = J_6\,\dot{q} \qquad \text{with } J_6 = \begin{pmatrix} 0_{6,4} & \tilde{J}_6 & 0_{6,n_{dof}-8} \end{pmatrix}$$

And so on. That makes a total of $n_b$ direct kinematic models written as functions of $\dot{q}$. Now we can use the law of velocity addition to write these models relatively to *ref* instead of *root*. First:

$$V^k_{k/ref} = V^k_{k/root} + V^k_{root/ref} = J_k\,\dot{q} + V^k_{root/ref}$$

Then, we rewrite $V^k_{k/ref} = V_k$ and use a change-of-frame formula for twists (see section 4.2.3 in chapter 4) to rewrite:

$$V^k_{root/ref} = {}^k\!Ad_{root} V^{root}_{root/ref} = {}^k\!Ad_{root} V_{root}$$

As a result, we get the following direct kinematic models:

$$V_k = {}^k\!Ad_0 V_0 + J_k\,\dot{q} \qquad \forall\, k \in [|1, n_b|] \tag{5.4}$$

These equations can easily include the root body: we just have to notice that ${}^0\!Ad_0 = I_6$, and to define $J_0 = 0_{6,n_{dof}}$. This results in the following $n_b + 1$ direct kinematic models:

$$V_k = {}^k\!Ad_0 V_0 + J_k\,\dot{q} \qquad \forall\, k \in [|0, n_b|] \tag{5.5}$$

### Direct kinematic model of the hand

For a more compact notation, we can stack all the $V_k$ and $J_k$ together and get an equation that can be described as the direct kinematic model of the hand:

$$V = J\,T \tag{5.6}$$

$$V = \begin{pmatrix} V_0 \\ V_1 \\ \vdots \\ V_{n_b} \end{pmatrix} \qquad J = \begin{pmatrix} {}^0\!Ad_0 & J_0 \\ {}^1\!Ad_0 & J_1 \\ \vdots & \vdots \\ {}^{n_b}\!Ad_0 & J_{n_b} \end{pmatrix} \qquad T = \begin{pmatrix} V_0 \\ \dot{q}_1 \\ \vdots \\ \dot{q}_{n_{dof}} \end{pmatrix}$$

The resulting $(6 + 6n_b, 6 + n_{dof})$ jacobian matrix maps the space of the root and articular velocities of the hand, $se_3(\mathbb{R}) \times \mathbb{R}^{n_{dof}}$, into the space of the cartesian velocities of the hand, $se_3(\mathbb{R})^{1+n_b}$.

## 5.1.4 Contact modeling

### Choice of a contact model

Contact models describe the interaction at the interface between two contacting bodies. They characterize "both the forces that can be transmitted through the contact as well as the allowed relative motions of the contacting bodies", these characteristics being "determined by the geometry of the contacting surfaces and the material properties of the parts, which dictate friction and possible contact deformation" (Kao, Lynch, and Burdick 2008).

Since contact forces are what robot hands use to grasp and manipulate objects, contact modeling is of prime importance to the analysis and control of manipulation. Contact models fall into one of two categories: rigid models and compliant models. In rigid contact models, there are no deformations of the contacting parts at their contact interface, which may be a point, a line, or a surface, depending of the geometry of the contacting surfaces. The contact forces between these parts "arise from two sources: the constraint of incompressibility and impenetrability between the rigid bodies, and surface frictional forces" (Kao, Lynch, and Burdick 2008). In compliant contact models however, the contacting parts deform, at least locally, and the forces of interaction are function of this deformation.

Since the modeling framework we have chosen is rigid body mechanics, the natural choice for a contact model is a rigid one. We further assume that all the contacts are points (no lines or surfaces), that there is dry friction between the contacting surfaces, and that this dry friction can be modeled with Coulomb laws. Therefore, our choice of contact model is the *rigid point contact with dry friction*, and our choice of friction model is the *Coulomb friction model*.

In the rest of this section, we give details about these two models, as well as a linear approximation of the Coulomb friction model.

### Kinematics of rigid body contact

Contact kinematics is the study of how two contacting bodies, here rigid bodies, can move relatively to each other while:

- staying in contact: no breaking of the contacts; and

- respecting the impenetrability constraint: no penetration of one body into the other.

Under these conditions, at a contact point, the relative motion between the two bodies is the addition of variable amounts of sliding, rolling, and twisting. Sliding and rolling are respectively translational and rotational motions in the tangent plane at the contact, and twisting is the rotational motion around the contact normal.

Let's take the contact between a phalanx and the object as an example. We note $V^{c_i}_{dp_i/obj}$ the twist of the relative motion between the $i$-th distal phalanx and the object, written in the contact frame $c_i$. The linear and angular velocities of this twist are:

$$V^{c_i}_{dp_i/obj} = \begin{pmatrix} v^{c_i}_{c_i \in dp_i/obj} \\ \omega^{c_i}_{dp_i/obj} \end{pmatrix} \qquad \forall\, i \in [|1, n_f|] \tag{5.7}$$

$v_{c_i \in dp_i/obj}$ is the velocity of the contact point $c_i$, considered as a point of the distal phalanx (i.e. rigidly linked to it), relative to the object; $\omega_{dp_i/obj}$ is the angular velocity of the distal phalanx relative to the object. Different components of these two velocities, in $c_i$ coordinates, are commonly known as the *sliding*, *rolling*, *twisting* and *breaking* velocities between the phalanx and the object. Namely:

$$\begin{aligned} (v^{c_i}_{c_i \in dp_i/obj})_{x,y} &= \text{sliding velocity} \qquad & (\omega^{c_i}_{dp_i/obj})_{x,y} &= \text{rolling velocity} \\ (v^{c_i}_{c_i \in dp_i/obj})_{z} &= \text{breaking velocity} \qquad & (\omega^{c_i}_{dp_i/obj})_{z} &= \text{twisting velocity} \end{aligned} \tag{5.8}$$

The notations $()_x$, $()_y$, $()_z$, $()_{x,y}$ and so on stand for the corresponding coordinates of the vector they enclose. In this case, since we are speaking about $c_i$ coordinates and since $c_i = (t^1_i, t^2_i, n_i)$, $()_x$ is the coordinate along $t^1_i$, $()_y$ is the coordinate along $t^2_i$, and $()_z$ is the coordinate along $n_i$, the outward-pointing normal to the object (see section 5.1.2).

It is worth taking a moment to really understand that the velocity $v_{c_i \in dp_i/obj}$ is *not* necessarily the velocity of the contact point $c_i$ relative to the object. That would be $v_{c_i/obj}$. Instead, $v_{c_i \in dp_i/obj}$ is the velocity of the point of the distal phalanx that coincides with the contact point $c_i$ at the current time. Hence the notation $c_i \in dp_i$ rather than just $c_i$. Both points $c_i$ and $c_i \in dp_i$ are at the same place at any given time, but with possibly different velocities. This important distinction has already been emphasized in chapter 4, in the section on twists, 4.2.1. In short, $v_{c_i \in dp_i/obj}$ measures, at the contact point, the relative motion of the contacting bodies, whereas $v_{c_i/obj}$ measures the motion of the contact point itself on one of the bodies. The same distinction exists on the other body, between the points $c_i$ and $c_i \in obj$, and the associated velocities [4].

The distinction between the contact point and the two coincident points on the contacting rigid bodies is of prime importance in the analysis of the kinematics of rolling contacts (Montana 1988), which itself is important in all situations where a relative rolling motion at a contact cannot be ignored. Dextrous manipulation is such a situation, since it often features non-negligible rolling at the contacts between the fingers and the object. For instance, our study of multifingered grasp stiffness, in chapter 7, specifically addresses stiffness modeling in the case of rolling contacts.

4. An insightful example is the contact between the wheel of a vehicle and the road, when the wheel rolls without sliding on the road (normal operation of a vehicle). Since there is no sliding at the contact, the sliding velocity is null, and assuming that there is no breaking of the contact either: $v_{contact\ point \in wheel/road} = 0_{3,1}$. Yet the contact point itself does move on the road since the vehicle moves: $v_{contact\ point/road} \neq 0_{3,1}$ (actually, the contact point moves at the same velocity than the vehicle).

### Force transmission at the contact interface

Three simple contact models are extremely common in the modeling of multifingered dextrous manipulation (Prattichizzo and Trinkle 2008; Kao, Lynch, and Burdick 2008): the *rigid point contact without friction* model, the *rigid point contact with friction* model, and the *soft finger* model. The forces that can be transmitted through the contact differ from one model to the next.

Let $W^{c_i}_{dp_i \to obj}$ denote the wrench of the actions exerted by the $i$-th distal phalanx on the object, aka the *contact wrench*, written in the contact frame. That is to say:

$$W^{c_i}_{dp_i \to obj} = \begin{pmatrix} f_i = f^{c_i}_{dp_i \to obj} \\ m_i = m^{c_i}_{c_i, dp_i \to obj} \end{pmatrix} \qquad \forall\, i \in [|1, n_f|] \tag{5.9}$$

with $f_i$ the force applied by the distal phalanx $i$ on the object and $m_i$ the moment in the contact point $c_i$ applied by the distal phalanx $i$ on the object, both written in the contact frame $c_i$. See section 4.3 in chapter 4 for more background about wrenches.

The contact wrenches that can be transmitted from one contacting body to the other, and reciprocally, are given below for the three common contact models. As previously, the notations $()_x$, $()_y$, $()_z$ stand for the corresponding coordinates of the vector they enclose; in this case, $c_i$ coordinates, i.e. along $t_i^1$, $t_i^2$, $n_i$ respectively, the last one being the outward-pointing normal to the object (see figure 5.2).

**Rigid point contact without friction** In this model, there are no frictional forces: only a normal force can be exerted between the contacting bodies. There is no transmissible moment either.

$$W^{c_i}_{dp_i \to obj} = \begin{pmatrix} 0 \\ 0 \\ (f_i)_z \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} (f_i)_z \qquad (f_i)_z \leq 0$$

**Rigid point contact with friction** In this model, there are tangential friction forces in addition to the normal force. There is still no transmissible moment.

$$W^{c_i}_{dp_i \to obj} = \begin{pmatrix} (f_i)_x \\ (f_i)_y \\ (f_i)_z \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} (f_i)_x \\ (f_i)_y \\ (f_i)_z \end{pmatrix} = \begin{pmatrix} I_3 \\ 0_{3,3} \end{pmatrix} f_i \qquad (f_i)_z \leq 0$$

$(f_i)_x$, $(f_i)_y$, and $(f_i)_z$ are related by a friction model, for instance the Coulomb laws of dry friction.

**Soft finger** In this model, there is a transmissible torsional moment with respect to the contact normal, in addition to the tangential and normal forces.

$$W^{c_i}_{dp_i \to obj} = \begin{pmatrix} (f_i)_x \\ (f_i)_y \\ (f_i)_z \\ 0 \\ 0 \\ (m_i)_z \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} (f_i)_x \\ (f_i)_y \\ (f_i)_z \\ (m_i)_z \end{pmatrix} \qquad (f_i)_z \leq 0$$

$(f_i)_x$, $(f_i)_y$, $(f_i)_z$, and $(m_i)_z$ are related by an elliptical equation (see Kao, Lynch, and Burdick 2008). The soft finger model can be explained by a local deformation of the finger at the contact interface (hence the name). The deformation forms a small contact patch which allows a moment around the contact normal to be applied. This can be observed, in the case of our fingers, by pressing a finger against a piece of paper on a flat surface: it is possible to rotate the piece of paper on the surface by using the deformation of the finger to apply a moment on the piece of paper.

Obviously, the two rigid point contact models are rigid contact models and the soft finger model is a compliant contact model [5]. Strictly speaking, in a ridig body model, the soft finger model cannot be used to model the contacts, because it would contradict the rigid body assumption. However, it is sometimes used in a sort of quasi-rigid body approach: the contacting bodies are supposed to be rigid for all geometric, kinematics and dynamics purposes, but are nevertheless able to transmit a torsion moment at the contact point. This is legit if the phalanges and the object are rigid enough for the deformation to be negligible compared to their respective dimensions.

The matrices of ones and zeros visible in all three models (and their transposes) are usually called *constraint* or *selection* matrices. Our choice of contact model being the rigid point contact with dry friction, let us note $\Pi = \begin{pmatrix} I_3 & 0_{3,3} \end{pmatrix}$ the adequate selection matrix: it selects the first component of the contact wrench:

$$f_i = \Pi \, W^{c_i}_{dp_i \to obj} \qquad\qquad W^{c_i}_{dp_i \to obj} = \Pi^T f_i$$

We have $(f_i)_z \leq 0$ in all models because the contact normal points out of the object whereas the contact force applied by the finger on the object points into the object. Of course it is merely a convention depending on the definition of the contact frame: a contact normal pointing into the object would yield $(f_i)_z \geq 0$. This property is called the *unilaterality* of the contact constraint: the normal force can only be applied in one direction, contrary to what happens with *bilateral* constraints. Loosely speaking, only pushing is possible, not pulling.

The most commonly used model of friction in robotic manipulation is the Coulomb dry friction model. It is a set of two experimental laws relating the tangential component and the normal component of the contact force, in two cases: when the contact is sliding and when it is not. French physicist Charles de Coulomb elaborated these laws from experimental studies on sliding, in the second half of the eighteenth century [6].

**Coulomb laws of dry friction** Two rigid bodies are in contact, one of them is applying a contact force $f = f_n + f_t$ on the other, $f_n$ being the normal component, $f_t$ being the tangential component or *friction force*, as illustrated on figure 5.3.

5. It is a generalization of the hertzian contact model: the hertzian model is about objects of linear elastic materials in contact, and the soft finger model is an extension to non-linear elastic materials (Xydas and Kao 1999; Kao and F. Yang 2004; Kao, Lynch, and Burdick 2008). The hertzian contact model is the oldest compliant contact model; it was formulated by German physicist Heinrich Hertz at the end of the nineteenth century.

6. His work on friction was continued by French physicist Arthur Morin during the nineteenth century, which is the reason why the Coulomb laws are sometimes called the Coulomb-Morin laws, mainly in books on the history of tribology though (tribology being the science and engineering of interacting surfaces in relative motion: study of friction, lubrication, wear, and so on).

1. If the contact is sliding:
    a) the contact force $f$ lies on the surface of a cone whose apex is the contact point and whose half-angle is $\phi_k$;
    b) the friction force $f_t$ opposes the direction of motion i.e. the sliding velocity;
    c) the friction force magnitude is related to the normal force magnitude by $\|f_t\| = \mu_k \|f_n\|$, where $\mu_k = \tan\phi_k$ is a coefficient depending on the two materials in contact and on the condition of the contacting surfaces; $\mu_k$ is called the *kinetic friction coefficient*.
2. If the contact is not sliding:
    a) the contact force $f$ lies inside or on the surface of a cone whose apex is the contact point and whose half-angle is $\phi_s$;
    b) the direction of the friction force $f_t$ is not known;
    c) the friction force magnitude is related to the normal force magnitude by $\|f_t\| \leq \mu_s \|f_n\|$, where $\mu_s = \tan\phi_s$ is a coefficient depending on the two materials in contact and on the condition of the contacting surfaces; $\mu_k$ is called the *static friction coefficient*.

It is noteworthy that the friction force is independent of the speed of sliding. Usually, $\mu_k$ is slightly smaller than $\mu_s$, which implies that "a larger friction force is available to resist initial motion, but once motion has begun, the resisting force decreases" (Kao, Lynch, and Burdick 2008). In other words, keeping an object in sliding motion is easier than putting it in sliding motion in the first place [7]. Usually also, the Coulomb friction model is simplified by merging the static and kinetic contact cones: for simplicity, we assume the simplest Coulomb friction model, with a single dry friction coefficient $\mu = \mu_s = \mu_k$.

Below is a summary of the rigid point contact model with dry Coulomb friction for the $i$-th contact between the distal phalanx $dp_i$ and the object:

$$W^{c_i}_{dp_i \to obj} = \begin{pmatrix} f_i \\ 0_{3,1} \end{pmatrix} \qquad (f_i)_z \leq 0 \tag{5.10}$$

$$\text{non sliding contact: } \|f_{i,t}\| \leq \mu \|f_{i,n}\| \quad \text{i.e.} \quad (f_i)_x^2 + (f_i)_y^2 \leq \mu^2 (f_i)_z^2 \tag{5.11}$$

$$\text{sliding contact: } \|f_{i,t}\| = \mu \|f_{i,n}\| \quad \text{i.e.} \quad (f_i)_x^2 + (f_i)_y^2 = \mu^2 (f_i)_z^2 \tag{5.12}$$

$$-f_{i,t} \text{ and } v^{c_i}_{c_i \in dp_i/obj} \text{ are negatively colinear}$$

It is $-f_{i,t}$ and not $f_{i,t}$ because $-f_i = f^{c_i}_{obj \to dp_i}$ and the friction force applied by the object on the phalanx opposes the sliding velocity of the phalanx relative to the object.

### Linear approximation of the Coulomb friction model

The Coulomb friction model has a quadratic nature:

$$\frac{(f_i)_x^2}{\mu^2} + \frac{(f_i)_y^2}{\mu^2} - \frac{(f_i)_z^2}{1^2} = 0$$

7. A fact one can easily feel at home when moving furniture.

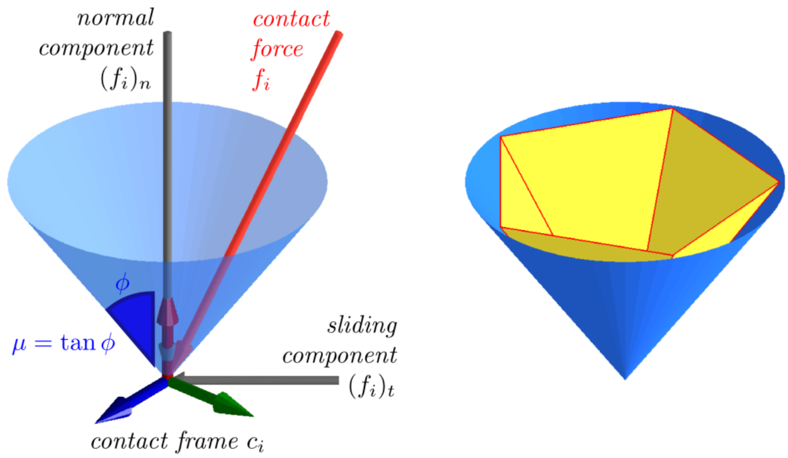



Figure 5.3 – A non-sliding contact, its exact contact cone and its five-faceted linearized contact cone

or equivalently:

$$f_i^T \tilde{C} f_i = 0 \qquad \text{with } \tilde{C} = \begin{pmatrix} 1/\mu^2 & 0 & 0 \\ 0 & 1/\mu^2 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

is a quadratic form of $\mathbb{R}^3$ which defines a circular cone in the tridimensional force space, whose axis is the third vector i.e. the contact normal $n_i$. One half of this cone is selected by the unilaterality condition $(f_i)_z \leq 0$: it is the Coulomb friction cone (strictly speaking a half-cone, then).

For computational purposes, it is sometimes useful to have a linear approximation of this quadratic model. This is traditionally done by approximating the circular friction cone as a pyramidal cone, as shown in figure 5.3. For instance, an early example of linearized contact cone utilization in multifingered dextrous manipulation may be found in an article by Kerr and Roth (1986): the cones have four faces. Of course, the more faces, the better the approximation, but the higher its dimensionality.

A multi-faceted contact cone results in a linear version of the Coulomb sliding and non-sliding conditions (5.11) and (5.12). Interestingly enough, the resulting linear version also accounts for unilaterality. That is to say, if we define:

$$f = \begin{pmatrix} f_1 \\ \vdots \\ f_{n_f} \end{pmatrix}$$

the column vector of all the contact forces, we may find matrices $C$ and $d$ such that all the non-sliding and unilaterality conditions read (for the sliding conditions, replace the inequality by an equality):

$$Cf + d \leq 0_{n_f \times n_e, 1} \tag{5.13}$$

In this linear approximation of the Coulomb friction model, $C$ is $(n_f \times n_e, 3n_f)$ in size, $n_e$ being the number of edges in the cone discretization, and $d$ is a column

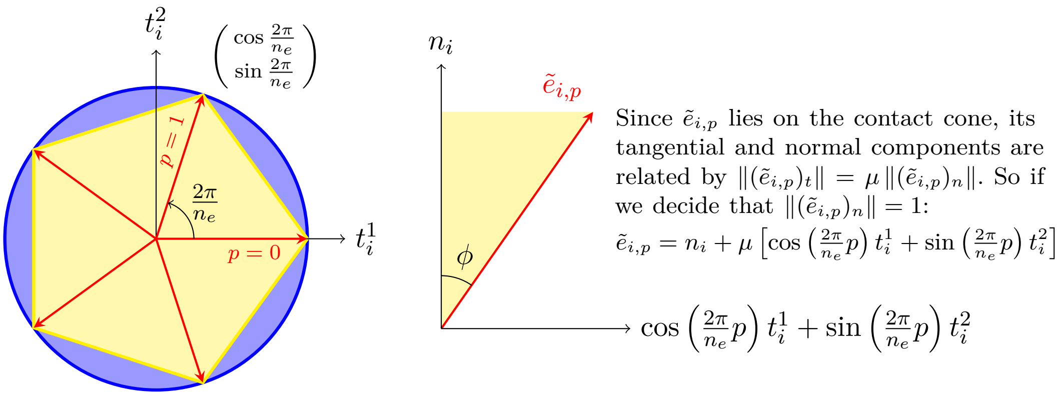



Figure 5.4 – Expression of the edges of a discretized contact cone. See also figure 5.3. Left: circular section seen from above; right: vertical section with respect to the $p$-th edge.

vector with $n_f \times n_e$ lines. When some contacts are sliding and others are not, the unilaterality and Coulomb conditions for all the contacts would have the form:

$$\begin{cases} C_{\bar{s}}f + d_{\bar{s}} \leq 0_{n_{\bar{s}}\times n_e,1} & \text{with } n_{\bar{s}} \text{ the number of non-sliding contacts} \\ C_s f + d_s = 0_{n_s\times n_e,1} & \text{with } n_s \text{ the number of sliding contacts, } n_{\bar{s}} + n_s = n_f \end{cases}$$

In the rest of this section, we give the expressions of $C$ and $d$, in the case that all contacts are non-sliding.

We start by finding the expression of the edges of the discretized cone at the contact $i$. Let $e_i = (e_{i,0}, \ldots, e_{i,n_e-1})$ denote normed vectors along these edges, originating from the apex of the cone. We can choose the discretization of the cone so that the first edge of the cone, defined by $e_{i,0}$, is in the direction of $t_i^1$, strictly speaking, so that it is in the plane defined by $t_i^1$ and $n_i$, as shown in figure 5.4. That way, it is easy to prove that the edge vectors $e_i$ have the following expression:

$$\left.\begin{aligned} \tilde{e}_{i,p} &= n_i + \mu\left[\cos\left(\frac{2\pi}{n_e}p\right)t_i^1 + \sin\left(\frac{2\pi}{n_e}p\right)t_i^2\right] \\ e_{i,p} &= \frac{\tilde{e}_{i,p}}{\|\tilde{e}_{i,p}\|} \end{aligned}\right. \qquad \forall\, p \in [|0, n_e - 1|]$$

Figure 5.4 gives an idea of the calculations to arrive at this result. Then, we can define the normal vector of each cone face by a simple cross product of its edge vectors:

$$\nu_{i,p} = \begin{cases} \dfrac{e_{i,p} \times e_{i,p+1}}{\|e_{i,p} \times e_{i,p+1}\|} & \forall\, p \in [|0, n_e - 2|] \\ \dfrac{e_{i,n_e-1} \times e_{i,0}}{\|e_{i,n_e-1} \times e_{i,0}\|} & \text{for } p = n_e - 1 \end{cases}$$

Each face's normal vector points into the inside of the cone, according to how we have numbered the edges ($p$ increasing clockwise in the tangent plane defined by $t_i^1$ and $t_i^2$). That way, for a contact force $f_i$ to be inside the discretized contact cone, it needs to be in the appropriate half-space defined by each face. According to the respective orientation of $f_i$ (pointing to the object) and $\nu_{i,p}$ (pointing into the cone), that means that the dot product of $f_i$ and each $\nu_{i,p}$ needs to be negative:

$$\begin{aligned}
f_i \in \text{discretized contact cone } i &\Leftrightarrow (\nu_{i,p}|f_i) \leq 0 \quad \forall p \in [|0, n_e - 1|] \\
&\Leftrightarrow {\nu_{i,p}^{c_i}}^T f_i^{c_i} \leq 0 \quad \forall p \in [|0, n_e - 1|] \\
&\Leftrightarrow \begin{pmatrix} {\nu_{i,0}^{c_i}}^T \\ \vdots \\ {\nu_{i,n_e-1}^{c_i}}^T \end{pmatrix} f_i^{c_i} \leq 0_{n_e,1} \\
&\Leftrightarrow \begin{pmatrix} \nu_{i,0}^{c_i} & \cdots & \nu_{i,n_e-1}^{c_i} \end{pmatrix}^T f_i^{c_i} \leq 0_{n_e,1}
\end{aligned}$$

Let $C_i$ denote the preceeding matrix, such that $C_i\, f_i \leq 0_{n_e,1}$, and:

$$C = \begin{pmatrix} C_1 & & \\ & \ddots & \\ & & C_{n_f} \end{pmatrix} \qquad f = \begin{pmatrix} f_1 \\ \vdots \\ f_{n_f} \end{pmatrix} \qquad d = 0_{n_f \times n_e, 1}$$

These are the matrices of the linearized non-sliding and unilaterality conditions of the equation (5.13):

$$C f + d \leq 0_{n_f \times n_e, 1}$$

### 5.1.5 Hand dynamics

#### Inverse dynamic model of the hand

The inverse dynamic model of a torque-controlled serial robot manipulator has the following usual form, in joint space (see e.g. Murray, Z. Li, and Sastry 1994, chapter 4, or any robotics textbook):

$$\tilde{M}(q)\ddot{q} + \tilde{C}(q,\dot{q})\dot{q} = -\tilde{g}(q) + \tilde{W} + \tau$$

In this equation, $q$ is the vector of articular positions, $\tilde{M}(q)$ is the mass/inertia matrix of the robot written in joint space, $\tilde{C}(q,\dot{q})\dot{q}$ is a vector that gives the Coriolis and centrifugal force terms, $\tilde{g}(q)$ is the vector of gravitational force terms, $\tilde{W}$ is the vector that gives the other forces applied on the robot by its environment (usually, loading), and $\tau$ is the vector of control torques.

Since every finger in a hand is a serial kinematic chain, their dynamics is of the previous form, and by combining the finger dynamic models together, it is possible to show that the inverse dynamic model of the hand is as follows:

$$J^T M J\, (\dot{T} - \mathcal{G}) + NT - J^T W_{ext} = L\, \tau \tag{5.14}$$

$$T = \begin{pmatrix} V_0 \\ \dot{q} \end{pmatrix} = \begin{pmatrix} V_0 \\ \dot{q}_1 \\ \vdots \\ \dot{q}_{n_{dof}} \end{pmatrix} \qquad \tau = \begin{pmatrix} \tau_1 \\ \vdots \\ \tau_{n_{dof}} \end{pmatrix}$$

In this system of $6 + n_{dof}$ equations, $M$ is the hand generalized mass matrix, $J$ is the hand jacobian defined in (5.6), $NT$ are the Coriolis and centrifugal forces, $\mathcal{G}$ is for gravity, and $W_{ext}$ denotes external wrenches that may be applied on the hand's segments. We give a little more detail about these notations below.

1. $M$ is the block-diagonal matrix of the generalized masses of the bodies of the hand (see section 5.1.2), written in their respective body frames:

$$M = \begin{pmatrix} M_0 & & & \\ & M_1 & & \\ & & \ddots & \\ & & & M_{n_b} \end{pmatrix}$$

   $M$ is symmetric definite-positive, because each $M_k$ is symmetric definite-positive too.

2. $J$ is the hand jacobian, it maps the root cartesian space and the joint space into the cartesian space of the segments of the hand (see equation (5.6), section 5.1.3). That way, $J^T M J$ is the hand generalized mass matrix written in the root and joint space, not in each body's cartesian frame.

3. $N$ is called the Coriolis matrix of the hand, it is the matrix $\tilde{C}(q, \dot{q})$ of the general dynamic model.

4. $W_{ext}$ is the vector of all the external wrenches applied on the segments of the hand, except gravity, wrenches applied by the other segments, and wrenches applied by the control torques. That is to say:

$$W_{ext} = \begin{pmatrix} W_0 \\ W_1 \\ \vdots \\ W_{n_b} \end{pmatrix} \qquad \text{with} \quad W_k = W^k_{ext\to k} = \begin{pmatrix} f^k_{ext\to k} \\ m^k_{K,ext\to k} \end{pmatrix}$$

   Each $W_k$ denotes the external wrench applied on the body $k$, written in the own frame of body $k$: $f^k_{ext\to k}$ is the external force and $m^k_{K,ext\to k}$ is the external moment at the center of mass $K$ of body $k$, both written in the basis of the frame $k$.

   "External" means that the wrenches are applied by the environment of each segment, they do not originate from the segment itself, that would be "internal" wrenches. Contact forces for instance are external wrenches. Since the segments are rigid bodies, there are no internal wrenches anyway. Wrenches applied by gravity and by the control torques are not taken into account in $W_{ext}$ since they have their own terms. Wrenches applied on a segment by the other segments are not taken into account either because if they were, they would compensate one another in $J^T W_{ext}$ anyway, so there is no need to care about them.

   From a control point of view, most $W_k$ are zero, except the $W_{dp_i}$ that are the contact wrenches $W^{dp_i}_{obj\to dp_i}$ resulting from the forces $-f_1, \ldots, -f_{n_f}$ applied by the object on the fingers. However, external wrenches other than contact wrenches may be taken into account when designing the hand's control, if it is reasonable to assume that the control may have knowledge of them. Disturbances for instance should not be taken into account.

5. $L$ is a matrix indicating how the control forces $\tau$ act on the hand. It merely moves $\tau$ from the joint space to the root and joint space:

$$L = \begin{pmatrix} 0_{6,n_{dof}} \\ I_{n_{dof}} \end{pmatrix}$$

6. $\mathcal{G}$ is the gravity acceleration vector, written in the root and joint space. For instance, if the third vector of the root frame is vertical and pointing upwards:

$$\mathcal{G} = \begin{pmatrix} 0 \\ 0 \\ -\tilde{g} \\ 0 \\ 0 \\ 0 \\ 0_{1,n_{dof}} \end{pmatrix} \qquad \tilde{g} = \text{gravity intensity}$$

If it is not, a simple change of basis is needed on the first three coordinates.

When the hand is in static equilibrium, the velocities and accelerations are zero and the inverse dynamic model reduces to the inverse static model:

$$-\,J^T M J\,\mathcal{G} - J^T W_{ext} = L\,\tau \tag{5.15}$$

It is possible to include the forces applied by gravity in one of the other terms, for a more concise model.

The inverse static model is still valid when the hand moves quasi-statically, that is to say when the inertia terms are negligible, as happens during slow motion.

**Gravity and gravity compensation**

For simplicity, it is possible to consider that the hand is not subject to gravity (i.e. $\tilde{g} = 0$) whereas at the same time, the manipulated object remains subject to gravity. This is unrealistic but not senseless, for two reasons.

The first reason is that when the hand is subject to gravity and no motor torques are applied, the phalanges fall because of their own weight. To avoid this, it is normally necessary to apply motor torques whose sole purpose is to oppose gravity: this is called gravity compensation. So when it is desired that the hand manipulates an object, the control torques that must be applied ($\tau$) feature two contributions: the torques necessary to manipulate the object (manipulation torques) and those necessary to oppose gravity (gravity compensation torques). Yet the problem we are concerned with is object manipulation control, not gravity compensation for the hand. So the values we are interested in are only the manipulation torques. This is why we can consider, in a first approach at least, that the hand is not subject to gravity: it removes the need for gravity compensation and makes it possible to design a control $\tau$ that is purely related to manipulation. It is worthwhile however to consider that gravity still works on the object, since the weight of the object is part of the manipulation problem (gravity compensation is about opposing the weight of the hand, not about opposing the weight of the object).

The second reason is that for simplicity, our hand model is not attached to a complete robot, so when it is subject to gravity, it falls. To avoid this, it is normally necessary to consider a whole robot. For instance, a possible satisfactory robot model is a two-handed humanoid standing on the ground. But here again, the problem we are interested in is object manipulation, so taking a whole robot into account would be pointless. A workaround is to consider that gravity compensation forces are artificially applied on the root body, by means of an adequate $W_{root}$. This simulates the attachment of the hand to a wrist, and therefore accounts for the hand not falling. The workaround we use is simpler: we assume a world without gravity on the hand and a high-inertia root body. That way, the hand does not fall since it is weightless, and because of its inertia the palm resists any motion. Consequently, the hand remains motionless in the environment.

It is easy to simulate a no-gravity world in computer environments: gravity just needs to be set to zero in the dynamical engine. We do so quite often in our computer simulations. Besides, turning off gravity is one of the first thing to do when debuging, because the contact forces and the control torques become easier to interpret: the contributions due to gravity disappear and only those related to manipulation remain. Also, in the Arboris dynamical engine it is possible to turn off gravity on a robot basis, not just globally: we often realize simulations where the hand is not subject to gravity, but the manipulated object is, since the weight of the object is part of the manipulation problem as explained before.

However, for real-life applications, gravity and gravity compensation terms cannot be ignored, as well as the attachment of the hand to a forearm or some sort of robotic support. These aspects must be correctly included in the control via terms in $W_{ext}$ and $\tau$ for instance, or the model of the hand must be blended appropriately in the model of the larger robot. But these are technical problems of little relevance to the study of manipulation in itself; they only pose technical difficulties.

### 5.1.6 Object dynamics

#### Relationship between contact forces and object motion

The object motion is the result of the forces the object is subject to: contact forces and weight. The object dynamics is therefore:

$$M_{obj}\left(\dot{V}_{obj} - g\right) + N_{obj} V_{obj} = W_{dp\to obj} \tag{5.16}$$

If a disturbance happens, an adequate external wrench must be added to complete this inverse dynamic model. However, from a control perspective, disturbances are unknown, and the object dynamics is as stated.

In this model, all quantities are written in the object frame: the generalized mass matrix of the object $M_{obj}$, its Coriolis matrix $N_{obj}$, its absolute twist $V_{obj} = V^{obj}_{obj/ref}$, the resultant wrench applied by the fingers $W_{dp\to obj}$, and the gravity acceleration vector $g$. We have:

$$M_{obj} = \begin{pmatrix} m_{obj} I_3 & 0_{3,3} \\ 0_{3,3} & [I]_{obj} \end{pmatrix} \quad \text{and} \quad g = \begin{pmatrix} {}^{obj}R_{ref} \begin{pmatrix} 0 \\ 0 \\ -\tilde{g} \end{pmatrix} \\ 0_{3,1} \end{pmatrix} \tag{5.17}$$

$$\text{so the gravity wrench is: } M_{obj}\, g = m_{obj}\, g$$

$$W_{dp\to obj} = W^{obj}_{dp\to obj} = \sum_{i=1}^{n_f} W^{obj}_{dp_i\to obj} = \sum_{i=1}^{n_f} {}^{obj}Ad_{c_i}^{-T}\, W^{c_i}_{dp_i\to obj} \tag{5.18}$$

In this last equation, $W^{c_i}_{dp_i\to obj}$ is the contact wrench applied by the $i$-th finger (see section 5.1.4), and ${}^{obj}Ad_{c_i}^{-T}$ is the co-adjoint matrix of ${}^{obj}H_{c_i}$, used to change the expression frame of each contact wrench (see section 4.3.2 in chapter 4):

$${}^{obj}Ad_{c_i}^{-T} = \begin{pmatrix} {}^{obj}R_{c_i} & 0_{3,3} \\ \hat{r}^{obj}_{obj,c_i}\, {}^{obj}R_{c_i} & {}^{obj}R_{c_i} \end{pmatrix} \qquad W^{c_i}_{dp_i\to obj} = \begin{pmatrix} f_i \\ 0_{3,1} \end{pmatrix}$$

with $\hat{}$ denoting the operation that returns a skew-symmetric matrix for left-wise cross-product by the input vector: $\hat{r}u = r \times u$ (see sections 4.2.2 and 4.A in chapter 4).

### Grasp matrix

Further developing the expression of equation 5.18, we can write:

$$W_{dp\to obj} = \begin{pmatrix} {}^{obj}Ad_{c_1}^{-T} & \dots & {}^{obj}Ad_{c_{nf}}^{-T} \end{pmatrix} \begin{pmatrix} W_{dp_1\to obj}^{c_1} \\ \vdots \\ W_{dp_{nf}\to obj}^{c_{nf}} \end{pmatrix} \tag{5.19}$$

$$= \begin{pmatrix} {}^{obj}R_{c_1} & \dots & {}^{obj}R_{c_{nf}} \\ \hat{r}_{obj,c_1}^{obj}\ {}^{obj}R_{c_1} & \dots & \hat{r}_{obj,c_{nf}}^{obj}\ {}^{obj}R_{c_{nf}} \end{pmatrix} \begin{pmatrix} f_1 \\ \vdots \\ f_{n_f} \end{pmatrix} \tag{5.20}$$

The matrix that allows to write $W_{dp\to obj}^{obj}$ as a linear function of the contact wrenches $W_{dp_i\to obj}^{c_i}$, or contact forces $f_i$, is called the *grasp map*, or *grasp matrix* of the grip. It is usually denoted $G$. Both the definitions (5.19) and (5.20) of this matrix can be encountered in the robotics literature[8]: as the matrix of the co-adjoints, shown in (5.19), or as the reduced form that features only one half of the co-adjoints, shown in (5.20). In this chapter and in the next one, we use the reduced expression. Thus:

$$W_{dp\to obj} = G\, f \tag{5.21}$$

with $G$ as in (5.20)

### Transpose of the grasp matrix

Generally speaking, it can be better to stick to the "complete" definition of $G$ of equation (5.19), because then the transpose of the grasp matrix has a meaning in terms of twists (since the twist space and the wrench space are dual spaces, see chapter 4):

$$\text{if } G = \begin{pmatrix} {}^{obj}Ad_{c_1}^{-T} & \dots & {}^{obj}Ad_{c_{nf}}^{-T} \end{pmatrix} \text{ as in (5.19), then } G^T = \begin{pmatrix} {}^{c_1}Ad_{obj} \\ \vdots \\ {}^{c_{nf}}Ad_{obj} \end{pmatrix}$$

$$\text{and then we have: } \begin{pmatrix} V_{obj}^{c_1} \\ \vdots \\ V_{obj}^{c_{nf}} \end{pmatrix} = G^T V_{obj}$$

In this chapter though, we will not need this last equation, so we can go for the reduced expression of $G$. It is noteworthy that the twists $V_{obj}^{c_i}$ in this equation are the absolute twists of the object at the contact points, *not* the twists of the distal phalanges:

$$\begin{pmatrix} V_{dp_1}^{c_1} \\ \vdots \\ V_{dp_{nf}}^{c_{nf}} \end{pmatrix} \neq G^T V_{obj}$$

8. Also, certain authors define the grasp matrix as the transpose of our grasp matrix. It is just a matter of conventions.

Yet this misconception can be found from time to time in the robotics literature [9], with problematic consequences (anything that results from this wrong equation is also wrong). Since the grasp matrix and its transpose are made of adjoint and co-adjoint matrices, they can only change the frame of expression of twists and wrenches, not the bodies these twists and wrenches are relative to. The only way for the previous equation to be true is when there is no relative motion between the object and the distal phalanges, as if they were rigidly linked; or at least, when the relative motion is small enough to be ignored. In multifingered dextrous manipulation, this is not often the case.

### Internal forces

Since the grasp matrix is obviously non-invertible, it has a non-trivial kernel (null space). That is to say, there are non-zero contact forces $f \in \mathbb{R}^{3n_f}$ such that the total contact wrench is null: $W_{dp\to obj} = G\,f = 0_{6,1}$.

Such a total contact wrench cannot produce any motion of the object, or cancel any other external wrench applied on the object (such as the gravitational forces). Yet since the contact forces themselves are non-zero, they can still squeeze the object. We can therefore separate the contact forces $f$ into two categories: those that can produce a motion of the object and those that result only in a tightening of the object.

$f \in \ker G$ The contact forces that are in the kernel of the grasp matrix result in a zero total contact wrench and therefore cannot produce any motion of the object, but only tightening. They are called *internal forces*.

$f \notin \ker G$ The contact forces that are not in the kernel of the grasp matrix result in a non-zero total contact wrench and are therefore able to produce a motion of the object. They may also produce tightening at the same time [10].

When $W_{dp\to obj}$ is given and $f$ is unknown in the linear equation (5.21), solving for $f$ results in making the two sides of the contact forces, motion and tightening, clearly visible. Indeed, the solution set of any linear equation is an affine space over the solution set of the corresponding homogeneous linear equation, that is to say over the kernel of the linear map. Noting $f_P$ one particular solution of the full, inhomogeneous linear equation (5.21), the complete solution set is:

$$f_P + \ker G = \{f_P + f_I,\ f_I \in \ker G\} \tag{5.22}$$

$f_P$ is a vector of forces that result in $W_{dp\to obj}$ and consequently produce a motion, and possibly tightening too. Any additional forces $f_I$ chosen in $\ker G$ produce only tightening that combines with the tightening already in $f_P$.

From a control point of view, it is desirable to control independently both these sides of manipulation, motion and tightening. As we will see in the following section, this is possible thanks to the form of the solution space (5.22).

9. For instance: Starr (1988, equation 6), B. H. Kim, Yi, S. R. Oh, and Suh (2003, equation 5).
10. As a matter of fact, the characterization of the contact forces that produce a motion only, no tightening, is not as straightforward as the characterization of the contact forces that produce a tightening only, no motion. For instance, see the so-called “non-squeezing” pseudo-inverse of the grasp matrix in I. Walker, Freeman, and Marcus (1991), and the analysis of “grasping” and “manipulation” forces by T. Yoshikawa and Nagai (1987, 1988, 1991).

## 5.2 Review on control in robotic manipulation

Given that each finger in a hand is a serial kinematic chain, a way of looking at a multifingered robot hand is to consider it a set of $n_f$ serial manipulators grasping and manipulating an object cooperatively. And since single-arm manipulators and multi-arm robot systems have been studied since the early years of robotics in the 1960s and 1970s, with a notable outburst of scientific activity in the 1980s, it is reasonable to think that the control laws developed during these decades for motion and force control of such systems might be adapted to robot hands.

Therefore, we present here a short review on control in robotic manipulation by serial manipulators (5.2.1), cooperative manipulators (5.2.2), and multifingered hands (5.2.3), to put things into context. We emphasize the differences between these systems, from a control perspective (in 5.2.2). We review thoroughly the "classical" hybrid force/position control strategies of multifingered hands (in 5.2.3), concentrating on what they have in common, in order to get the general idea of how control of multifingered dextrous manipulation is usually done. This makes it easier to draw the comparison with our own optimization-based force/position control scheme, introduced in the following section (5.3).

### 5.2.1 Control of serial robot manipulators

A simple situation where a multifingered hand may be controlled as $n_f$ serial manipulators is when it is moving in free space, that is to say without any object in grasp. This situation happens when the hand moves from one articular posture to another, for instance in preshaping for a grasp. In this case, a simple concatenation of $n_f$ motion control laws, one per finger, can do the trick, assuming that the control objectives are chosen to avoid any collision between the fingers of course. For instance, a trivial open-loop motion control of the hand in joint space would be defined as follows:

1. Joint trajectory that we want to track:

$$q^{[d]}(t) = \begin{pmatrix} q_1^{[d]}(t) \\ \vdots \\ q_{n_{dof}}^{[d]}(t) \end{pmatrix} \qquad \text{the } {}^{[d]} \text{ superscript stands for "desired"}$$

2. We suppose that this trajectory is at least twice differentiable, and that the palm remains motionless:

$$T^{[d]}(t) = \begin{pmatrix} 0_{6,1} \\ \dot{q}^{[d]}(t) \end{pmatrix} \qquad \dot{T}^{[d]}(t) = \begin{pmatrix} 0_{6,1} \\ \ddot{q}^{[d]}(t) \end{pmatrix}$$

   Controlling the palm motion in addition to the articular motion, though, would simply require using the external wrench $W_0$ applied on the palm (in $W_{ext}$) as a control input, in addition to $\tau$.

3. We also suppose that $q(0) = q^{[d]}(0)$ and $\dot{q}(0) = \dot{q}^{[d]}(0)$.

4. Then the following computed-torque control law, obtained from the hand inverse dynamic model (5.14), realizes trajectory tracking in the joint space:

$$L\,\tau = J^{[d]T} M J^{[d]} \,(\dot{T}^{[d]} - \mathcal{G}) + N^{[d]} T^{[d]} - J^{[d]T} W_{ext}$$

because both $q$ and $q^{[d]}$ satisfy the same differential equation (5.14), and have the same initial conditions: so it follows from the uniqueness of the solutions of differential equations that $q(t) = q^{[d]}(t),\ \forall\, t \geq 0$. Notes:

- $L\,\tau$ is basically the control variable $\tau$; to get $\tau$ alone: $\tau = L^T L\,\tau$;
- time dependency of all the matrices but $L$, $M$, $\mathcal{G}$, dropped for brievity;
- $J$ is a function of $q$, and $N$ is a function of $q$ and $\dot{q}$, hence the $^{[d]}$ superscript;
- $W_{ext}$ is likely to be zero since the hand is supposed in free space.

Of course, open-loop control is not a very robust control strategy with respect to initial condition errors, modeling errors, or disturbances. But it is just an example, and any position control or force control developed for a serial manipulator can be used to control each of the $n_f$ fingers of the hand in position or force. And there are numerous control laws available for serial robot manipulators, if only because of the prime importance of these robots in the early development of robotics.

### Motion control

For instance, for motion control of robot manipulators, the most classical closed-loop control law is the proportional-derivative control, possibly augmented with an integral term (Ziegler and Nichols 1942), a gravity compensation term (Takegaki and Arimoto 1981), and/or a model-based feedforward term (Koditschek 1984). This last variation is a special case of the class of computed-torque controls, also called inverse dynamic controls because they are based on the inverse dynamic model. In fact, most of the robot control schemes that have been proposed through the years from the beginning of the 1970s are model-based and can be considered as special cases of computed-torque controls (see e.g. Luh, M. Walker, and R. Paul 1980, 1982; Freund 1982b,a; An, Atkeson, and J. Hollerbach 1988; Kreutz-Delgado 1989; Isidori 1985/1995). The first examples of computed-torque controls, by R. Paul (1972a,b), Markiewicz (1973), and Bejczy (1974), actually pre-dated the development of their theoretical framework, which is the more general differential-geometric method of feedback linearization, now a canonical method of non-linear control theory (Brockett 1979; Jakubczyk and Respondek 1980; Hunt, Su, and Meyer 1983a,b). For rigid manipulators, the feedback linearization technique is equivalent to the inverse dynamics approach: they result in the same computed-torque control laws (Tarn, Bejczy, Isidori, and Y. Chen 1984).

Proportional-derivative and computed-torque controls are simple and provide closed-loop stability and sufficiently good tracking performance for typical robotic manipulation tasks; consequently they are common and popular. They may be formulated in the joint space, either directly or after inverse kinematics resolution, or in the cartesian space at end-effector level, that is to say directly in end-effector coordinates (in the case of a finger, the end-effector is the distal phalanx). More advanced control strategies may be used too, associated with computer-torque control laws, for instance robust control (e.g. Corless and Leitmann 1981; Slotine 1985) or adaptive control (e.g. Craig, P. Hsu, and Sastry 1986, 1987; Slotine and W. Li 1987, 1988).

### Force control

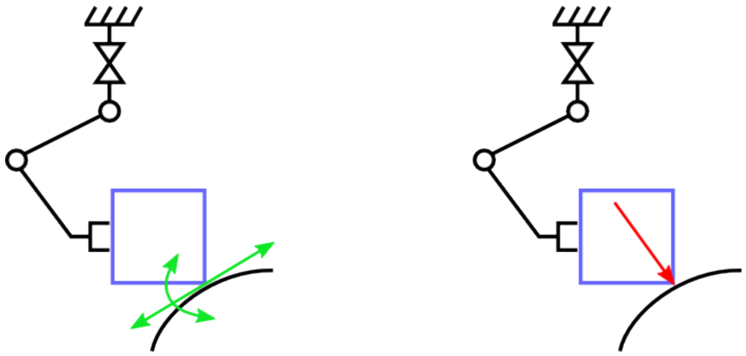
When force control of a robot manipulator must be enforced, it is usually in addition to motion control. In the combined control strategy that results, the force part at least is usually formulated in the cartesian space: force control objectives are seldom written in the joint space since the interaction forces at the end-effector are naturally described in the cartesian space.

Force control may be "direct" or "indirect" (Siciliano, Sciavicco, Villani, and Oriolo 2009, chapter 9). In "indirect" strategies, force control is achieved via position control, without explicit closure of a force feedback loop. Force objectives are not specified; instead, the control objective is the desired dynamic behavior of the manipulator around the setpoint of the position control (i.e. around the desired position). This dynamic behavior is either a mechanical stiffness or, more generally, a mechanical impedance, hence the two indirect force control strategies: stiffness control (aka compliance control) and impedance control (aka admittance control) [11]. On the other hand, if it is desirable to control the interaction forces to specific desired values, "direct" force control strategies featuring explicit closure of a force feedback loop are better suited. Hybrid force/position control, for instance, is a direct force control strategy.

The idea of using compliance for the control of serial robot manipulators was introduced by R. Paul and Shimano in the late 1970s, as a solution to the problem of tolerance in assembly operations, such as mating or fastening parts (R. Paul and Shimano 1976, 1982; R. Paul 1979a,b). They indicated that compliance could be controlled in a cartesian coordinate system, and shortly thereafter, Salisbury (1980) provided the relationship between the stiffness of the joints of a manipulator and the cartesian stiffness of its end-effector. This relationship was revised much later by S.-F. Chen and Kao (2000a), with an additional term depending on the interaction force and the geometry of the manipulator (see cited references and chapter 7 for more on this subject). As for impedance control, it was developed by Hogan (1984, 1985c,b,a) in the 1980s. Simply put, in stiffness control, the manipulator is reduced to a spring-like system: the interaction force it applies is related to the displacement of its end-effector from its desired position by a Hooke-like law. In impedance control, the manipulator is reduced to a mass-spring-damper system, hence a more complete desired dynamic behavior around the end-effector desired position. These methods are illustrated schematically in figure 5.6.

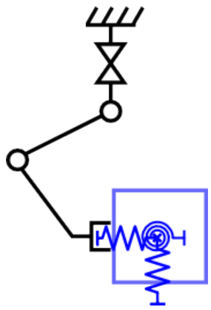
At their simplest, direct force control schemes can be obtained from a motion control scheme by the addition of an outer force control loop around it, generating the input for the inner position loop (De Schutter and Van Brussel 1988). This design results in a pure force control law that does not allow position control, since the inner loop is entirely masked. It might be slightly modified though, if it is desired to specify a desired end-effector position: the resulting control scheme is called parallel force/position control (Chiaverini and Sciavicco 1993). Other combined force and position strategies are the well-known hybrid force/position control (Raibert and Craig 1981, 1982; Khatib 1987; T. Yoshikawa 1987; T. Yoshikawa, Sugie, and Tanaka 1988), and hybrid impedance control, which combines hybrid force/position and impedance control (R. Anderson and Spong 1987, 1988; G. Liu and Goldenberg 1991). Hybrid force/position control features a position control loop and a force control loop in parallel. It controls simultaneously the force in some directions of the task space (the constrained ones) and the position in other directions of the task space (the free ones). Figure 5.5 illustrates this method schematically.

11. Compliance is the inverse of stiffness, admittance is the inverse of impedance.



(a) Directions of position control (b) Directions of force control

Figure 5.5 – Principle of hybrid force/position control, for a single manipulator (adapted from T. Yoshikawa 2010)



Impedance enforced on the grasped object

Figure 5.6 – Principle of compliance control and impedance control, for a single manipulator, with only the virtual spring elements depicted (adapted from T. Yoshikawa 2010)

#### Further information

All the above-cited references are classic works and only a small selection of the historically significant papers on robot control. Extensive information about the cited control strategies may be found in these references, in subsequent articles by the same authors, in a couple of review papers (for instance T. Yoshikawa 2000b), and in a large number of modern textbooks on the modeling and control of robot manipulators (for instance W.-K. Chung, Fu, and H. Hsu 2008, on motion control; Villani and De Schutter 2008, on force control; Murray, Z. Li, and Sastry 1994, pages 189–199, on motion control; Siciliano, Sciavicco, Villani, and Oriolo 2009, chapters 8 and 9, on motion and force control respectively; R. Kelly, Santibáñez, and Loría 2005, on motion control in the joint space; Patel and Shadpey 2005, chapters 4 and 5 on force control of redundant robot manipulators).

### 5.2.2 Control of cooperative robot manipulators

#### Differences between serial manipulators, cooperative manipulators, and multifingered hands

**Joint space, end-effector cartesian space, object cartesian space** A common feature of the previously mentionned control strategies is that they have been developed for serial robot manipulators. Using them directly with multifingered hands or cooperative manipulators is inconvenient. Indeed, they assume the control objectives to be expressed in joint coordinates or end-effector cartesian coordinates. Yet for multifingered manipulation or cooperative manipulation, the natural space for the specification of control objectives is the object's cartesian space. For instance, in the case of multifingered manipulation and motion control, it is difficult to formulate a joint or end-effector desired trajectory for each finger, such that the hand as a whole realizes a certain, desired motion of the object. Force control objectives are just as hard to formulate: each force applied by a finger on the object influences the other fingers. It is more natural to formulate the control problem at object level. Therefore, except possibly for motion control in free space, it is necessary to adapt the control strategies from the single manipulator case to the multi-arm or multifingered case.

Another reason why adapted control strategies are necessary is the occurence of specific problems, which do not happen when the workpiece is grasped by only one manipulator. These problems need to be dealt with accordingly, and single-manipulator control schemes are not meant for it. We review them briefly below.

**Internal forces** The most important of these problems is the control of the internal forces and moments acting on the object, that is to say, the interaction forces between the manipulators and the grasped object which do not produce any motion of the object because they are in the kernel of the grasp matrix (see section 5.1.6; the definition of the grasp matrix applies to cooperative robot manipulators just as well as it does to robot hands). These interaction forces are mechanical stresses for the object and are usually undesirable effects in the case of industrial cooperative manipulators, because they may damage the workpiece and cause unnecessary loading of the actuators. Thus, a control objective is to keep them at a minimum.

On the contrary, in the case of multifingered manipulation, the internal forces are usually a desired effect, because when suitably controlled they can enhance the stability of the grasp. They can indeed steer the contact forces from the edge of the contact cones, limiting the risk of slippage, or they can apply tightening on the object, which can come in handy to keep grasp if a disturbance force suddenly loads the object. Therefore, the control of multifingered dextrous manipulation usually includes a part about determining desired internal forces, from certain desired control objectives, and then servoing the hand to these forces. We give more information about this subject in the following text. Also, in chapter 6, we give our own shot at computing contact forces achieving a secure grip in face of external disturbances, of unknown direction (but among a set of expected disturbance directions) and unknown intensity (but less than an expected maximal intensity). This is a related problem that could be called "robust holding" or "optimal tightening" of the object.

**Load sharing** Another problem specific to cooperative manipulation is "load sharing", also known as "load distribution". It is the problem of optimally distributing the load of the workpiece among the manipulators composing the robotic system. For instance, a strong manipulator should bear more load than a weak one, or a manipulator approaching a critical point of its actuation system should bear less load than one whose actuators are all in their nominal ranges. Load sharing is a significant issue in cooperative carrying and handling of heavy or large payloads, in industrial settings for instance. It can be done by tuning the internal forces and moments so that the interaction forces are smaller or larger depending on the arm. It is not so much of a problem in multifingered dextrous manipulation, since the fingers are usually relatively similar in force and the object to manipulate is usually moderately heavy (if not, the handling mode is power grasping rather than dextrous manipulation). Interesting papers about load distribution for cooperative robot manipulators are those by Orin and Y. Oh (1981), Y.-F. Zheng and Luh (1989a,b), I. Walker, Marcus, and Freeman (1989; 1991), and M. Uchiyama (1990).

**Relative motion** A third problem specific to cooperative manipulation is rolling and sliding at the contact interface. This is more precisely a problem relative to multifingered hands, because cooperative robot manipulators usually grasp their common payload tightly with conventional grippers, so their end-effectors are rigidly linked to the payload (figure 5.7 shows an example of multi-arm system). This occurence of rigid fixtures makes actually many things simpler, from a modeling and control point of view. Another difference with multifingered hands is that the interaction forces transmitted through the fixtures are fully-fledged wrenches with bilateral forces and moments, whereas contact forces applied by fingers are unilateral and depend on the contact model (see section 5.1.4). That being said, there are a few unified studies of multifingered hands and cooperative manipulators: T. Yoshikawa and X.-Z. Zheng (1990, 1993) use selection matrices to transmit only certain components of the interaction wrenches (see the matrices of ones and zeros in section 5.1.4), and Chiacchio, Chiaverini, and Siciliano (1996) take rolling and sliding of the contacts into account by modeling them with rotational and prismatic joints.

(a) This machine consists of a small vehicle with a hydraulic manipulator moving two seven-function manipulators (six rotational joints and a gripper).

(b) Coordinated manipulation of the two arms in order to cut a pipe.

Figure 5.7 – Dual-arm mobile robot system for nuclear decommissioning tasks, from Lancaster University, Lancaster, United Kingdom (Bakari, Zied, and Seward 2007)

### Control of cooperative manipulators

From what we have explained previously, in summary, the control of cooperative robot manipulators must achieve the following goals at the same time:

**Motion control** Tracking a given trajectory of the common workpiece.

**Force control** Controlling the internal forces applied to the workpiece, as well as the interaction force between the workpiece and the environment, if any.

Therefore, the natural control approaches to cooperative manipulation are force/motion control schemes. They "decompose the control action in a motion control loop, aimed at tracking of the desired object motion, and a force control loop, aimed at controlling the internal loading of the object", and possibly the interaction force between the object and its environment (Caccavale and M. Uchiyama 2008).

**Master/slave control** Early force/motion approaches to the control of cooperative robotic systems, in the 1970s, were based on the "master/slave" concept (e.g. E. Nakano, Ozaki, Ishida, and Kato 1974). That is to say, one manipulator, called the master arm, is in charge of imposing the motion of the object: it is position-controlled to track a desired trajectory, in spite of loading due to the interaction with the other cooperating arms through the payload. In other words, it is controlled so as to have a stiff behavior. The other manipulators are called the slave arms and are in charge of sharing the load of the workpiece without hindering its motion: they are force-controlled but not position-controlled so that they can follow the motion imposed by the master arm, as smoothly as possible. They have a very compliant behavior.

**Cooperative control** Master/slave control decouples the motion and force actions somewhat crudely. It is more natural to see the cooperative system as a whole, and to devise control laws where all the arms participate equally, hence denominations such as "cooperative control" or "coordinated control". To this aim, in the 1980s, the kinematics and dynamics of the closed kinematic chain formed by the manipulator arms and the workpiece were investigated (Dauchez and Zapata 1985; McClamroch 1986a,b; Tarn, Bejczy, and Yun 1987), and several extensions of hybrid force/position control, recently developed by Raibert and Craig (1981), were proposed for the multi-arm case (Hayati 1986, 1989; Tarn, Bejczy, and Yun 1987; M. Uchiyama, Iwasawa, and Hakomori 1987; M. Uchiyama and Dauchez 1988; Khatib 1988). Master/slave and hybrid force/position control schemes were experimentally compared by Kopf and Yabuta (1988) with a two-arm manipulator. They found smaller force errors and better position tracking in the case of hybrid control, a fact which they say can be explained by the arms cooperating by "sharing" information (internal force error and position error), whereas in the master/slave strategy the slave arm reacts to the master arm.

Non-master/slave control approaches were further investigated in the 1990s. In these approaches, "the reference motion of the object is used to determine the motion of all the arms in the system and the interaction forces acting at each end-effector are fed back so as to be directly controlled" (Caccavale and M. Uchiyama 2008). To this aim, it is necessary to know the mappings between the generalized velocity of the workpiece and those of each end-effector, and between the generalized forces applied by each end-effector and the total wrench exerted on the workpiece. The force mapping is embodied by the grasp matrix, and since there is usually no relative motion between the workpiece and the end-effectors, the velocity mapping is represented by the transpose of the grasp matrix (see section 5.1.6), which makes this mapping much simpler than in the case of multifingered manipulation.

More generally, the absence of rolling and sliding at the interface with the workpiece makes many things simpler in the modeling of the cooperative manipulators. For instance, it facilitates their kinematic and static analysis as a kinematic chain closed by the workpiece, simplifies the parameterization of the internal forces (i.e. of the kernel of the grasp matrix, see e.g. I. Walker, Freeman, and Marcus 1991, D. Williams and Khatib 1993), and makes it possible to find an univocal mapping [12] between the generalized velocity of the object and the joint velocities (see for instance the so-called "symmetric formulation" proposed by M. Uchiyama and Dauchez 1992). On the contrary, in the case of multifingered hands, this mapping is not univocal because it includes terms for rolling and sliding. As for the dynamic analysis, it is also affected by the strong kinematic coupling between the manipulators through the rigidly grasped object. Namely, the closed-chain constraints arising from this coupling reduce the number of independent variables in the dynamic model of the manipulators/workpiece system. To obtain a model whose variables are independent, it is possible to incorporate the constraints into the model by eliminating certain equations: this yields a "reduced-order dynamic model". Papers by Unseren and Koivo give more information about reduced-order modeling of closed chains, and determine control laws for the reduced-order model so as to decouple the force-controlled and position-controlled degrees of freedom (Unseren and Koivo 1989; Koivo and Unseren 1991; Unseren 1991).

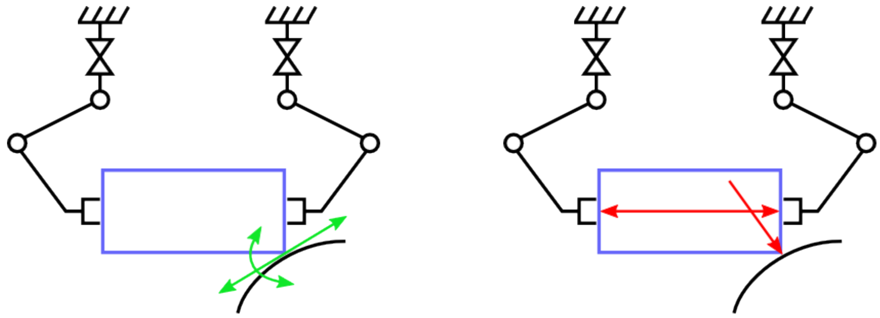
In addition to the reduced-order model-based control approach, a few other control strategies proposed in the 1990s are worth of mention. They are based either on hybrid force/position control or impedance control. For instance, T. Yoshikawa and X.-Z. Zheng (1990, 1993) designed a hybrid force/position control method that makes it possible to control not only the motion of the object and the internal forces, but also the interaction force between the object and its environment (at least the normal component of this force), in the case that the object is in contact with something else than the manipulators, that is to say in the case that its motion is constrained (not in free space). Their control system is based on a non-linear state feedback law that linearizes and decouples the robot system with respect to the object motion, the internal forces, and the constraint force. Their mathematical formulation is generic enough to apply to both cooperative manipulators and multifingered hands.

Also notable among hybrid force/position control strategies are a method to control object position, internal forces, and load sharing, proposed by P. Hsu (1993), hybrid force/position control laws whose position part is a proportional-derivative with gravity compensation, proposed by Wen and Kreutz-Delgado (1992), and so-called hybrid external control, developed by Perdereau and Drouin. In hybrid external control, the force control loop and the position control loop are organized into a hierarchy – outer force loop around inner position loop – rather than separated and organized in parallel, as in "classical" hybrid force/position control (Perdereau 1991; Perdereau and Drouin 1993b,a, 1996). Also, adaptive hybrid force/position control schemes may be designed for when there is uncertainty in the dynamic models (Y.-R. Hu, Goldenberg, and C. Zhou 1995; Y.-H. Liu and Arimoto 1998). Figure 5.8 illustrates schematically the principle of hybrid force/position control, for a system of two cooperative manipulators.

Alternatively, impedance-based control strategies were proposed by various researchers. For instance, a control scheme by Schneider and Cannon (1989, 1992) enforces a mechanical impedance behavior between the displacement of the object and the object/environment interaction force. Another one by Bonitz and Hsia (1993,

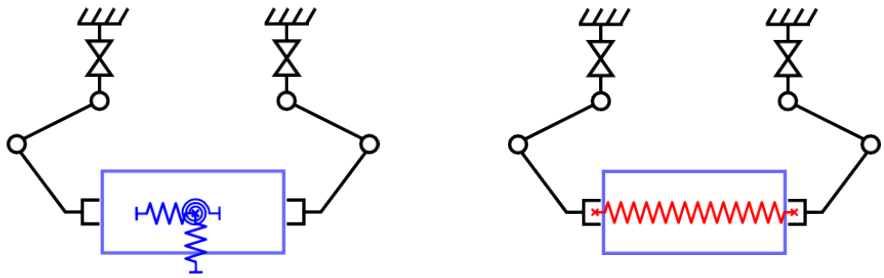
12. Though not invertible of course, i.e. not bi-univocal.

1996) enforces a mechanical impedance behavior between the displacements of the end-effectors and the internal forces. Caccavale and Villani (2000b,a, 2001) combined these two approaches in a control scheme with two control loops, one for the control of the impedance at object level (external forces) and the other for the control of the impedance at end-effector level (internal forces). These methods are illustrated schematically in figure 5.9, for a system of two cooperative manipulators.



(a) Directions of position control (b) Directions of force control

Figure 5.8 – Principle of hybrid force/position control, for manipulators (adapted from T. Yoshikawa 2010)



(a) Impedance enforced on the object (b) Impedance enforced between the end-effectors

Figure 5.9 – Principle of compliance control and impedance control, for manipulators, with only the virtual spring elements depicted (adapted from T. Yoshikawa 2010)

**Further information** For more information about the history, modeling, and control of cooperative robot manipulators, including advanced non-linear control strategies developed in the 2000s and not mentionned here, topics related to cooperative systems having some degree of flexibility, and bibliographic pointers to the relevant literature, a few specialized textbooks are available (fewer than books about single-arm manipulators). The monographs by Chiacchio and Chiaverini (1998) and by Živanović and Vukobratović (2006) are notable. The chapters written by Kosuge and Y. Hirata (2005) for the *Robotics and Automation Handbook* edited by Kurfess (2005), and by Caccavale and M. Uchiyama (2008) for the huge *Handbook of Robotics* edited by Siciliano and Khatib (2008), are also very interesting.

### 5.2.3 Control of multifingered robot hands

In the previous pages, we have reviewed the control of cooperative robot manipulators, and explained the differences between these systems and multifingered hands, from a control point of view [13]. To sum up these differences, they are mainly the possible rolling and sliding at the contacts, and the interaction forces which are unilateral. This doesn't make the control objectives of multifingered dextrous manipulation so different:

**Motion control** Tracking a given object trajectory, and achieving some relative motion between the fingertips and the object, if any such motion is desired (controlled rolling and/or sliding at one or more contacts).

**Force control** Controlling the internal forces applied to the object, as well as the interaction force between the object and the environment, if any.

Controlled rolling and controlled sliding aside, the objectives of robot hand control and cooperative manipulator control are basically the same. To realize them, we use the same control approaches, roughly divided into the same two groups depending on whether the force objectives are specified directly or indirectly: on the direct side, hybrid force/position control and related schemes, and on the indirect side, impedance or at least compliance control. Figures 5.10 and 5.11 illustrate these approaches schematically for two fingers.

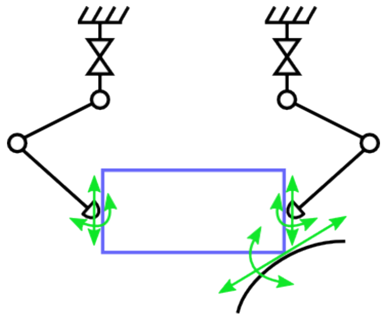
### Hybrid force/position control

The first hybrid force/position control laws targeted at multifingered dextrous manipulation were developed at the same time as those for cooperative manipulators, at the end of the 1980s. For instance, Nakamura, Nagai, and T. Yoshikawa (1987, 1989) proposed a force/position control scheme based on a two-phase approach, for both multiple robot manipulators and multifingered robot hands. The first phase is "determining the resultant force by multiple robotic mechanisms", used for the manipulation of the object (motion control objective). The second one is "determining the internal force between them, [...] used to satisfy the static frictional constraints and related to contact stability" (force control objective). In their study, the internal force objective is the internal force "which yields the minimal-norm force satisfying static frictional constraints". It is determined using a non-linear programming method.

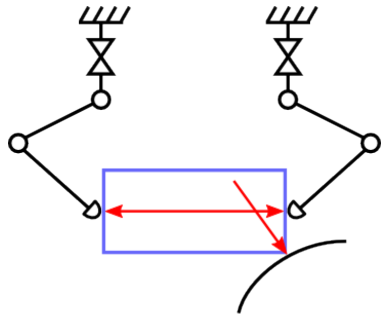
Shortly thereafter, P. Hsu, Z. Li, and Sastry developed a computed-torque-like control law for coordinated manipulation, specific to hands because it assumes point contact models (P. Hsu, Z. Li, and Sastry 1988; Z. Li, P. Hsu, and Sastry 1989). Their control algorithm, "which takes into account both the dynamics of the object and the dynamics of the hand, will realize simultaneously both the position trajectory of the object and any desired value of internal grasp force" (Z. Li, P. Hsu, and Sastry 1989). The contacts are supposed to be fixed point contacts with friction; however, "the formulation of the control scheme can be easily extended to allow rolling and sliding motion of the fingers with respect to the object" (Z. Li, P. Hsu, and Sastry 1989), but not in a controlled manner.

Rolling and sliding are actually central matters in the articles of Cole, Hauser, and Sastry (1988, 1989) and Cole, P. Hsu, and Sastry (1989, 1992). Cole, Hauser, and

13. Of course, there are other differences if we consider other aspects such as the actuation, the sensorization or the kinematic structure. For instance, the manipulators used in industrial multi-arm systems are usually six-axis manipulators, whose end-effectors move in the six directions of space. Distal phalanges have less kinematic freedom. Also, there is an obvious size difference: multifingered hands are approximately human-sized, whereas multi-manipulator systems are usually much larger, with actuation systems adapted accordingly.

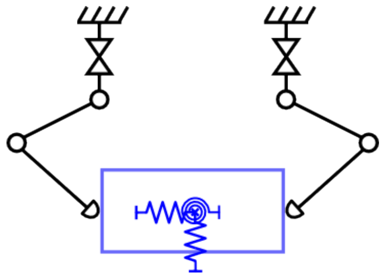


(a) Directions of position control

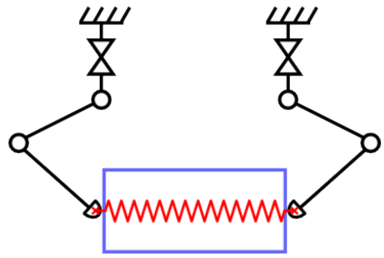


(b) Directions of force control

Figure 5.10 – Principle of hybrid force/position control, for fingers (adapted from T. Yoshikawa 2010)



(a) Impedance enforced on the object



(b) Impedance enforced between the fingers

Figure 5.11 – Principle of compliance control and impedance control, for fingers, with only the virtual spring elements depicted (adapted from T. Yoshikawa 2010)

Sastry derived the kinematics of rolling contact for two surfaces of arbitrary shape rolling on each other and applied these kinematic equations to a multifingered hand manipulating some object of arbitrary shape, in two dimensions (1988) or in three dimensions (1989), in order to design a computed-torque-like control law that takes into account rolling at the contacts during the motion of the object and fingers. Their control scheme is able to track a desired trajectory for the object, and to regulate the internal forces in order to maintain non-slipping contacts by producing contact forces which lie within the friction cones. On the contrary, Cole, P. Hsu, and Sastry (1989, 1992) investigated desired sliding: they proposed a dynamic control law which enables one to control the sliding motion of the fingertips along the object surface, for regrasping and reorientation of the object for instance. Their work is specific to the planar case (two-dimensional object manipulated by a two-dimensional hand), and does not seem to generalize to three-dimensional situations. Algorithms for controlled sliding in the spatial case would follow, though: for instance the one by X.-Z. Zheng, Nakashima, and T. Yoshikawa (1994, 2000), which realizes desired object motion, desired grasping force, and desired sliding of one finger in a three-fingered robot hand, or the one by T. Yoshikawa (2000a), which is more general and based on the author's "virtual truss" representation of the internal forces (T. Yoshikawa 1998, 1999), and realizes desired object motion, desired internal forces, and desired sliding motion.

Another interesting early hybrid force/position control scheme for dextrous manipulation was proposed by T. Yoshikawa and X.-Z. Zheng (1990, 1993). It makes it possible to control the motion of the object, the internal forces, and the interaction force between the object and its environment (at least the normal component of this force). Their control method is usable with both multiple robot manipulators and multifingered robot hands, and takes the manipulator dynamics and object dynamics into consideration. It uses a non-linear state feedback law to linearize and decouple the robot system "with respect to the object motion, the constraint force, and the internal force". Then it controls this linearized system with a servo compensation for each of the three objectives: proportional-derivative action for the position control loop and integral actions for the force control loops.

Following these early instances, other force/position control schemes were proposed during the 1990s and 2000s, for instance by Speeter (1990b), Nagai and T. Yoshikawa (1993), W.-Y. Chung and Waldron (1994, 1995), X.-Z. Zheng, Nakashima, and T. Yoshikawa (1994, 2000), T. Yoshikawa (2000a), J. Chen and Zribi (2000), G. Chen and S. Wang (2004), or Remond, Perdereau, and Drouin (2002), and the list is far from complete. Usually, they all control at least the motion of the object and the internal forces. They differ in multiple design and implementation details, such as how internal forces are parameterized, whether the hand dynamics is expressed in joint or cartesian space, or what feedback laws they use. They also differ in their taking into account rolling and sliding motions. For instance, certain control schemes assume fixed point contacts (e.g. Z. Li, P. Hsu, and Sastry 1989) or at least non-sliding contacts (e.g. T. Yoshikawa and X.-Z. Zheng 1990), or don't model rolling and sliding in any particular fashion, letting them free to happen (e.g. J. Chen and Zribi 2000). Others model rolling kinematics, to account for rolling changing the location of contacts during manipulation, and to compensate for the motion/force errors caused by these deviations (e.g. Cole, Hauser, and Sastry 1989; Remond, Perdereau, and Drouin 2002). Others enforce non-sliding contacts through appropriately designed internal force objectives (e.g. Nakamura, Nagai, and T. Yoshikawa 1987, 1989; W.-Y. Chung and Waldron 1994, 1995). Last but not least, certain control laws realize controlled rolling (e.g. Sarkar, Yun, and Kumar 1993, 1997, motion control only though, no control of internal forces) or controlled sliding (e.g. Cole, P. Hsu, and Sastry 1992; X.-Z. Zheng, Nakashima, and T. Yoshikawa 1994, 2000; T. Yoshikawa 2000a) as part of their objectives.

In order to control object motion and internal forces simultaneously, all those hybrid force/position control strategies rely on the fact that the contact forces have a mathematically simple decomposition into forces which result in motion of the object and forces which don't (internal forces). More precisely, as we have seen in section 5.1.6, equations (5.21) and (5.22), the contact forces $f$ which yield a given total contact wrench $W_{dp\to obj}$ may be written as the sum of one particular vector of forces, $f_P$, which produces the motion of the object (and, possibly, a certain tightening of the object too), and another vector of forces, $f_I$, which can only contribute to tightening of the object. In other words, $G$ being the grasp matrix:

$$\begin{gathered} W_{dp\to obj} = G\, f \\ \text{solution set:} \quad f_P + \ker G = \{f_P + f_I,\ f_I \in \ker G\} \\ G\, f_P = W_{dp\to obj} \qquad\qquad G\, f_I = 0_{6,1} \end{gathered}$$

This decomposition explains that the two problems of motion and force control can be decoupled as follows (this is actually the two-phase approach of Nakamura, Nagai, and T. Yoshikawa (1987, 1989), mentionned earlier):

1. First, we find some forces $f_P$ which produce a certain total contact wrench $W_{dp\to obj}$ which itself results in the desired trajectory for the object.
2. Then, we find some forces $f_I$ such that the contact forces $f_P + f_I$ achieve the desired force objective.

Since $f_I$ are internal forces they do not change the resulting contact wrench $W_{dp\to obj}$, which means that the contact forces $f = f_P + f_I$ achieve both the desired motion and the force objective. Then, the problem of control consists in finding motor torques $\tau$ that realize these contact forces.

More precisely, the general idea of the control follows three steps, given below in broad outline:

**Dynamics of the object** Using the equations of motion of the object (5.16), we calculate the total wrench $W^{[d]}_{dp\to obj}$ that realizes the desired object motion (in the free directions, where it is possible for the object to move), and/or the desired interaction force with the environment (in the constrained directions, where it is possible for the object to apply a force).

**Contact forces** Using the grasp matrix in equation (5.21), we find forces $f_P^{[d]}$ which realize $W^{[d]}_{dp\to obj}$. We also determine internal forces $f_I^{[d]}$ such that the contact forces $f^{[d]} = f_P^{[d]} + f_I^{[d]}$ realize the other desired force objectives. This step implements the two points listed above, and is further detailled below.

**Dynamics of the hand** Using the equations of motion of the hand (5.14), we calculate the motor torques $\tau$ that realize the desired contact forces $f^{[d]}$.

Implementation details differ between control laws, but this is the general idea behind most hybrid force/position control schemes (T. Yoshikawa 2010). We can note that the first step is for the object, the second one is for the contacts, and the third one is for the hand, hence the procedure is physically very clear.

The first and third steps are rather direct, in the sense that the dynamic models of the hand (5.14) and of the object (5.16) give $\tau$ as a function of the contact forces and $W_{dp\to obj}$ as a function of the object motion, respectively. On the contrary, the equation (5.21) behind the second step gives $W_{dp\to obj}$ as a function of $f$, and we need to solve for $f$ as a function of $W_{dp\to obj}$ (with $^{[d]}$ superscripts since we are speaking about control objectives, but we drop this notation for simplicity). As explained previously, the inversion of this equation is in two parts: the choice of a particular solution $f_P$ and the determination of internal forces $f_I$ (once again, with $^{[d]}$ superscripts). We give details about these two parts below.

1. The particular solution $f_P$ is usually obtained through the Moore-Penrose pseudo-inverse of the grasp matrix, which we will note $G^+$:

$$f_P = G^+ W_{dp\to obj}$$

   A pseudo-inverse, or generalized inverse, is a matrix that has some properties of an inverse but not necessarily all of them, and that can be defined for arbitrary, non-invertible matrices [14]. The Moore-Penrose pseudo-inverse is a particular type of generalized inverse, and the most widely known. It was independently

14. Which is just the case of the grasp matrix $G$ of course; it isn't even a square matrix.

described by Eliakim Moore in 1920, Arne Bjerhammar in 1951, and Roger Penrose in 1955. It is defined and unique for all matrices [15].

The pseudo-inverse solution $f_P = G^+ W_{dp\to obj}$ is a particular solution of (5.21), that is to say $GG^+ W_{dp\to obj} = W_{dp\to obj}$, but that doesn't mean that $GG^+ = I_6$. However, in the case that $G$ has less rows than columns and the rows are linearly independent (in other words $G$ is full row rank), this equality is true: it can be shown that $GG^T$ is invertible and that an explicit expression of $G^+$ is:

$$G^+ = G^T (GG^T)^{-1}$$

and it follows that $G^+$ is a right inverse of $G$: $GG^+ = I_6$. The conditions for this to happen are almost always verified. First, as long as the grasp has at least two fingers, the number of rows in $G$, 6, is less than or equal to the number of columns, $3n_f$ (in the case of rigid point contacts with friction). Second, the range (image, or column span) of $G$ has dimension 5 for two-finger grasps and 6 for three-finger grasps, therefore $G$ is full rank as long as the grasp has at least three fingers. Indeed, if we consider two points in space where arbitrary forces $u_1$ and $u_2$ in $\mathbb{R}^3$ may be applied (no moments, just forces), the only wrenches $G\left(\begin{smallmatrix} u_1 \\ u_2 \end{smallmatrix}\right)$ impossible to realize are the moments around the line joining the two points: this explains the dimension 5 for the two-finger grasp. The addition of a third point not aligned with the others makes these wrenches possible.

The pseudo-inverse gives a solution of (5.21) which has a particular meaning. First, if $W_{dp\to obj}$ is in the range of $G$, then $f_P = G^+ W_{dp\to obj}$ is the unique vector of smallest magnitude satisfying $Gf_P = W_{dp\to obj}$, in other words, the pseudo-inverse solution is the solution whose euclidian norm is minimal. Second, if $W_{dp\to obj}$ is not in the range of $G$ (moments around the joining line in a two-finger grasp), the equation $Gf_P = W_{dp\to obj}$ is impossible, however $f_P = G^+ W_{dp\to obj}$ has the property that it minimizes the magnitude of the difference $Gf_P - W_{dp\to obj}$, in other words, the pseudo-inverse solution is the least-squares solution to the problem $Gf_P = W_{dp\to obj}$.

2. It is important to note that even though the forces $f_P$ generate the total wrench $W_{dp\to obj}$, there is no guarantee that they represent contact forces. Indeed, they are obtained using a mathematical inversion which has no consideration for physics whatsoever: $f_P$ are forces in $\mathbb{R}^3$ but not necessarily in the contact cones, or even not necessarily unilateral. This makes the point for the internal forces $f_I$: we can design them so that $f = f_P + f_I$ are actual, physically-consistent contact forces.

   To this aim, we must ensure that $f_I$ are such that $f = f_P + f_I$ are unilateral and lie within their contact cones. This is also the opportunity to take into account other control objectives which can be realized through internal forces. For instance, a common control objective is that the contacts must be non-sliding.

15. More information about generalized inverses and the Moore-Penrose pseudo-inverse, including proofs of the properties stated here, can be found in Penrose's seminal papers (1955; 1956), as well as in various books in mathematics (especially Ben-Israel and Greville 2003) or in robotics (for instance Nakamura 1991, pages 41–62). On the other hand, Moore's work (1920; 1935) is difficult to read. According to Ben-Israel, it uses "unnecessarily complicated notations" and is "illegible for all but very dedicated readers": a reason why "Moore's work was sinking into oblivion even during his lifetime", and had to be rediscovered later. Still, Ben-Israel (2002) gives a summary and restatement of Moore's results, "in plain English and modern notation".

To realize that, we must determine $f_I$ so that the contact forces lie strictly within their contact cones. On the contrary, if it is desired that certain contacts slide in some direction, then the corresponding forces must lie on the surface of their cones in accordance with this direction. Another possible control objective is a certain amount of tightening on the object, in order to make provision for a possible disturbance for instance, as explained in chapter 6. All these objectives can be realized by appropriately tuning the internal forces to get the adequate contact forces, and then servo the hand to these forces.

The determination of the desired internal forces is very often a matter of mathematical programming, because it is naturally represented by a constrained optimization problem. For instance, in the study of Nakamura, Nagai, and T. Yoshikawa (1987, 1989), the internal force objective is the internal force "which yields the minimal-norm force satisfying static frictional constraints", in other words:

$$f_I^{[d]} \text{ solution of the mathematical program:}$$

$$\begin{cases} \min\limits_{f_I \in \ker G} \|f_P + f_I\| \\ \text{subject to the (inequality) constraints:} \\ \quad f_P + f_I \text{ unilateral} \\ \quad f_P + f_I \text{ in contact cones} \end{cases}$$

Nakamura, Nagai, and T. Yoshikawa solved this problem with a non-linear programming method. Depending on the control objectives and on how we want the contact forces to be optimal, many other constrained optimization problems can be formed in order to synthetize desired internal forces to use in the control.

For instance, another interesting example of internal force determination is found in a famous classic article by Kerr and Roth (1986). Their method is more geometric but also boils down to a constrained optimization problem. They suggest to linearize the contact cones using four-sided pyramids, and show that each of the resulting linear inequality constraint can be interpreted as a hyperplane in $\mathbb{R}^{k_G}$ ($k_G$ being the dimension of $\ker G$ [16]) separating a permissible half-space and an impermissible half-space for the contact forces. Then they mention that joint torque limits can be treated the same way, since joint torques are linearly related to contact forces through the hand static model (see equation 5.15): joint torque limits result in linear inequality constraints on the contact forces, that can again be interpreted as hyperplanes in $\mathbb{R}^{k_G}$. Taken together, the friction limit constraints, the joint torque limit constraints, and the already known part of the contact forces ($f_P$) define a polygonal region in $\mathbb{R}^{k_G}$, and Kerr and Roth suggest to choose for internal forces the point in this constraint polygon which is located where the distance to the closest constraint plane is a maximum. Eventually, that happens to form a linear programming problem, which returns the "safest" contact forces, that is to say those as far as possible from violating any friction or joint torque limit constraint, while still realizing the object motion through $f_P$.

16. That would be $k_G = 3n_f - 6$ according to the rank-nullity theorem, since $G$ is almost always full rank i.e. of rank 6, as explained previously.

Since $f_I$ is searched for in $\ker G$, it is necessary in most of the approaches to internal force synthesis to have some sort of description of $\ker G$, that is to say a parameterization of the internal forces. The most common one is simply to write $\ker G$ as the vector space spanned by one of its basis. Let $E_G$ denote a matrix whose columns are the vectors of a basis of $\ker G$. Then $E_G$ is $(3n_f, k_G)$ in size, and by definition:

$$\ker G = \left\{ E_G\,\eta,\ \ \eta \in \mathbb{R}^{k_G} \right\} \qquad\qquad G\,E_G = 0_{6,k_G}$$

For any internal force $f_I$, there exists one unique parameter vector $\eta \in \mathbb{R}^{k_G}$ such that $f_I = E_G\,\eta$. Reciprocally, any $\eta \in \mathbb{R}^{k_G}$ results in a particular internal force $f_I$. The parameter vector $\eta$ represents the magnitudes of the components of the corresponding $f_I$ in the direction of the column vectors of $E_G$. In other words, $\eta$ is the vector of the coordinates of $f_I$ in the chosen basis of $\ker G$.

Another common parameterization is to use a spanning set of $\ker G$ instead of a basis (which is a particular spanning set, one with linearly independent vectors only). For instance, let us choose a spanning set of $\ker G$ that counts $3n_f$ vectors, and let $E'_G$ denote a matrix whose columns are the vectors of this set. Then $E'_G$ is a $(3n_f, 3n_f)$ square matrix and:

$$\ker G = \left\{ E'_G\,\eta',\ \ \eta' \in \mathbb{R}^{3n_f} \right\} \qquad\qquad G\,E'_G = 0_{6,3n_f}$$

The most important difference is that this parameterization of the internal forces is not unique, contrary to the one obtained with a basis; this may be inconvenient. Besides, this is visible in the size of $\eta'$, which has more elements than necessary: using $k_G < 3n_f$ elements would be enough. The interest of this parameterization lies in that it is possible to show that $\ker G$ is spanned by the columns of the matrix $I_{3n_f} - G^+G$, in other words this matrix is a possible choice for $E'_G$, and a common one indeed:

$$E'_G = I_{3n_f} - G^+G$$

It is of course possible to extract a basis of $\ker G$ from the columns of $E'_G$, and obtain a matrix $E_G$ by this process. As a matter of fact, any basis of $\ker G$ is suitable for forming a matrix $E_G$. However, it may be appealing to use one that has some physical or geometrical meaning, rather than an arbitrary one, be it only for ease of its calculation. It is the case, for instance, of the representation of internal forces introduced by T. Yoshikawa and Nagai (1987, 1988, 1991) for three-fingered grasps, later generalized to multifingered grasps by T. Yoshikawa (1998, 1999) as the “virtual truss” representation of internal forces. In this model, every pair of contact points is connected by a line, and the axial forces along these lines are used as a basis of $\ker G$, after a redundancy reduction step. In the words of its authors, this model “provides a very simple representation of the internal force and has a clear physical image”. A control law using this representation of internal forces is given by T. Yoshikawa (2000a).

As an end remark on the contact forces and internal forces, it is worth noting that $f_P$ and $f_I$ do not exactly represent, respectively, “manipulating” and “gripping” contact forces, even though it is tempting to say so and we sometimes misname them. In reality, this is not adequate from a physical point of view, as $f_P$ is not guaranteed to result only in the motion of the object ("manipulating" action) without any tightening of the object ("gripping" action). Moreover, $f_P$ and $f_I$ are not even guaranteed to be physically consistent contact forces, i.e. unilateral and in their contact cones; only their sum is. T. Yoshikawa and Nagai (1987, 1988, 1991) investigate the problem of finding physically reasonable definitions of the "manipulating" and "grasping" contact forces for three-fingered hands, with possible extension to two and four fingers. A more general, less geometric approach is developed by Bicchi (1994). T. Yoshikawa and Nagai come up with an algorithm for "decomposing a given fingertip force into manipulating and grasping forces"; later, they also propose a control law using the decomposition of the contact forces into manipulating and grasping components, rather than the decomposition into the pseudo-inverse solution and internal forces (Nagai and T. Yoshikawa 1993).

#### Impedance control

An alternative approach to force/position control of dextrous hands is impedance control, or at least stiffness control. In this approach, the main control objective is the mechanical impedance of the grasped object, that is to say its dynamic behavior against external forces, around a given position. A typical impedance control aims at realizing the following desired dynamic behavior of the object, called the target impedance:

$$M_{obj}^{[d]}\,\ddot{X}_{obj} + B_{obj}^{[d]}\,(\dot{X}_{obj} - \dot{X}_{obj}^{[d]}) + K_{obj}^{[d]}\,(X_{obj} - X_{obj}^{[d]}) = W_{ext\to obj}$$

In this equation, $X_{obj}$ is the actual position and orientation of the object (in $\mathbb{R}^6$ rather than in $SE_3(\mathbb{R})$, to make matters simpler), $X_{obj}^{[d]}$ is the desired position and orientation, $W_{ext\to obj}$ is an external wrench causing the deviation of the object from its desired position and orientation, and $M_{obj}^{[d]}$, $B_{obj}^{[d]}$, $K_{obj}^{[d]}$ are respectively the desired inertia, damping, stiffness of the impedance we want to enforce on the object (three $(6,6)$ matrices written in the object's frame). This differential equation describes the dynamics of a mass-spring-damper system working in translation and rotation, attached to the reference position and orientation $X_{obj}^{[d]}$, which is possibly moving according to $\dot{X}_{obj}^{[d]}$. The goal of impedance control is to ensure that the actual dynamics of the object coincides with this desired mass-spring-damper dynamics.

The actual dynamics of the object is, as a matter of fact:

$$M_{obj}\,(\ddot{X}_{obj} - g) + N_{obj}\dot{X}_{obj} = W_{dp\to obj} + W_{ext\to obj}$$

This equation is adapted from the object dynamic model (5.16) presented in section 5.1.6, with an external wrench in addition to the wrench applied by the distal phalanges, and $\dot{X}_{obj} = V_{obj}$ or at least they are closely related [17].

Substituting the desired dynamics into the actual dynamics, we get the resultant wrench needed to realize the desired impedance of the object:

$$\begin{aligned} W_{dp\to obj} = {} & (M_{obj} - M_{obj}^{[d]})\,\ddot{X}_{obj} - B_{obj}^{[d]}\,(\dot{X}_{obj} - \dot{X}_{obj}^{[d]}) - K_{obj}^{[d]}\,(X_{obj} - X_{obj}^{[d]}) \\ & + N_{obj}\dot{X}_{obj} - M_{obj}g \end{aligned}$$

17. Depending on the chosen parameterization for the orientation part in $X_{obj}$, it may often be necessary to have some sort of transformation matrix between $\dot{X}_{obj}$ and $V_{obj}$ rather than a strict equality. Here we give the general outline of impedance control, so we skip the implementation details.

Therefore, impedance control can follow the same three-step procedure as hybrid force/position control – dynamics of the object, contact forces, dynamics of the hand – except the first step is replaced by this one (T. Yoshikawa 2010):

**Dynamics of the object** Using the equations of motion of the object and the equations of motion of the mass-spring-damper system we want the object to be equivalent to, we calculate the total wrench $W^{[d]}_{dp\to obj}$ that realizes the desired object impedance.

Then the following steps translate this $W^{[d]}_{dp\to obj}$ into desired contact forces (with the possibility to take internal forces into account), and ultimately into command torques.

We can note from the expression of $W_{dp\to obj}$ that we need to know the value of the object acceleration $\ddot{X}_{obj}$ to perform the first step. This value is difficult to measure in real systems. Therefore, a convenient and common choice of desired inertia $M^{[d]}_{obj}$ is to take it to be the same as the real inertia $M_{obj}$ (e.g. Wimböck, Ott, and Hirzinger 2007). This makes $W_{dp\to obj}$ simpler:

$$\begin{aligned} W_{dp\to obj} = &-B^{[d]}_{obj}\,(\dot{X}_{obj} - \dot{X}^{[d]}_{obj}) - K^{[d]}_{obj}\,(X_{obj} - X^{[d]}_{obj}) \\ &+ N_{obj}\dot{X}_{obj} - M_{obj}g \end{aligned} \tag{5.23}$$

Without inertia shaping, the impedance behavior can be seen as a damped spatial spring attached to the object. This is actually what we implement for the control of the object in our own control strategy: see the desired motion of the object in section 5.3.3.

In stiffness control, only the spring part of the impedance is kept, which further reduces the expression of $W_{dp\to obj}$, and typically quasi-static motion is assumed, since stiffness in general is a local linearization of the expression linking a force and the resulting displacement, or reciprocally a displacement and the restoring force. Therefore:

$$W_{dp\to obj} = -K^{[d]}_{obj}\,(X_{obj} - X^{[d]}_{obj}) - M_{obj}g$$

The resultant force $W_{dp\to obj}$ is a restoring force that ensures the position control of $X_{obj}$ on $X^{[d]}_{obj}$, with the dynamics of a mass-spring-damper system of parameters $M^{[d]}_{obj}, B^{[d]}_{obj}, K^{[d]}_{obj}$. If the desired position is not attainable because of an obstacle between it and the actual position, the resultant force $W_{dp\to obj}$ results in an interaction force being exerted between the object and the obstacle, function of the parameters of the target impedance: this is how impedance control realizes indirect force control.

Impedance control strategies for multifingered manipulation have been proposed by Nagai and T. Yoshikawa (1995) for a hand/arm system, and at the Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center) for the DLR series of hands, by H. Liu and Hirzinger (1999, for DLR Hand I), Biagiotti, H. Liu, Hirzinger, and Melchiorri (2003, for DLR Hand II), and Z. Chen, Lii, Jin, Fan, and H. Liu (2010, for DLR/HIT Hand II). Also, Stramigioli, Melchiorri, and Andreotti developed an impedance control strategy at object level based on the so-called “virtual object” concept: the fingers are connected to this virtual object [18] through virtual springs, and the virtual object is in turn connected to a desired position through another

18. Think of it as a smaller version of the object, located inside the object.

virtual spring (Stramigioli 1998, 1999; Stramigioli, Melchiorri, and Andreotti 1999; Melchiorri, Stramigioli, and Andreotti 1999; Stramigioli 2001). This enables to define naturally the stiffness behavior between the fingers and the object (through the first set of springs) and between the object and its desired position (through the other spring). To complete the impedance, dissipation can be introduced in the modeling through the so-called “damping injection” principle, developed previously by Stramigioli (1996). Still at the Deutsches Zentrum für Luft- und Raumfahrt, impedance control strategies based on Stramigioli’s approach were designed for the four-fingered DLR Hand II, and experimented in a one-hand configuration (Wimböck, Ott, and Hirzinger 2006, 2008) and in a two-hand configuration with DLR’s two-arm humanoid manipulator Justin (Wimböck, Ott, and Hirzinger 2007).

#### Stiffness control

In all the studies mentionned before, the target impedance is realized through specifically designed contact forces, so ultimately it is realized by appropriate motor torques. An alternative approach is to have it realized through the joint impedances, assuming they can be changed. This is particularly possible when stiffness only is considered in the impedance, that is to say in stiffness control (or compliance control). The idea of this approach is that the stiffness of the fingers results naturally in a certain stiffness of the grasped object. If we can find the relationship between them, it may be possible to adjust the stiffness of the fingers in order to realize a certain, desired object stiffness, in other words, control the object stiffness through the finger stiffness.

Anatomically speaking, this idea is equivalent to muscle co-contraction: by contracting simultaneously the agonist and antagonist muscles relative to some joint, we are able to stiffen the joint without moving it. By doing so for all the joints of the hand, we can very easily produce grasps that are more or less compliant. In a humanoid robot hand, this phenomenon can be simulated by adjusting the gains of the actuators. For instance, let say that the hand’s motor control is a trivial proportional action:

$$\tau = K_q \left(q^{[d]} - q\right)$$

with $K_q$ the diagonal matrix of the gains of the actuators (in this simplified case, one actuator per degree of freedom, all degrees of freedom being independent). Then $K_q$ represents the stiffness of the joints, in other words it is the stiffness matrix of the hand in the joint space. This stiffness results in a certain stiffness of the distal phalanges, in the cartesian space, which in turn results in a certain stiffness of the object, in the cartesian space too. Stiffness control is about finding $K_{obj}$ as a function of $K_q$, then solving the inverse problem: how to choose the servo gains in $K_q$ in order to achieve a desired object stiffness $K_{obj}^{[d]}$.

Unfortunately, the stiffness analysis of a multifingered grasp is not trivial:

1. First, the stiffness of a finger does not depend only on joint servoing, but also on a wide range of other factors, among which mechanical properties such as actuator compliance, elasticity in the transmission chain, and fingertip materials, structural properties such as couplings between joints or fingers, through underactuation for instance, and changes in the finger configuration (joint angles). Therefore, the joint stiffnesses are not limited to servo gains $K_q$; they form a more complete stiffness matrix $K_{art}$, a part of which only can be arbitrarily specified.

2. Second, the stiffness of the grasped object does not depend only on the stiffness of the involved fingers, but also on several factors such as the contact forces between the object and the fingers, the curvature of the surfaces in contact, and the changes in the grasp configuration (changes of contact locations). This makes the expression of the object stiffness as a function of the finger stiffnesses difficult to find without simplifying assumptions, such as fingertips being fixed and hard point contacts for example. Stiffness modeling for stiffness control, in the case of rolling contacts, is actually the topic of chapter 7.

The role of stiffness/compliance in multifingered grasping started to be investigated very early in the history of robot hands, by Hanafusa and Asada (1977, 1978, 1982b,a) for their "hand with elastic fingers", a planar gripper of three linear springs, and by Mason and Salisbury (1985) for the Stanford/JPL three-fingered hand. The relationship between the stiffness of the joints of a finger and the stiffness of its distal phalanx was actually first given by Salisbury (1980), for the general case of a serial manipulator. He proposed a classical change-of-frame formula between joint coordinates and cartesian coordinates:

$$K_{art} = J^T K_{e.e.} J$$

where $K_{art}$ is the articular stiffness matrix, i.e. the stiffness matrix of the manipulator in joint space, $K_{e.e.}$ is the end-effector stiffness matrix, i.e. the stiffness matrix of the manipulator in cartesian space, and $J$ is the jacobian matrix of the manipulator. So for the $i$-th finger of a robot hand, that would be:

$$K_{art,i} = J_i^T K_{dp_i} J_i$$

This relationship was generally accepted and applied in studies on stiffness analysis and stiffness control of manipulators and hands (Nguyen 1987b, 1989; Cutkosky and Kao 1989; Kao and Cutkosky 1992; Y.-T. Lee, J.-H. Kim, W.-K. Chung, and Youm 1993; Y.-T. Lee, H.-R. Choi, W.-K. Chung, and Youm 1994; H.-R. Choi, W.-K. Chung, and Youm 1994, 1995). For hands, the resulting cartesian stiffness produced on the object by the fingers, $K_{obj}$, is usually taken as the sum of the finger cartesian stiffnesses, $K_{dp,i}$, possibly after some change of frame since $K_{obj}$ will typically be written in object coordinates and $K_{dp,i}$ in distal phalanx coordinates. That is to say, something like this (see e.g. Kao and Cutkosky 1992, equation 11):

$$K_{obj} = \sum_{i=1}^{n_f} {}^{obj}\!Ad_{dp_i}^{-T} K_{dp_i} \, {}^{dp_i}\!Ad_{obj}$$

This simple summation formula, however, is very incomplete: it takes into account the finger stiffnesses and the changes in the grasp configuration (changes of contact locations, through the change-of-frame matrices), but as we mentionned, object stiffness also depends on the contact forces between the object and the fingers, and on the curvature of the surfaces in contact. We prove this fact in chapter 7 by deriving a more complete relationship between $K_{obj}$ and $K_{dp_i}$. Besides, the original relationship proposed by Salisbury between $K_{e.e.}$ and $K_{art}$ (or $K_{dp_i}$ and $K_{art,i}$) is incomplete too: it misses the contribution of the loading of the end-effector and of the changes in the configuration of the joints as they move under the effect of loading. This contribution was proven, quantized, and added to Salisbury's relationship in a corrected "conservative congruence transformation" by S.-F. Chen and Kao (1999, 2000a). All in all, the relationship between object stiffness and joint stiffness is not easy to come up with, at least in non overly-simplified cases, and the whole problem of stiffness analysis requires careful modeling in order to be able to control the object stiffness through the servo gains in a reliable manner.

**Further information**

For more information about the control of dextrous manipulation by multifingered robot hands, in addition to the references cited in this section, a few interesting reviews and textbooks are interesting: for instance articles by T. Yoshikawa (2010), Pons, Ceres, and F. Pfeiffer (1999), Okamura, Smaby, and Cutkosky (2000), Murray and Sastry (1990a,b), and the books by Murray, Z. Li, and Sastry (1994, pages 300–310 in particular) and Mason (2001).

## 5.3 Dynamic optimization-based control of dextrous manipulation

### 5.3.1 Introduction

In the previous sections of this chapter, we described the kinematics, dynamics, and contact modeling of the hand and the object (section 5.1), and we reviewed the history and basics of robotic manipulation control, with a particular emphasis on control of multifingered dextrous manipulation (section 5.2, see also figure 5.12). To sum up the big picture on control, we can say that all control strategies of dextrous manipulation are able to achieve several objectives at the same time. In short:

1. Motion control of the object, or force control of a contact interaction between the object and the environment, or impedance control of the object, or a combination of them, are possible via the forces $f_P$ solution of the problem $W_{dp \to obj} = G\,f$.
2. Enforcement of physical consistency for the contact forces (unilaterality and friction constraints), sliding or non-sliding, and contact stability (choice of the contact forces to be as far as possible from the edge of the cone), are possible via the internal forces $f_I$.

So basically, control objectives are realized either through $f_P$, for the "main" control objectives, or through $f_I$, for all the others.

It is possible, for instance, to use $f_I$ to take into account limits on the control torques $\tau$, because the control torques are easily related to the contact forces through the hand static model (in short, $\tau = J^T f$, see equation 5.15). This is how Kerr and Roth (1986) are able to synthetize internal forces $f_I$ that make contact forces $f$ such that the torques $\tau$ which produce them remain in the nominal range of actuator power ($\tau_{min} \leq \tau \leq \tau_{max}$).

It seems conceivable that their method can be extended to other constraints on the control torques: for instance, torque minimality, that is to say when we want the torques to be as small as possible in order to reduce the strain on the actuators and save power, while still achieving the motion/force objectives.

But the problem is that this method relies on the hand static model, which is only valid at static equilibrium. It fails when the hand realizes a manipulation of the object, unless this manipulation is slow enough to be assumed quasi-static, which is of course not always the case. So, another method must be designed to take into account motor limitations, torque optimality, and generally speaking any constraint or objective on the torques.

Other constraints that are difficult to take into account with the usual control strategies are those related to joint configuration (see figure 5.13), because there is

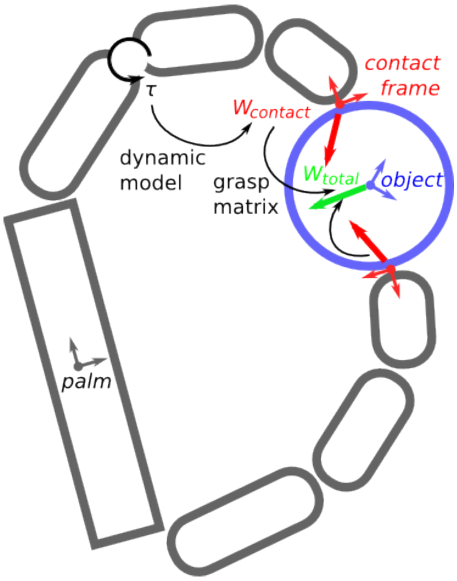
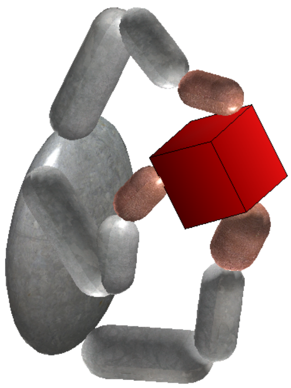



Figure 5.12 – A very shortened description of multifingered hand control.

no simple relation between the hand geometry $q$ and the contact forces $f$, so it is not possible to realize such constraints through the internal forces. Therefore, joint limits ($q_{min} \leq q \leq q_{max}$) and redundancy management (since each fingers is a slightly redundant kinematic chain) are difficult to account for.



This simulation result was realized by removing from our control scheme the equations specifying that articular limits are supposed to be respected (5.25) and that a human-like coupling is desired between the last two joints of each finger (5.43). Even if the result looks wrong, the control torques were actually correct: they realized all the other objectives left in the control scheme, such as object motion, tightening forces, contact non-sliding and minimality of joint torques.

Figure 5.13 – A bad case of kinematic redundancy and articular limit violation during a three-fingered manipulation. If anthropomorphism of joint configuration is not specified as a control objective, there is no reason for the control to achieve it.

So the loopholes in the classical control methods are, in short, the possible motor limit violations, torque non-optimality, joint limit violations, and joint configuration non-optimality.

It is possible to overcome these drawbacks by formulating the manipulation problem as a constrained optimization problem, in other words a mathematical program (both terms mean the same). Indeed, as explained in the introduction of this chapter, putting a control problem into mathematical programming terms is a good way to get control torques that satisfy multiple requirements. The general idea is as follows:

we begin by listing all the requirements of the control problem, that is to say all the control objectives and equations that are supposed to be satisfied, and we divide them into two groups:

**Optimization constraints** Those that must be satisfied at all costs, for instance:

- unilaterality of the contact forces and observance of friction constraints, since the contact forces must be physically consistent;
- joint limits, since fingers cannot move past them;
- torque limits, since actuators cannot output any arbitrary power.

**Optimization criteria** Those that should be satisfied as much as possible, for instance:

- object motion: the position error should be minimized;
- redundancy management: the articular configuration should be as human-like as possible; that requires defining what is a human-like configuration and minimizing some sort of error between it and the current configuration: see equation (5.43) in section 5.3.3;
- torque minimality: their value should be minimized.

Now, we can put the control objectives of the second group together in one function to be minimized, subject to the constraints described by the control objectives of the first group. This is the formulation of the control problem as a constrained optimization problem, and the function to be minimized is called the objective function [19]. The solution of this problem, that is to say the value of $\tau$ that minimizes the objective function, is the best possible control, in the sense of the chosen optimization criteria, that complies with the chosen optimization constraints.

As noted in the introduction of this chapter, the division of the various control objectives into the two groups of criteria and constraints is up to the roboticist in charge of designing the control, because it depends on the control problem. However, a rule of thumb is to take as constraints the equations that correspond to physical realities that cannot be violated (friction constraints or joint limits are good examples), and to take as criteria the equations that correspond to a desired behavior that is not a physical imperative and/or that is not always guaranteed to be feasible (object motion, anthropomorphism of motion).

The weighting of the different criteria in the objective function is another aspect of the method that is left at the discretion of the control designer. Indeed, it is possible to prioritize criteria relative to each other, by appropriate weighting. For instance, object motion will typically be given a higher priority than torque minimality. Thanks to this freedom in the control scheme, it is possible to ensure a certain trade-off between the multiple criteria. This possibility is fortunate because the criteria represent different objectives, that may very well be conflicting. So it makes sense to favor some of them rather than have all of them of equal importance.

19. There are control objectives and optimization objectives, to add some confusion. Strictly speaking, control objectives are the desired values in the control law, like $W^{[d]}_{dp\to obj}$ or $f^{[d]}_I$. Loosely speaking, they are any equation or inequation that the control torques $\tau$ are supposed to be designed to satisfy, for instance friction constraints. The optimization objectives are the control objectives that can be formulated as the minimization of some value; in other words, optimization criteria.

Looking for the control torques as the solution of an optimization problem is a rather new control approach in robotics. The idea was prefigured in the work of Wieber (2000) on the control of walking humanoid robots. Then, optimization-based motion control of virtual humans was proposed independently by Cyrille Collette and Alain Micaelli at the Atomic Energy Commission in France, and Yeuhi Abe, Marco da Silva, and Jovan Popović at the Massachusetts Institute of Technology in the United States (Collette and Micaelli 2007a,b, 2008; Collette 2009; Abe, Silva, and J. Popović 2007; Silva, Abe, and J. Popović 2008). Their works deal with walking, standing, and balance control of virtual humans and humanoid robots (figure 5.14), in the presence of multiple non-coplanar contact interactions with the environment, such as standing on an uneven ground, sitting, or while holding on a support – a problem unresolved until then. Their control algorithms are optimization-based and take physics into account; conflicting control objectives ("tasks") such as reaching for an unattainable object while keeping balance are prioritized via appropriate weighting in their objective functions.

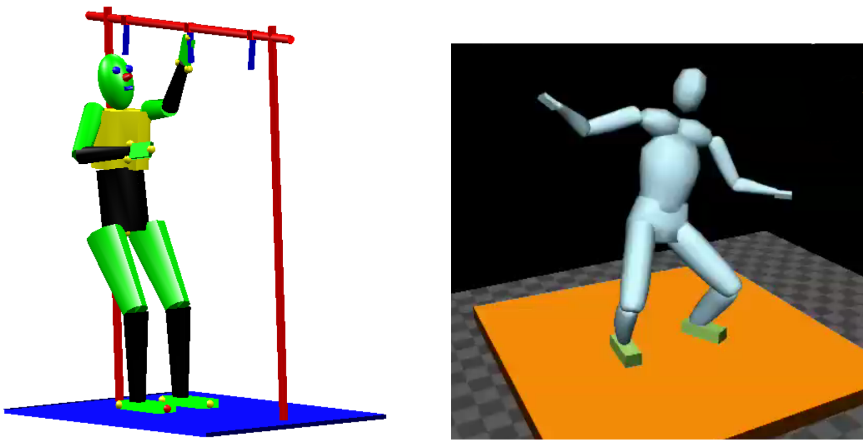


Figure 5.14 – The virtual humans controlled by the optimization-based control schemes of Collette and Micaelli (2007a,b), on the left, and Abe, Silva, and J. Popović (2007), on the right. On these pictures, both are under balance control and recovering from a disturbance.

A related topic is the research conducted in computer animation by Karen Liu (2008, 2009) at the Georgia Institute of Technology in the United States. She investigates hand motion and dextrous manipulation synthesis from an animator's point of view, but with a concern for physics, in order to obtain "natural-looking" animations. To this aim, she proposes physics- and optimization-based algorithms that generate animations of object manipulations. For instance, in her first paper, she formulates hand manipulation as a non-linear minimization of the change in joint torques, subject to two constraints: the dynamics of the object and a geometrical condition of contact. The purpose of her work is much different from the purpose of a roboticist's, a distinction exemplified by the fact that her first algorithm does not return control torques: control is not a problematic of computer graphics. Instead, she looks for articular positions that can be used to animate a computer-rendered model (figure 5.15). Generally speaking, her work draws inspiration from physics more than it tries to comply with it: it is physics-based animation, not dynamic control for robotics.

Figure 5.15 – A frame from a physics-based animation realized by the optimization-based technique of K. Liu (2008)

So, to the best of our knowledge, optimization-based motion control of humanoids, such as in the works of Collette and Micaelli (2007a,b) and Abe, Silva, and J. Popović (2007), had not yet been ported, adapted and implemented in the domain of robot hand control. We did this work, and came up with a rather complete dynamic optimization-based control scheme of multifingered dextrous manipulation (Michalec and Micaelli 2009a). In this scheme, control of object motion and internal contact forces is provided, as well as management of non-sliding contacts, motor constraints, joint limits and articular redundancy. In a complementary paper (Michalec and Micaelli 2009b), we explained how to design adequate contact forces to have the grasp withstand a set of unknown but expected disturbances, and achieve robust manipulation; chapter 6 gives more information about this issue.

In the rest of this section, we describe our optimization-based control law, with a couple of improvements and supplements to our original presentation (Michalec and Micaelli 2009a). The outline is very simple: section 5.3.2 lists the optimization constraints, section 5.3.3 lists the optimization criteria, section 5.3.4 constructs the objective function and sums up the control law as a quadratic program, that is to say an optimization problem whose objective function is quadratic and constraints are linear. The model is the one described in section 5.1, and the notations are those defined in this same section and in chapter 4.

### 5.3.2 Constraints

We have already listed most constraints in the previous section: the unilaterality of the contact forces, their observance of friction constraints, the articular limits, and the torque limits. That is to say, four constraints, respectively on the contact forces $f$, on the joint coordinates $q$, and on the motor torques $\tau$. Last but not least, there is another equation that the hand/object system must absolutely meet: the hand dynamic model (5.14). This equation links $f$, $\ddot{q}$, and $\tau$ together, and therefore makes sure that the control torques we want to find are consistent with the contact forces and hand motion. We give the expressions of all these constraints below.

#### Physical consistency

The constraints that ensure physical consistency are the hand dynamics, the unilaterality of the contact forces, and the friction constraints.

We explained in section 5.1.4 that the linear approximation (5.13) of the Coulomb friction model also accounts for unilaterality; we remind this equation here for convenience:

$$Cf + d \leq 0_{n_f \times n_e,1}$$

The matrix $C$ describes the faces of the discretized contact cones, and $d = 0_{n_f \times n_e,1}$ actually. If non-sliding is desired, the inequality should be strict. To this aim, a slightly smaller value of the friction coefficient $\mu$ may be used in the expression of $C$ to ensure a more conservative approximation, or $d$ can be set to a small negative value.

The hand dynamic model is described in detail in section 5.1.5; we remind its expression (5.14) here for convenience:

$$J^T M J\,(\dot{T} - \mathcal{G}) + NT - J^T W_{ext} = L\,\tau$$

$$T = \begin{pmatrix} V_0 \\ \dot{q} \end{pmatrix} = \begin{pmatrix} V_0 \\ \dot{q}_1 \\ \vdots \\ \dot{q}_{n_{dof}} \end{pmatrix} \qquad L = \begin{pmatrix} 0_{6,n_{dof}} \\ I_{n_{dof}} \end{pmatrix} \qquad \tau = \begin{pmatrix} \tau_1 \\ \vdots \\ \tau_{n_{dof}} \end{pmatrix}$$

$$W_{ext} = \begin{pmatrix} W_0 \\ W_1 \\ \vdots \\ W_{n_b} \end{pmatrix} \qquad \text{with } W_{dp_i} = W_{ext \to dp_i}^{dp_i} = {}^{dp_i}Ad_{c_i}^{-T} \begin{pmatrix} -f_i \\ 0_{3,1} \end{pmatrix}$$

and usually zero for the other wrenches

and $M$ the hand generalized mass matrix, $J$ the hand jacobian, $N$ the hand Coriolis matrix, $NT$ the Coriolis and centrifugal forces, $\mathcal{G}$ the gravity acceleration vector written in the root and joint space.

### Joint constraints

The constraints relative to the joints are the motor limits (actuators are not infinitely powerful) and the articular limits (robot joints have end stops).

Therefore, we must compute the control torques according to the following motor constraints:

$$\tau_{min} \leq \tau \leq \tau_{max} \tag{5.24}$$

And we must make the control aware of the articular limits so that it does not try to break them. To this aim, we make use of the fact that in the dynamic simulator we use, the physical engine integrates the joint accelerations using backward Euler integration [20]: $\dot{q}_t = \dot{q}_{t-dt} + \ddot{q}_t dt$ and then $q_t = q_{t-dt} + \dot{q}_t dt$. With these two equations we get: $q_t = q_{t-dt} + \dot{q}_{t-dt} dt + \ddot{q}_t dt^2$.

Therefore, constraints on $q_t$ result in constraints on $\ddot{q}_t$:

$$q_{min} \leq q_t \leq q_{max} \Rightarrow$$
$$\frac{(q_{min} - q_{t-dt} - \dot{q}_{t-dt} dt)}{dt^2} \leq \ddot{q}_t \leq \frac{(q_{max} - q_{t-dt} - \dot{q}_{t-dt} dt)}{dt^2}$$

The resulting constraints have the following form:

$$\ddot{q}_{min}(q_{t-dt}, \dot{q}_{t-dt}) \leq L^T \dot{T}_t \leq \ddot{q}_{max}(q_{t-dt}, \dot{q}_{t-dt}) \tag{5.25}$$

20. Also known as the implicit Euler method: $u_{n+1} = u_n + \dot{u}_{n+1} dt$. In comparison, forward Euler integration, also known as the explicite Euler method: $u_{n+1} = u_n + \dot{u}_n dt$. Implicit integration is always stable, explicit integration is not.

### Conclusion

The constraints we enumerated are summarized in table 5.1, together with the unknowns they are relative to.

| | Constraint | Unknowns |
|---|---|---|
| (5.13) | $C f + d \leq 0_{n_f \times n_e, 1}$ | $f$ |
| (5.14) | $J^T M J\,(\dot{T} - \mathcal{G}) + NT - J^T W_{ext} = L\,\tau$ | $\dot{T},\, f,\, \tau$ |
| (5.24) | $\tau_{min} \leq \tau \leq \tau_{max}$ | $\tau$ |
| (5.25) | $\ddot{q}_{min}(q_{t-dt}, \dot{q}_{t-dt}) \leq L^T \dot{T}_t \leq \ddot{q}_{max}(q_{t-dt}, \dot{q}_{t-dt})$ | $\dot{T}$ |

Table 5.1 – Constraints and their unknowns

### 5.3.3 Objectives

In this section, we list the control objectives that we implement as optimization criteria. They are equations that the hand/object system need not meet perfectly, but should comply with to the best of its abilities. Eventually the control problem should be written as the following constrained optimization problem:

$$\begin{cases} \text{optimize } \textit{criteria} \\ \text{with respect to the variables } \tau,\, \dot{T},\, f \\ \text{and subject to the } \textit{constraints} \text{ (5.13), (5.14), (5.24), (5.25)} \end{cases} \tag{5.26}$$

The resulting optimal $\tau$ is the vector of control torques at the current time.

#### Object motion

The object dynamics (5.16) shows that the object motion $\dot{V}_{obj}$ must be controlled through $W_{dp \to obj}$, i.e. through the contact forces $f$. That is to say, a user-specified high-level objective on $\dot{V}_{obj}$ induces a lower-level objective on the $f$ variable.

We let ${}^{root}H^{[d]}_{obj} \in SE_3(\mathbb{R})$ and $V^{[d]}_{obj/root} \in se_3(\mathbb{R})$ denote desired trajectories for the object, respectively in position and orientation and in linear and angular velocities. Both are relative to the palm, as it is a natural reference frame for object manipulation.

We have the following expressions for the quantities to control, and the same expressions with a ${}^{[d]}$ superscript for their desired values:

$$ {}^{root}H_{obj} = \begin{pmatrix} {}^{root}R_{obj} & r^{root}_{root,obj} \\ 0_{3,1} & 1 \end{pmatrix} \qquad\qquad V^{obj}_{obj/root} = \begin{pmatrix} v^{obj}_{obj/root} \\ \omega^{obj}_{obj/root} \end{pmatrix}$$

To be precise, $v^{obj}_{obj/root} = v^{obj}_{G_{obj} \in obj/root}$, with $G_{obj}$ the origin of the $obj$ frame, usually the center of mass or at least some characteristic point. But we leave this point out for simplicity.

The errors are as follows, all written in $obj$ coordinates:

$$\begin{aligned} \varepsilon_x &= {}^{obj}R_{root}\left(r^{root,[d]}_{root,obj} - r^{root}_{root,obj}\right) \\ \varepsilon_R &= \left[\text{skew}\left({}^{root}R^T_{obj}\,{}^{root}R^{[d]}_{obj}\right)\right]^{\vee} \\ \varepsilon_v &= v^{obj,[d]}_{obj/root} - v^{obj}_{obj/root} \\ \varepsilon_\omega &= \omega^{obj,[d]}_{obj/root} - \omega^{obj}_{obj/root} \end{aligned} \tag{5.27}$$

with skew ( ) denoting the skew-symmetric part of a matrix and $^\vee$ being the operation that returns a vector for cross-product from a skew-symmetric matrix, i.e. the inverse function of the function $\hat{}$ which returns a skew-symmetric cross-product matrix from a vector (see sections 4.A and 4.2.2 in chapter 4). This is a common method to get a measure of the difference in orientation between two bases. Indeed, the two orientations of the object, current and desired, differ in a rotation of a certain angle $\Delta\theta$ around a certain axis $e$. The matrix of this rotation is ${}^{root}R_{obj}^{T}\,{}^{root}R_{obj}^{[d]} = {}^{obj}R_{root}\,{}^{root}R_{obj}^{[d]} = {}^{obj}R_{obj,[d]}$, and it is possible to show that the skew-symmetric part of this matrix is a measure of the orientation difference, of the following form in a basis whose third axis is $e$:

$$[\text{skew}({}^{obj}R_{obj,[d]})]^\vee = \begin{pmatrix} 0 \\ 0 \\ \sin(\Delta\theta) \end{pmatrix}$$

Alternatively, another possibility to define an orientation error $\varepsilon_R$ is to find a basis such that the matrix, written in this basis, of the rotation between the two orientations of the object (current and desired), has the canonical form:

$$\begin{pmatrix} \cos(\Delta\theta) & -\sin(\Delta\theta) & 0 \\ \sin(\Delta\theta) & \cos(\Delta\theta) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

which makes it possible to identify $\Delta\theta$. This method is more complicated but remains standard linear algebra; besides, it enables to get the real orientation error rather than a non-linear measure of it. In any case, both work fine.

We use the errors (5.27) to design a proportional-derivative corrective action for the object motion $\dot{V}_{obj/root}$, and since $V_{obj/root} = V_{obj}$ because we assumed that the palm does not move (in section 5.1.1), we write:

$$\dot{V}_{obj}^{[d]} = \dot{V}_{obj/root}^{[d]} = \begin{pmatrix} k_x\, \varepsilon_x + k_v\, \varepsilon_v \\ k_R\, \varepsilon_R + k_\omega\, \varepsilon_\omega \end{pmatrix} \tag{5.28}$$

The gain matrices $k_x$, $k_R$, $k_v$, and $k_\omega$ are $(3,3)$ diagonal matrices whose coefficients have effect on the $obj$ coordinates of the errors.

Using the object dynamic model (5.16) and the servo compensations (5.28), we get the following expression of the wrench that should be applied on the object to realize the desired object motion:

$$W_{dp\to obj}^{[d]} = M_{obj}\,(\dot{V}_{obj}^{[d]} - g) + N_{obj} V_{obj} \tag{5.29}$$

At this moment, we could do like the majority of control schemes of dextrous manipulation: use the pseudo-inverse $G^+$ of the grasp matrix to write $f_P^{[d]} = G^+ W_{dp\to obj}^{[d]}$, and then go on to determine desired internal forces $f_I^{[d]}$ (see section 5.2.3). Yet we rather write directly the following optimization criteria for the problem (5.26):

$$\min_f \frac{1}{2} \left\| W_{dp\to obj}^{[d]} - W_{dp\to obj} \right\|_{Q_W}^2$$

This criteria reads: find contact forces $f$ that minimize the difference between the wrench that should be applied and the wrench that is currently applied. $Q_W$ is a weight matrix for this criteria (symmetric positive-definite matrix). The expanded form of this criteria is:

$$\begin{aligned}\min_f \frac{1}{2}\left\|W^{[d]}_{dp\to obj} - W_{dp\to obj}\right\|^2_{Q_W} \\ = \min_f \left[\frac{1}{2} W^T_{dp\to obj} Q_W W_{dp\to obj} + W^T_{dp\to obj} r_W\right]\end{aligned} \tag{5.30}$$

with $r_W = -Q_W W^{[d]}_{dp\to obj}$. Eventually we use the grasp matrix (5.21) to rewrite (5.30) as this criteria:

$$\begin{aligned}\min_f \frac{1}{2}\left\|W^{[d]}_{dp\to obj} - W_{dp\to obj}\right\|^2_{Q_W} \\ = \min_f \left[\frac{1}{2} f^T Q_{obj} f + f^T r_{obj}\right]\end{aligned} \tag{5.31}$$

with:

$$Q_{obj} = G^T Q_W G \qquad\qquad r_{obj} = G^T r_W = -G^T Q_W W^{[d]}_{dp\to obj}$$

### Object impedance

The control approach taken to servo the object position is nothing more than impedance control: through the gain matrices $k_x$, $k_R$, $k_v$, and $k_\omega$, we specify a desired dynamic behavior of the object around the desired position and orientation ${}^{root}H^{[d]}_{obj}$. More precisely, this is impedance control without inertia shaping, that is to say that the target impedance of the object has a desired inertia equal to the real inertia $M_{obj}$: see section 5.2.3, equation (5.23). The equivalent system is simply the object connected to its desired position and orientation by a damped spatial spring.

To make it clearer, let us define the following target impedance for the object (in *obj* coordinates):

$$M^{[d]}_{obj} = M_{obj} \qquad B^{[d]}_{obj} = M_{obj}\begin{pmatrix} k_v & 0_{3,3} \\ 0_{3,3} & k_\omega \end{pmatrix} \qquad K^{[d]}_{obj} = M_{obj}\begin{pmatrix} k_x & 0_{3,3} \\ 0_{3,3} & k_R \end{pmatrix}$$

Then from (5.29), (5.28), and (5.27) we have:

$$\begin{aligned} W^{[d]}_{dp\to obj} &= M_{obj}\begin{pmatrix} k_x\,\varepsilon_x + k_v\,\varepsilon_v \\ k_R\,\varepsilon_R + k_\omega\,\varepsilon_\omega \end{pmatrix} - M_{obj}\,g + N_{obj}V_{obj} \\ &= M_{obj}\begin{pmatrix} k_x & 0_{3,3} \\ 0_{3,3} & k_R \end{pmatrix}\begin{pmatrix} \varepsilon_x \\ \varepsilon_R \end{pmatrix} + M_{obj}\begin{pmatrix} k_v & 0_{3,3} \\ 0_{3,3} & k_\omega \end{pmatrix}\begin{pmatrix} \varepsilon_v \\ \varepsilon_\omega \end{pmatrix} - M_{obj}\,g + N_{obj}V_{obj} \\ &= K^{[d]}_{obj}\,(X^{[d]}_{obj} - X_{obj}) + B^{[d]}_{obj}\,(V^{[d]}_{obj} - V_{obj}) - M_{obj}\,g + N_{obj}V_{obj} \\ &= -B^{[d]}_{obj}\,(V_{obj} - V^{[d]}_{obj}) - K^{[d]}_{obj}\,(X_{obj} - X^{[d]}_{obj}) + N_{obj}V_{obj} - M_{obj}\,g \end{aligned}$$

and this last equation is indeed characteristic of impedance control without inertia shaping, see equation (5.23).

Therefore, the optimization criteria (5.31) does not describe only the desired object position and orientation, but rather the desired object impedance around a certain desired position and orientation. Through this impedance, it is possible to realize motion control of the object or, if there is an obstacle between the object and its desired position, indirect force control of the interaction between the object and this obstacle.

### Tightening

The desired object motion, or more exactly the desired object impedance, is not the only objective on the contact force variable $f$. Usually, we also want the hand to apply a certain amount of tightening on the object, especially to resist potential disturbances.

A very basic approach to tightening is to specify desired values for the normal components of the contact forces:

$$f^{[d]} = \begin{pmatrix} 0 \\ 0 \\ f^{[d]}_{1,n} \\ \vdots \\ 0 \\ 0 \\ f^{[d]}_{n_f,n} \end{pmatrix} \tag{5.32}$$

Intuitively, this means: find contact forces $f$ whose normal components are not too small, so as to result in some non-negligible tightening. The optimization criteria corresponding to this desired value is:

$$\min_f \frac{1}{2} \left\| f^{[d]} - f \right\|^2_{Q'_f} = \min_f \left[ \frac{1}{2} f^T Q'_f f + f^T r'_f \right] \tag{5.33}$$

with $r'_f = -Q'_f f^{[d]}$.

Now, criteria (5.31) and (5.33) are somewhat incompatible. The first one is about finding contact forces $f$ that make the resultant contact wrench $W_{dp\to obj}$ as close as possible to a certain desired contact wrench $W^{[d]}_{dp\to obj}$. The second one is about finding contact forces $f$ that are as close as possible to normal contact forces $f^{[d]}$, forces which result in a certain desired contact wrench that has no reason to be $W^{[d]}_{dp\to obj}$. In other words, the desired value $W^{[d]}_{dp\to obj}$ of (5.29) is not produced by the desired value $f^{[d]}$ of (5.32): both objectives are incompatible.

This is where the trade-off nature of the optimization proves useful: we can make the criteria (5.31) take precedence over the criteria (5.33) by careful weighting. First, the weight matrix $Q'_f$ should not outweight $Q_{obj}$ for the manipulation to have priority over the tightening. Second, the coefficients in $Q'_f$ relative to the zeros in $f^{[d]}$ should be much smaller [21] than those relative to the $f_{i,n}$, because these zeros are bogus objectives: the criteria lays on the normal components $f_{i,n}$, not on the tangential components $f_{i,t}$. By doing so, we can make sure that the zeros in $f^{[d]}$ are not treated as significant desired values, but instead the tangential components $f_{i,t}$ are left entirely free to be set by the higher-priority objective (5.31).

An advantage of this method is that the objective $f^{[d]}$ is very easy to design, but a drawback is that it is pretty heuristic. A better method would be to make sure that $f^{[d]}$ and $W^{[d]}_{dp\to obj}$ are compatible, for a start. For instance, we could set $f^{[d]}$ as follows instead of (5.32):

$$f^{[d]} = G^+ W^{[d]}_{dp\to obj} + f^{[d]}_I \tag{5.34}$$

and specify the tightening objective via desired internal forces $f^{[d]}_I$ instead of desired contact forces $f^{[d]}$. Of course, this is less easy to do, since we have to make sure that

21. Actually they should be zero but then the weight matrix would not be positive-definite any more.

the chosen $f_I^{[d]}$ is in $\ker G$, we cannot just take some arbitrary normal forces as in (5.32). But this is doable; after all, the determination of desired internal forces is a classical problem of robotic manipulation, investigated since the 1980s (see the relevant references in section 5.2.3). And by doing so, we ensure that the criteria (5.31) and (5.33) resulting from the objectives $W_{dp\to obj}^{[d]}$ and $f^{[d]}$ are compatible.

An even better method of specifying a tightening task is to conduct a dedicated study of grasp robustness, as we do in chapter 6 (or in Michalec and Micaelli 2009b). In this study, we define a desired tightening objective in terms of the grasp withstanding certain disturbances, and eventually we are able to design contact forces $f^{[d]}$ that keep the grasp in face of a set of disturbances *and* are compatible with the object dynamics. In other words they produce the resultant wrench $W_{dp\to obj}^{[d]}$ at the same time that the required tightening. We can then use these contact forces $f^{[d]}$ in (5.33). We believe this method is even better than (5.34) because it allows to spare oneself the trouble of investigating internal forces (the whole method remains at contact force level) and it also models an anatomical reality, namely tightening of the object even when no disturbance is present, in order to better keep the grasp in case a disturbance happens (in contrast, most methods of contact force optimization deal with canceling a disturbance only when it happens, without pre-tightening). More information about this topic is in chapter 6.

### Non-sliding

We may also define objectives regarding the interface between the object and the hand. This is useful for the management of non-sliding.

Non-sliding contacts are characterized by a zero sliding velocity:

$$v_s = v_{c_i\in dp_i/obj} = 0_{3,1} \tag{5.35}$$

We should provide for the satisfaction of this equation through a constraint on the contact acceleration, which would induce a constraint on the joint accelerations $\dot{T}$. But this would be too restrictive a constraint and (5.26) could become over-constrained. To avoid no-solution situations, we rather provide for the satisfaction of (5.35) through an objective on the contact acceleration, resulting in a criteria on $\dot{T}$.

To this aim, we let $c_i \in obj$ denote the $i$-th contact point on the object and $c_i \in dp_i$ denote the same contact point, but on $dp_i$. Both points are at the same place, but may have different velocities [22]. The sliding velocity is this difference:

$$v_s = v_{c_i\in dp_i/obj} = v_{c_i\in dp_i} - v_{c_i\in obj} \tag{5.36}$$

We control $c_i \in dp_i$ to limit sliding through the following objective:

$$v_{c_i\in dp_i}^{[d]} = v_{c_i\in obj} \tag{5.37}$$

In this way, we make sure that the error $\varepsilon_s = v_{c_i\in dp_i}^{[d]} - v_{c_i\in dp_i} = -v_s$ is minimized. We use a basic proportional correction:

$$\dot{v}_{c_i\in dp_i}^{[d]} = k_s\,\varepsilon_s = k_s\,(v_{c_i\in dp_i}^{[d]} - v_{c_i\in dp_i}) \tag{5.38}$$

22. See the remarks in section 4.2.1, chapter 4.

To get an optimization criteria on $\dot{T}$ from this control, we must write $\dot{v}_{c_i \in dp_i}$ in terms of the unknown $\dot{T}$ and $\dot{v}^{[d]}_{c_i \in dp_i}$ in terms of known values.

Using a few adjoint matrices [23], the hand direct kinematics (5.6), and the fact that the palm is supposed to be fixed ($V_0 = 0_{6,1}$), it is very easy to prove the following expressions:

$$\begin{aligned} v^{[d]}_{c_i \in dp_i} &= v_{c_i \in obj} \\ &= \Pi\, {}^{c_i}\!Ad_{obj} V_{obj} \end{aligned} \qquad\qquad \begin{aligned} v_{c_i \in dp_i} &= \Pi\, {}^{c_i}\!Ad_{dp_i} V_{dp_i} \\ &= \Pi\, {}^{c_i}\!Ad_{dp_i} [{}^{dp_i}\!Ad_0 V_0 + J_{dp_i} \dot{q}] \\ &= \Pi\, {}^{c_i}\!Ad_{dp_i} J_{dp_i} L^T T \end{aligned}$$

with $\Pi = \begin{pmatrix} I_3 & 0_{3,3} \end{pmatrix}$ the selection matrix that returns the first component of a twist (the linear velocity). Therefore, from these expressions and (5.38):

$$\dot{v}^{[d]}_{c_i \in dp_i} = k_s \left( \Pi\, {}^{c_i}\!Ad_{obj} V_{obj} - \Pi\, {}^{c_i}\!Ad_{dp_i} J_{dp_i} L^T T \right) \tag{5.39}$$

Time differentiation of the expression of $v_{c_i \in dp_i}$ yields:

$$\begin{aligned} \dot{v}_{c_i \in dp_i} &= \Pi\, {}^{c_i}\!Ad_{dp_i} J_{dp_i} L^T \dot{T} + \Pi\, {}^{c_i}\!Ad_{dp_i} \dot{J}_{dp_i} L^T T \\ &\overset{\text{def}}{=} F_i \dot{T} + \dot{F}_i T \end{aligned} \tag{5.40}$$

We do not take ${}^{c_i}\!\dot{Ad}_{dp_i}$ into account because $c_i \in dp_i$ is fixed on $dp_i$, by definition.

In the end, the optimization criteria accounting for non-sliding is:

$$\min_{\dot{T}} \frac{1}{2} \left\| \dot{v}^{[d]}_{c_i \in dp_i} - \dot{v}_{c_i \in dp_i} \right\|^2_{Q_{c_i}} = \min_{\dot{T}} \left[ \frac{1}{2} \dot{T}^T Q_{s,i} \dot{T} + \dot{T}^T r_{s,i} \right] \tag{5.41}$$

with:

$$Q_{s,i} = F_i^T Q_{c_i} F_i \qquad\qquad r_{s,i} = F_i^T Q_{c_i} (\dot{F}_i T - \dot{v}^{[d]}_{c_i \in dp_i})$$

This criteria is for one non-sliding contact only; we may get a similar criteria relative to all the contacts, and associated parameters $Q_s$ and $r_s$, by concatenating adequately vectors and matrices.

### Torque minimality

Among all the motor torques $\tau$ that satisfy the previous constraints and objectives, reason tells to choose the smallest for the sake of the motors. Hence the desired $\tau^{[d]} = 0_{n_{dof},1}$ and the following criteria:

$$\min_{\tau} \frac{1}{2} \left\| \tau^{[d]} - \tau \right\|^2_{Q_\tau} = \min_{\tau} \left[ \frac{1}{2} \tau^T Q_\tau \tau + \tau^T r_\tau \right] \tag{5.42}$$

where $Q_\tau$ is a low-priority weight matrix and $r_\tau = -Q_\tau \tau^{[d]} = 0_{n_{dof},1}$.

23. See chapter 4 for a recap.

### Redundancy management

As pointed out in the introduction of this section (5.3.1), the articular configurations induced by the control of the hand should be as human-like as possible. In particular, non-anthropomorphic joint postures such as those illustrated in figure 5.13 should be avoided.

Redundancy management is already taken care of in part by the joint limit constraints (5.25), which eliminate most of the impossible configurations. In addition, it is a good idea to take into account the anatomical coupling between the proximal and distal interphalangeal joints: in our fingers, these joints are not totally independant, the latter's articular coordinate is partially set by the former's.

This coupling is usually considered almost linear, and constraints between $q_{dip} = \frac{2}{3} q_{pip}$ (e.g. Rijpkema and Girard 1991; J. Lee and Kunii 1995) and $q_{dip} = q_{pip}$ (e.g. Biagiotti, H. Liu, Hirzinger, and Melchiorri 2003) are of common use, $_{dip}$ and $_{pip}$ being for distal interphalangeal and proximal interphalangeal of course. It is better to make this coupling an objective rather than a constraint since it has anatomical precision: fairly large errors are accepted. In particular, we can see from our fingers that loading of the distal phalanx can easily override this relationship.

To enforce this new control objective, we use a basic articular proportional-derivative corrective action with desired articular values $q_{dip}^{[d]} = q_{pip}$:

$$\ddot{q}_{dip}^{[d]} = k_{q_{dip}} \, (q_{dip}^{[d]} - q_{dip}) - b_{q_{dip}} \, \dot{q}_{dip}$$

Then we define dummy objectives for the other joints: $\ddot{q}_{other}^{[d]} = 0$, similarly to the dummy objectives on the tangential contact forces in (5.32) and (5.33). We concatenate those objectives into one vector $\ddot{q}^{[d]}$, define an adequate weight matrix $Q_q$ with hardly any weight for the dummy objectives, and write the following optimization criteria:

$$\min_{\dot{T}} \frac{1}{2} \left\| \ddot{q}^{[d]} - L^T \, \dot{T} \right\|_{Q_q}^2 = \min_{\dot{T}} \left[ \frac{1}{2} \dot{T}^T Q'_{\dot{T}} \dot{T} + \dot{T}^T r'_{\dot{T}} \right] \tag{5.43}$$

with $Q'_{\dot{T}} = L \, Q_q \, L^T$ and $r'_{\dot{T}} = -L \, Q_q \, \ddot{q}^{[d]}$.

This last criteria is important because it helps manage the redundancy of the finger kinematic chains. It improves the visual realism of the grasp by limiting unusual, non-anatomical joint configurations, without eliminating finger redundancy totally.

### Conclusion

We end up with the criteria summarized in table 5.2, together with the unknown they are relative to (i.e. the optimization variable).

## 5.3.4 Summary

### Objective function

All the criteria we formed are quadratic with respect to their optimization variable, $f$, $\dot{T}$, or $\tau$ (see table 5.2). To define a quadratic objective function which accounts for these criteria, we define the unknown vector:

$$y = \begin{pmatrix} \tau \\ \dot{T} \\ f \end{pmatrix}$$

| | Objective | Weight | Criteria | Unknown |
|---|---|---|---|---|
| (5.31) | $W^{[d]}_{dp\to obj}$ | $Q_W$ | $\to \min_f \left[\frac{1}{2}f^TQ_{obj}f + f^Tr_{obj}\right]$ | $f$ |
| (5.33) | $f^{[d]}$ | $Q'_f$ | $\to \min_f \left[\frac{1}{2}f^TQ'_ff + f^Tr'_f\right]$ | $f$ |
| (5.41) | $\dot{v}^{[d]}_{c_i\in dp_i}$ | $Q_{c_i}$ | $\to \min_{\dot{T}} \left[\frac{1}{2}\dot{T}^TQ_s\dot{T} + \dot{T}^Tr_s\right]$ | $\dot{T}$ |
| (5.42) | $\tau^{[d]}$ | $Q_\tau$ | $\to \min_\tau \left[\frac{1}{2}\tau^TQ_\tau\tau + \tau^Tr_\tau\right]$ | $\tau$ |
| (5.43) | $\ddot{q}^{[d]}$ | $Q_q$ | $\to \min_{\dot{T}} \left[\frac{1}{2}\dot{T}^TQ'_{\dot{T}}\dot{T} + \dot{T}^Tr'_{\dot{T}}\right]$ | $\dot{T}$ |

Table 5.2 – Criteria and their unknowns

as well as the block-diagonal weight matrix $Q$ and the objective vector $r$ [24]:

$$Q = \begin{pmatrix} Q_\tau & & \\ & Q_{\dot{T}} = Q_s + Q'_{\dot{T}} & \\ & & Q_f = Q_{obj} + Q'_f \end{pmatrix} \qquad r = \begin{pmatrix} r_\tau \\ r_{\dot{T}} = r_s + r'_{\dot{T}} \\ r_f = r_{obj} + r'_f \end{pmatrix}$$

And we define the following quadratic objective function:

$$f(y) = \frac{1}{2}y^TQy + y^Tr$$

### Equality and inequality constraints

We also define matrices $A_{eq}$, $b_{eq}$, $A_{neq}$ and $b_{neq}$ such that the equality and inequality constraints (5.13), (5.14), (5.24), and (5.25) (see table 5.1) end up as:

$$A_{eq}\,y + b_{eq} = 0 \qquad\qquad A_{neq}\,y + b_{neq} \leq 0$$

### Quadratic program

Eventually, the optimization problem that makes our control law is [25]:

$$\begin{cases} \min\limits_y \dfrac{1}{2}y^TQy + y^Tr \\ A_{eq}\,y + b_{eq} = 0 \\ A_{neq}\,y + b_{neq} \leq 0 \end{cases} \tag{5.44}$$

The existence and unicity, on the feasible region, of a global minimizer of the objective function, in other words, the existence and unicity of a solution to this constrained optimization problem, should be discussed thoroughly. It is well-known that if the objective function $f(y)$ is strictly convex, or equivalently if $Q$ is positive-definite, then this problem has at most one solution, and exactly one if there exists some feasible vector $y$ (i.e. satisfying the constraints, in other words, if the feasible region is not

24. The objective of each criteria has been embedded in the corresponding vector $r_{something}$, hence the name.

25. Actually, it's $\arg\min_y$ rather than $\min_y$, i.e. we are more interested in the $y$ that minimizes the objective function than in the minimal value of this function. This is often the case with optimization problems, so $\arg\min$ is just implied.

the null set). However, even though the original weight matrices $Q_W, Q'_f, Q_{c_i}, Q_\tau, Q_q$ have been chosen to be positive-definite, it is not necessarily the case of the matrices $Q_{obj}, Q_s, Q'_{\dot{T}}$, and therefore it is not necessarily the case of $Q$ either. In the general non-convex case, there can be several minima of $f(y)$ on the feasible region.

Unfortunately, we did not investigate further, and assumed that it is always possible to find a solution $y^{sol}$ to the quadratic program. Hopefully, this solution is the global minimizer on the feasible region. From it, we get $\tau^{sol}$: optimal control torques, in the sense of the criteria, which comply with all the constraints, for the current time $t$.

A variety of algorithms is available to solve a constrained quadratic programming problem (i.e. find a minimum). In our computer simulations, we used Lemke's algorithm on the linear complementarity form of (5.44). Indeed, it is possible to show that any quadratic program is a particular case of linear complementarity problem (see e.g. Murty 1988; Cottle, Pang, and Stone 1992/2009), that is to say finding vectors $w$ and $z$ such that:

$$\begin{cases} w - Mz = q \\ w \geq 0 \text{ and } z \geq 0 \\ w^T z = 0 \end{cases}$$

with $M$ a certain square matrix and $q$ a certain vector. Lemke's algorithm is a procedure for solving such problems, originally proposed by the mathematician Carlton Lemke (1965), and subsequently extended in a variety of ways by many others [26]. It terminates on a solution, when such exists, after a finite number of steps, which is interesting from a computational point of view. The physical engine Arboris features an implementation of Lemke's algorithm (Micaelli and Barthélémy 2006–2010).

## 5.4 Simulation-based validation

### 5.4.1 A simple simulation example

In this section, we demonstrate the use of our control in a simple manipulation task involving translation and rotation of a spherical object by a four-fingered hand, in dynamic simulation, with the dynamical engine Arboris (see section 5.1.1).

#### Control objectives

The desired motion is illustrated on figure 5.16. It is made of three parts. During the first part, from 1 s to 2 s, the desired motion is set to the initial position of the object. From 2 s to 3 s, it is made of a rotation of 45° around the object's $y$ axis in 0.5 s, combined with a translation of 2 cm along the same $y$ axis in 1 s. From 3 s to 4 s, the object is desired to be at rest again.

The whole motion makes up a trajectory in $SE_3(\mathbb{R})$, and it is actually implemented as such before being given to the controller: a collection of matrices ${}^{root}H^{[d]}_{obj}$, one per time step between $t = 1$ s and $t = 4$ s (and our time step is $dt = 2$ ms). Each of those matrices is given as input to the controller at the adequate instant.

26. Lemke was one of the pioneers in the study of this class of problems, defined in the 1960s. According to Cottle, Pang, and Stone (1992/2009), "diverse instances of the linear complementarity problem can be traced to publications as far back as 1940, [but] concentrated study of the LCP began in the mid-1960s".

The desired motion is clearly not quasi-static, so the dynamics of the hand and the dynamics of the object play a non-negligible role.

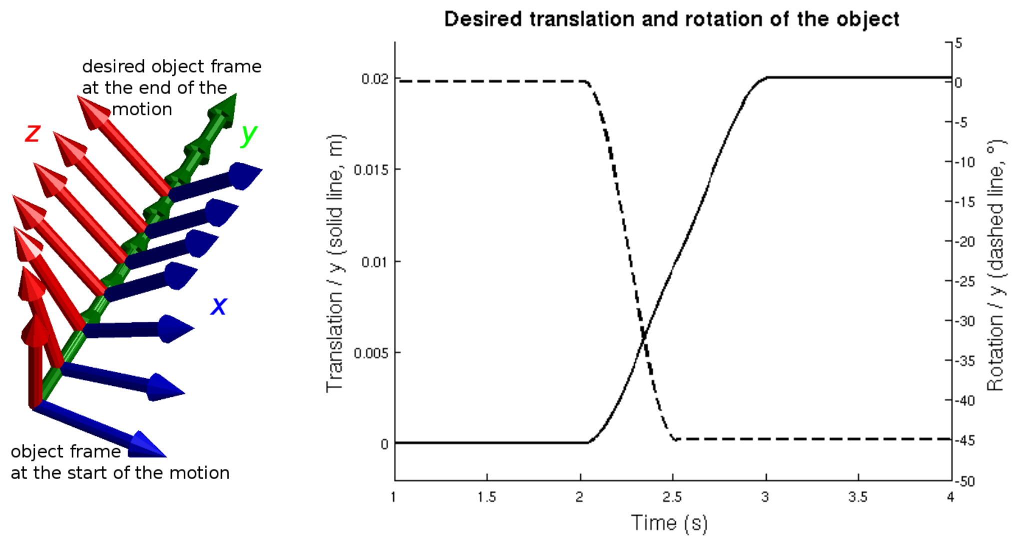



Figure 5.16 – Desired motion for the object's body frame

The time gap from 0 s to 1 s is for the hand to set contact on the object. Its initial articular posture encircles the object, and contact is set through proportional-derivative control of the fingertips: for each distal phalanx, a position error is defined as the distance between the object and the phalanx, that is to say the distance between the point on the object and the point on the phalanx that are the nearest one another (they are the future contact point). This proportional-derivative control is itself embedded as a criteria (minimization of said position error) in a simplified and adapted version of our optimization-based control.

A contact force objective accounts for light squeezing of the object with normal forces $f_{i,n}^{[d]} = 0.5\,\mathrm{N}$, for all $i \in [|1,4|]$: see equation (5.33) in section 5.3.3. As we explained in that section, this objective is incompatible with the desired total contact wrench $W_{dp\to obj}^{[d]}$ which stems from the desired object motion. This is why we do not choose larger force values in the contact force objectives $f_{i,n}^{[d]}$: we do not want to hinder motion control with an incompatible desired contact wrench resulting from the $f_{i,n}^{[d]}$, possibly large comparatively to the actual desired contact wrench $W_{dp\to obj}^{[d]}$. For the same reason, the priority of this objective is well below the priority of the desired object motion: we set $Q'_f = 10\, I_{3n_f} \ll Q_W = 10000\, I_6$.

All the weight matrices we use are diagonal for convenience, and chosen very heuristically (table 5.3). Gravity is set to zero for simplicity, and the friction coefficient between the material of the object and the material of the fingers is set to $\mu = 0.8$. In the discretization of the contact cones, we use $n_e = 8$ faces.

### Programming and simulation

To make Arboris run a simulation with the parameters and desired values described above, we have to implement computer models of the robots, provide them with ways to read data from the simulated environment, and write the code of their control. All of this is done in object-oriented Matlab, since Arboris is written in that language

| | | |
|---|---|---|
| (5.31) | object motion | $Q_W = 10000\, I_6$ |
| (5.33) | object tightening | $Q'_f = 10\, I_{3n_f}$ |
| (5.41) | non-sliding contacts | $Q_{c_i} = 10000\, I_{3n_c}$ |
| (5.42) | minimal motor torques | $Q_\tau = 1\, I_{n_{dof}}$ |
| (5.43) | coupling of distal and middle joints | $Q_q = 1000\, I_{n_{dof}}$ |

Table 5.3 – Weight matrices for the criteria

and therefore used from within the Matlab programming environment. In (very) broad outline:

**Robots** There are two robots in our simulated world: the hand and the object. The tree-like structure of the hand is described body after body, starting with the root body. For each segment, we define *a*) its geometric properties: shape, dimensions; *b*) its kinematic properties: how and where it is articulated with respect to the previous body in the tree; *c*) its physical properties: mass, inertia, material; and *d*) its graphical properties: graphic primitives, colors, transparency, texture mapping, surface shading, surface reflection. The object consists solely of its root body. The names and formats of the properties are standardized in order to be understood by Arboris.

**Sensors** The dynamical simulator computes the matrices of the model of each robot at the first time step, and updates them at every subsequent time step of the simulation. Among them: $J$, $M$, $N$, $\dot{V}_{root}$, $V_{root}$, ${}^{ref}H_{root}$, $\ddot{q}$, $\dot{q}$, $q$, not to mention the data related to the interactions between the robots, such as ${}^{dp_i}H_{c_i}$, ${}^{obj}H_{c_i}$, $W_{ext}$. Any of these matrices can be accessed by any robot's controller, provided the appropriate accessor functions exist or may be written to fetch the desired data. This means that any robot's controller can have a total and perfect knowledge, not only of its own robot, but also of any other robot in the simulated world, and of the interactions between them: this is a convenience of computer simulation that is unfortunately not found in real life. We are therefore able to write, for the hand's controller, a set of simulated sensors which bring the controller any data it needs to compute the matrices $Q$, $r$, $A_{eq}$, $b_{eq}$, $A_{neq}$, $b_{neq}$ of the control law (5.44).

**Controller** The controller itself implements the control law and returns its solution $\tau$ for the current time step. It is written as an object, with a data structure embedding various information about the controller's robot and its control objectives, and a certain number of methods (class functions). Among these methods, one of them calls the various sensors of the hand to refresh the data stored in the controller, and another uses this new data to compute the matrices of the control law (5.44), solve the optimization problem, and output the control torques $\tau$.

Once the robots, the sensors, and the controller have been defined and coded, we can start a simulation with them. Roughly speaking, at each time step, the dynamical engine runs a collision detection algorithm and solves the constraints it finds, that is to say, it computes the forces between the contacting bodies ($W_{ext}$). Then, it calls the controller of every robot, in our case only the hand's controller since the object doesn't have any, and gets back the control torques for the current time step ($\tau$). Using the contact forces and the control torques, it is able to find the accelerations of the various bodies, integrate these accelerations to find the velocities and the positions, and start a new time step with this new data.

During this simulation loop, a fair amount of data is written to the memory for future analysis or saving to disk. In particular, at the end of the simulation, a visualization loop loads some of this data and displays it as three-dimensional animated graphics of the robots' motion in the simulated world.

#### Simulation results

Figure 5.17 illustrates the resulting tracking of the desired object trajectory. Errors are fairly small and are the result of our controller's design to try and satisfy multiple conflicting objectives while being constrained by equality and inequality constraints. A trade-off is found between the objectives.

Figure 5.18 illustrates the trade-off nature of this control strategy even more: the same manipulation was executed at $Q_W = 1000\, I_6$ and $Q'_f = 3000\, I_{3n_f}$ for more tightening. As a result, the manipulation task is impaired. As we already mentionned, this is not a correct way to take grasp robustness into account.

### 5.4.2 Two more complex extensions

#### Withstanding disturbances

A first extension to our control strategy is to conduct a dedicated study of grasp robustness beforehand, in order to come out with a tightening objective which is compatible with the manipulation objective.

We do so in chapter 6. More precisely, we specify a dual tightening/manipulation objective in terms of the contact forces being able to withstand a certain set of disturbances while still assuring the tracking of a desired object trajectory. The formulation of this problem leads to additional mathematical programs. Once solved, they give desired contact forces $f^{[d]}$ which account for tightening, in the sense of withstanding the specified set of disturbances, and are compatible with the manipulation objective, in the sense that they produce the desired resultant wrench $W^{[d]}_{dp\rightarrow obj}$.

Therefore, the criteria (5.33) that results from these $f^{[d]}$ can be safely combined with the criteria (5.31) that results from $W^{[d]}_{dp\rightarrow obj}$. Actually, it can even replace it.

The next chapter deals with this problem of grasp robustness, and provides simulation examples of grasps withstanding disturbances.

#### Manipulation with sliding contacts

A second extension to our control strategy is to make it possible for fingers to slide on the object, or for the object to slide under the fingers, as long as this behavior is intentional of course.

Indeed, while unintentional slip is a sign of grasp failure, controlled sliding plays an important part in dextrous, in-hand manipulation. We use it extensively, in particular when we change the grasp configuration, that is to say the location of the contact

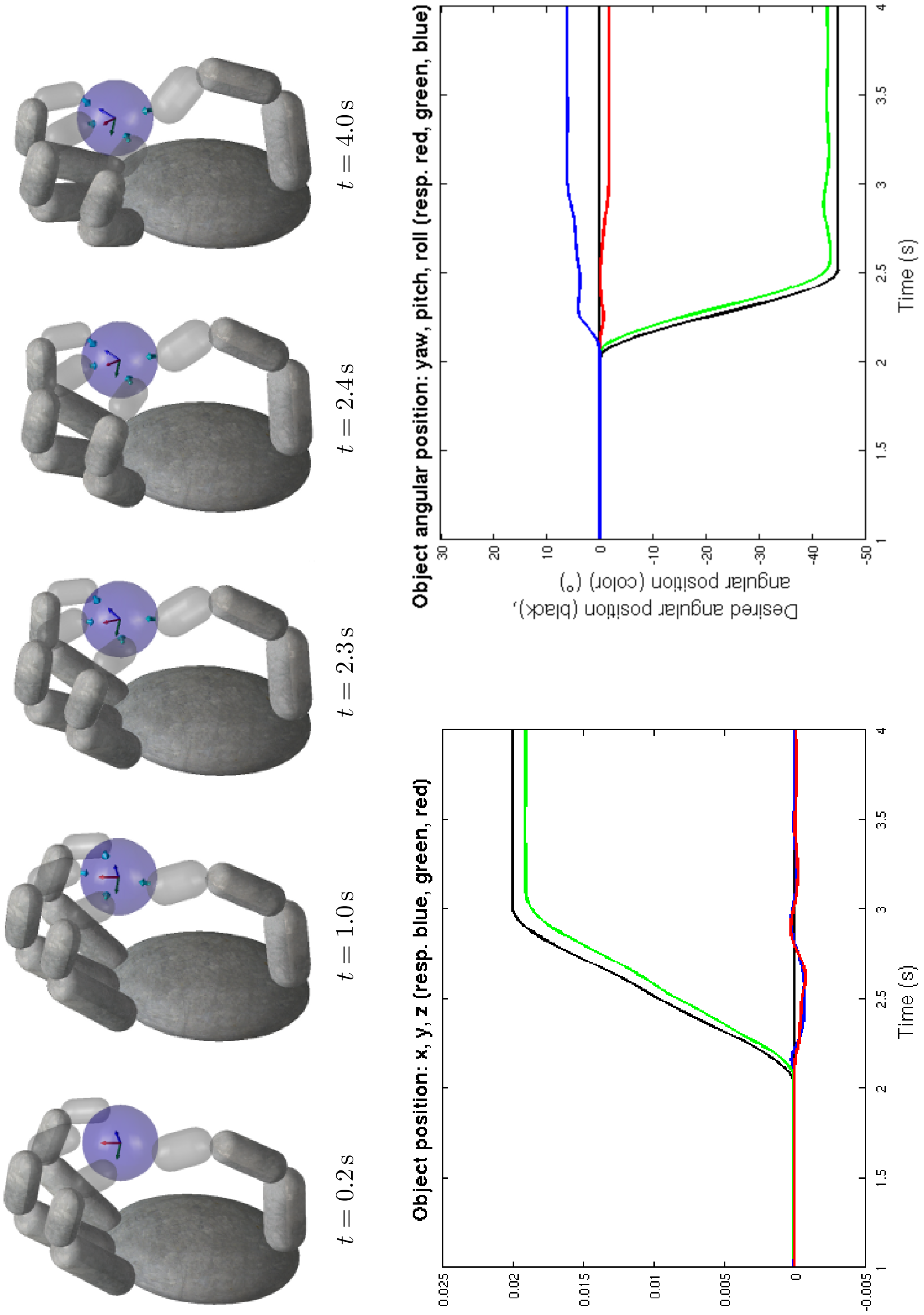



Figure 5.17 – Tracking of the desired object trajectory

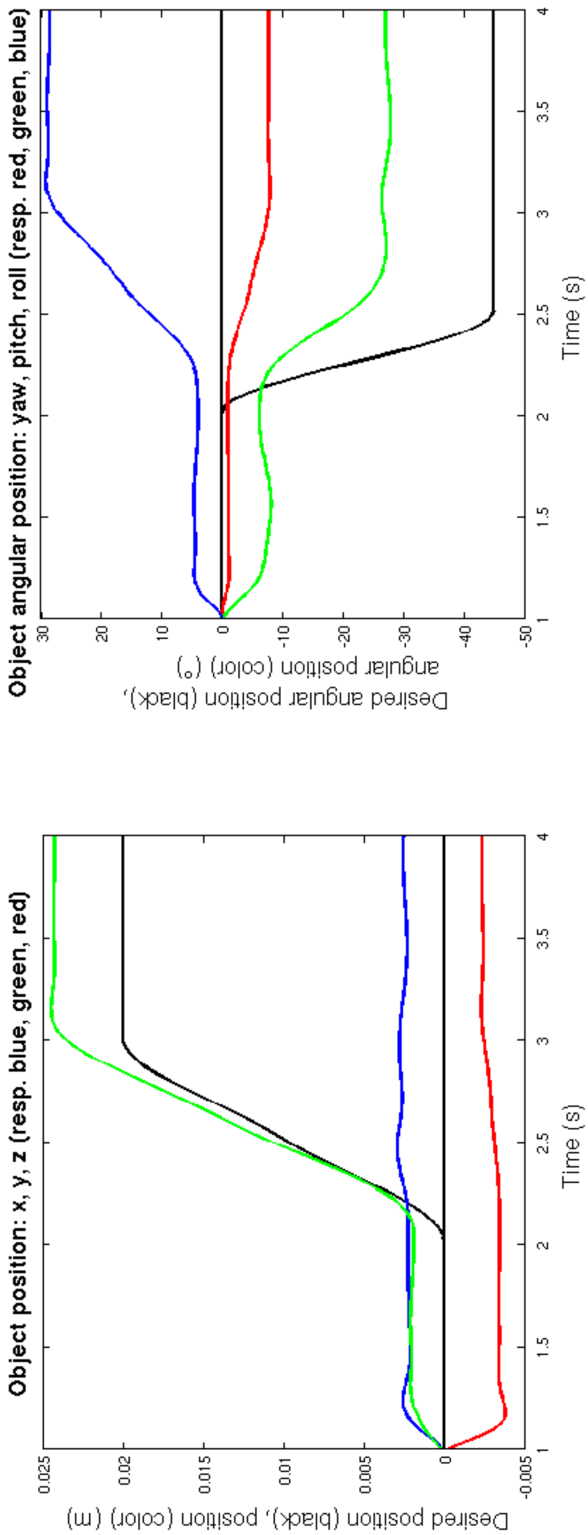
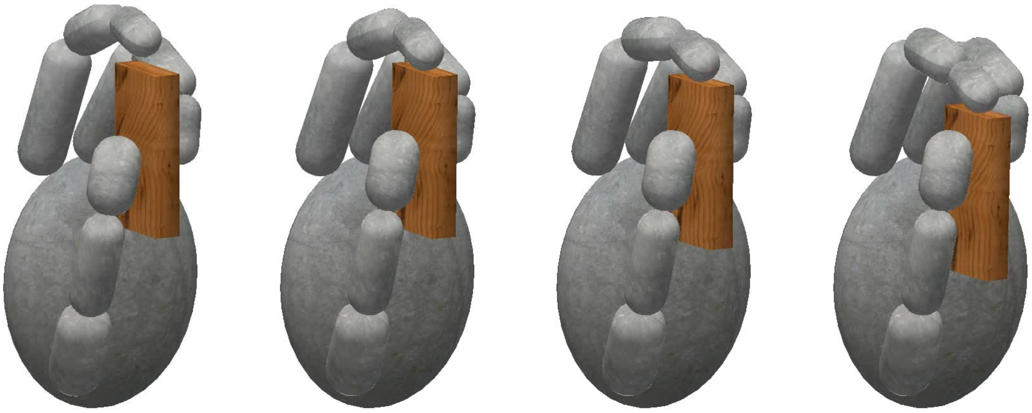



Figure 5.18 – A bad choice of weight matrices impairs tracking

points on the object and/or on the hand. Such regrasping [27] is often executed rapidly and subconsciously, perhaps because it is hardly a task in itself but rather part of a larger, purposeful task: the examples that spring to mind are picking up a pencil and moving the fingers towards tip to form a grip adapted for writing, and picking up a fork or a knife and quickly regrasping to put these items in the correct grip to cut up food.

A short, introductory bibliography on controlled sliding is given at the beginning of section 5.2.3. As for us, regardless of the importance of controlled sliding, we did not investigate it thoroughly enough; it is something that needs to be addressed in the future, though. As a first approach, we modified our control law to make it realize the manipulation reported in figure 5.19: sliding a flat object between the thumb and the middle finger by pushing it with the index finger. This is something that is part of a common way of keeping one's fingers busy, while thinking about something else: we slide the object between the fingers, then rotate it upside-down in a fast motion, and resume sliding from this new position until the object has slid all its way down and must be rotated upside down again, and so on, without actually paying attention. This absent-minded play is most likely to be performed at work with a pen, an eraser, or any card-sized object like a business card or a subway access card.



$t = 0\,\mathrm{s}$ $t = 1\,\mathrm{s}$ $t = 2\,\mathrm{s}$ $t = 5\,\mathrm{s}$

Figure 5.19 – Sliding an object between the fingers
(from $t = 1\,\mathrm{s}$ to $t = 5\,\mathrm{s}$)

To realize this manipulation, we removed the criteria about non-sliding (5.41) from our optimization problem and replaced it with a criteria expressing position control of the distal phalanges of the thumb and middle finger. Indeed, we can feel from trying out this manipulation by ourselves that these two digits remain stiff and in place during the sliding of the object. So an idea to reproduce this behavior is to servo their distal phalanges in position and orientation on a fixed posture, in the cartesian space. From this control we obtain quite easily a quadratic optimization criteria on $\dot{T}$, expressing the minimization of the position and orientation errors. This criteria replaces the criteria about non-sliding of the thumb and middle finger; the one about non-sliding of the index finger remains. An alternative option to distal phalanx position control, though, and perhaps a better one or at least a more human-like one, would be to control the stiffness of the thumb and middle finger.

27. The term “regrasping” encompasses sliding and/or rolling as well as finger gaiting, that is to say breaking some contacts (but not all) and re-forming them elsewhere. Thus regrasping can be with or without contact break.

Also, in addition to distal phalanx position control, we changed the constraint on the contact forces (5.13), or more precisely we changed only the part relative to the thumb and middle finger, not the part relative to the index finger. Indeed, this constraint expresses the unilaterality of the contact forces and their physical consistency, as well as the linearized Coulomb condition of non-sliding. To change it into the Coulomb condition of sliding, we must write that the contact force lies on the surface of the contact cone, with the friction force opposite to the direction of motion. Since the direction of motion is known in this test case, it is possible to write the second part of these requirements without too much difficulty [28]. The first part means that a linear relationship exists between the norms of the tangential and normal components of the contact force (see the Coulomb friction model in section 5.1.4), and this means a quadratic relationship between the components $(f_i)_x$, $(f_i)_y$, and $(f_i)_z$ at the thumb and middle finger ($i = 1$ and $i = 3$). However, for an appropriate choice of contact frame, this quadratic relationship reduces to an equivalent linear one: we just have to choose the contact frame so that $(f_i)_x = f_{i,t}$, $(f_i)_y = 0$, and $(f_i)_z = f_{i,n}$. In the end, we get a linear equality constraint on $f$ (thumb and middle) in addition to the remaining inequality constraint (index).

It is worth noting that changing the constraint expressing the Coulomb condition of non-sliding into a constraint expressing the Coulomb condition of sliding is not by itself guaranteed to make the box slide between the fingers. Indeed, the Coulomb condition of sliding also describes a non-sliding situation on the verge of sliding. But combined with the position control of the distal phalanges of the thumb and middle finger and with the fact that the index finger pushes on the top of the box, it does produce the desired controlled sliding.

As an end remark, we can point out that our optimization-based control strategy has the advantage of making it easy to remove, add, or modify an equation according to the situation: it boils down to changing the criteria and constraints that make up the matrices of the optimization problem (5.44).

## 5.5 Conclusion

### 5.5.1 Summary

In this chapter, we investigated the control of multifingered dextrous manipulation for humanoid robot hands. We first described the hand model, the object model, and the contact model (5.1), and we reviewed the basics of manipulation control, its history and its litterature (5.2). Then we proposed a new control strategy (5.3), inspired by the work of Collette and Micaelli (2007a,b) and Abe, Silva, and J. Popović (2007) on humanoid motion control. This strategy is based on the formulation of the control problem as a mathematical optimization problem. It finds control torques that:

- Satisfy a set of equations and inequations: the constraints of the optimization problem.
- Realize a trade-off between different and possibly conflicting control objectives: the criteria of the optimization problem, assembled into its objective function.

28. In the general case, we have to compute the sliding velocity in order to find the direction of motion. That is to say, we have to implement a simulated sensor of sliding velocity for the hand's controller. This work has been done, but the resulting piece of code is still bug-ridden and doesn't really work reliably yet. Hence the simplified test case investigated here.

The control scheme is able to ensure, in addition to the observance of the hand dynamics of course:

1. Motion control of the object, or force control of the contact force between it and the environment, both through impedance control actually.
2. Tightening of the object, through an appropriately designed objective on the internal forces, or thanks to a dedicated study on grasp robustness as presented in the next chapter.
3. Enforcement of physical consistency for the contact forces (unilaterality and friction constraints), and non-sliding of the contacts.

These three points are basic requirements for any modern control algorithm of multifingered dextrous manipulation. In addition, the method we propose is able to ensure:

4. Observance of torque limits, to account for the fact that actuator power is limited.
5. Observance of joint limits, so the control torques do not go against end stops, something that could damage the hand or the actuators.
6. A weak form of coupling between the distal and proximal interphalangeal joints, to limit the redundancy of the finger kinematic structure and produce more anthropomorphic articular configurations.
7. Minimal control torques, in order to relieve the strain on the actuators and save power.

The method is easily adaptable through adjustment of the weight matrices of the various criteria, and through addition or removal of constraints and criteria. With our choice of constraints and criteria, the optimization problem is quadratic with linear constraints, which means that it is not difficult to solve numerically.

### 5.5.2 Future work

Much remains to be done. For instance, in section 5.4.2, we introduce a first approach to controlled sliding, an important ability of our hands because it greatly improves the dexterity of the grasp, together with controlled rolling. Both aspects deserve to be investigated thoroughly. Indeed, they are of such a constant use in our everyday manipulations, particularly during in-hand regrasping, that any control of dextrous hands should account for it.

Also, we left out the control of palm motion. Although our hand model and our control scheme feature $V_{root}$ and $W_{ext \to root}$ here and there, the details about the palm have been overlooked, and palm usage remains entirely untested. In particular, we did not investigate how to set a motion objective on the palm, how to integrate it with the other criteria, and how in definitive the palm participates in grasping and manipulation. At least, palm usage enlarges the motion range of feasible manipulations, but the palm could also be in contact with the object by one or more points. Besides, it shall not participate too much in dextrous, fingertip manipulations, to avoid situations where a manipulation performed with the fingers by a human hand is performed with more palm usage by a robot hand. All those questions deserve to be investigated.

An easier extension to our control is to take into account contacts between the object and the proximal and middle phalanges, not just the distal phalanges. This seems to be a fairly minor modification of our modeling and control: we begin by making the distinction between $n_f$, the number of fingers, and $n_c$, the number of contacts, rather than using $n_f$ for both. Then we modify the various calculations according to this distinction. This should yield a control law for a grasp with $n_c$ point contacts distributed among $n_f$ fingers. The downside is that the more contacts there are, the more constrained the grasp is, and the more likely it becomes that the outcome of manipulation control will be poor: fine manipulations are not easily performed with contacts on all phalanges (power grasps versus precision grasps, see section 2.2 in chapter 2).

Before closing this chapter, let us also mention that possible research perspectives with our optimization-based control scheme is its application to two-handed manipulations, and to multifingered hands with compliant contacts. Both situations are fairly different from our original problem, so a great deal of adaptation will probably be necessary. In particular, compliant contacts, even though they model reality much better than rigid point contacts with Coulomb friction, have the disadvantage of invalidating the rigid-body assumption. Consequently, adaptation of our optimization-based control scheme to such contacts, if at all possible, is unlikely to be straightforward.

6

# Optimal tightening forces for robust manipulation

## Contents



In the previous chapter, we have mentioned on several occasions that the control of multifingered dextrous manipulation must ensure not only the motion of the object, that is to say the manipulation itself, but also a certain tightening of the object, particularly to make the hand withstand potential disturbances. We stated that these two objectives, manipulation and tightening, had to be compatible with each other so that none of them hinders the realization of the other. We explained how it is done classically in robotics: by taking advantage of the internal forces, this part of the contact forces which does not produce a motion of the object (see sections 5.1.6 and 5.2.3). Also, we wrote that we were going to present a dedicated study of grasp robustness, that is to say the ability to withstand disturbances, or more generally cancel external loads. This study would make it possible to find contact forces able to keep hold of an object in spite of a set of disturbances, and still produce the required motion. Unlike the classical approach, this method would not separate the contact forces into internal forces and a force producing the motion, thereby sparing the trouble of investigating the kernel of the grasp matrix (which is the space of internal forces). It would be formulated entirely and directly in terms of contact forces.

This is what this chapter is about: we propose a method for calculating contact forces which are able to manipulate an object according to a certain desired motion, and to tighten it according to a certain desired robustness to disturbances. This method was first described in an article presented at the IEEE/RSJ International Conference on Intelligent Robots and Systems in 2009 (Michalec and Micaelli 2009b), and this chapter is a revised and expanded rewriting of it. In this approach, the robustness objective is specified in two parts as follows [1]:

**Some directions in the wrench space** They indicate along which directions the grasp is desired to withstand the disturbances that might be applied on the object. For instance, a direction in the wrench space [2] could indicate positive forces along the axis $x$ of the object's frame, or negative moments around some vector $u$ fixed in that frame.

**A percentage of a sort of maximal robustness** Since there is no such thing as a robot hand with unlimited actuator power, there is a limit to the wrenches that the hand can apply on the object, and therefore, there is a limit to the disturbances that the hand can counteract. In other words, it is possible to define some sort of "maximal robustness" of the grasp.

Therefore, it is possible to describe a robustness objective in terms of the grasp being desired to withstand disturbances happening in the chosen directions of the wrench space and having intensity up to the chosen fraction of the maximal robustness.

All this may sound somewhat abstract for now, but this chapter will make it clearer. It begins in section 6.1 by explaining our approach of grasp robustness, and how it compares to related notions in the robotic litterature. Also, some notations and definitions are reminded from the previous chapter. In section 6.2, we define the problem of "grasp robustness to expected disturbance wrenches", and explain how to get suitable contact forces. In this section, the disturbances are considered known in direction and intensity (they are expected to happen): it is a preparatory study for the next section, where they are considered known in direction only (they are expected to happen in such and such direction). So, in section 6.3, we define the problem of "grasp robustness to expected disturbance directions". We explain how to calculate the above-mentioned maximal robustness, how to calculate contact forces suited to this maximal robustness, and how to calculate contact forces suited to a fraction of the maximal robustness. Finally, section 6.4 demonstrates the validity of our approach with examples of robust manipulation in dynamic simulation, and section 6.5 concludes the chapter.

## 6.1 Introduction

We begin this first section by introducing some classical concepts of grasp analysis, such as the set of wrenches a grasp can realize, the quality of a grasp, and the admissible external wrenches, aka resisted disturbance wrenches. These concepts make it possible to explain the physics behind our approach to the problem of tightening, in an equation-free and all-illustrated way. Indeed, the actual, mathematical treatment

1. This description is not entirely accurate, but this is the general idea, in simplified outline.
2. Wrenches are generalized forces: force and moment, see chapter 4.

of our approach is in sections 6.2 and 6.3, but it may look abstruse without any physical interpretation. Hence this introduction.

Once this is done (section 6.1.1), we review some closely related research, in order to make the differences with the problem we investigate appear clearly (section 6.1.2). Then, we introduce the notations that we will use in our study of grasp robustness (section 6.1.3), and move on to this study, in sections 6.2 and 6.3.

### 6.1.1 Disturbances and robustness

#### Tightening forces: statement of the problem

Tightening forces are important because humanoid robot hands are meant to be used in unstructured environments, as explained in chapter 3, section 3.1.3. In these settings, contrary to industrial settings such as assembly lines, unforeseen and unexpected events are bound to happen frequently. In particular, human-adapted environments such as homes, offices, stores, gardens, and streets are extremely diverse and complex, and may change at any moment because of the presence and actions of humans, or even pets. For a robot to deal with this unexpected, then, and operate safely in such environments, a certain amount of robustness in the prehensile abilities is required. Disturbances may happen, and keeping hold of objects in spite of them is necessary. Also, given the huge variety of objects in human environments, the robot may sometimes be wrong in its estimation of an object's characteristics (mass, mass distribution, surface friction, rigidity, and so on), and this also results in unexpected forces when picking up the object or manipulating it.

Human hands provide the required amount of robustness through power grasps and/or tightening contact forces that squeeze the manipulated object in order to resist a disturbance more easily, in case one happens. This is this tightening behavior that we are trying to emulate in a robot hand. We are not so much interested in the contact forces that would cancel such and such disturbance [3] (figure 6.1(a)), but rather in the contact forces that the robot hand could apply in the absence of any disturbance, as a pre-strain, in case a disturbance happens (figure 6.1(b)). We call the first ones *opposing forces* and the second ones *tightening forces*, in accordance with their effects.

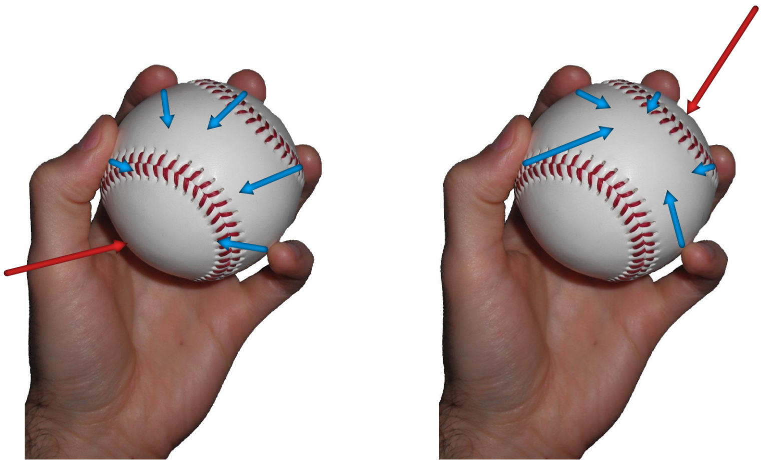
Let's consider a set of disturbances applied one after another on an object in grasp. Two strategies seem possible to keep hold of the object:

**Large variations between tightening and opposing forces** No specific pre-strain whatsoever is applied on the object, so the tightening forces are low, and consequently each disturbance is canceled by opposing forces which are substantially larger than the tightening forces.

**Small variations between tightening and opposing forces** A certain amount of pre-strain is applied on the object, through larger tightening forces, and consequently each disturbance is canceled by opposing forces which are close to the tightening forces.

In the second strategy, the tightening forces appear as a compromise between the various sets of opposing forces: a kind of optimal middle value, close to each set of opposing forces (one set of opposing forces per disturbance, see figure 6.1(a)). So a

3. Because they are of little practical use for control purposes; we explain why in section 6.2.1.



(a) Opposing forces. They cancel the external load in red (possibly a disturbance).

(b) Tightening forces. The sum of these contact forces is zero, so they do not produce any motion of the object, they are "pure" tightening forces. Obviously, the grasp on the right is more robust than the grasp on the left.

Figure 6.1 – Opposing contact forces and tightening contact forces

way to choose "good" tightening forces, with respect to the chosen set of disturbances, would be to minimize the variations between them and the opposing forces.

This is what we do in this chapter (in sections 6.2.3 and 6.3.1), and it explains a part of its title: "optimal tightening forces". The other part of the title, "robust manipulation", expresses the fact that we look for tightening forces in relation to disturbances to resist to (robustness), and that these tightening forces are in fact not necessarily pure tightening forces as in figure 6.1(b): they may also participate in the motion of the object (manipulation). In other words, the purpose of this chapter, and the problem we are dealing with, is "manipulation with optimal tightening according to a certain robustness objective expressed in terms of disturbances to withstand".

So, in order to address this problem, we need some background about disturbances, robustness, and how to specify a robustness objective in terms of disturbances to withstand. We provide this introductory material in the rest of this section 6.1.1.

### Grasp wrench space and disturbances

A grasp can generate only certain wrenches, not the whole wrench space. For instance, as mentioned in the introduction of this chapter, the hand actuators are limited in power, so the contact forces are somehow limited in magnitude, therefore the fingers cannot produce arbitrarily large resultant wrenches.

More precisely, the wrenches a grasp can apply on the object depend on two factors:

- The grasp configuration, that is to say the number of contacts and where they are located. This information is embedded in the grasp matrix $G$, see section 6.1.3.
- The contact forces that can be applied, that is to say how large they can be in friction and in magnitude. This information is embedded in the contact cones, see section 6.1.3, and in limits on the magnitude of the forces, see section 6.2.1. In other words, the contact forces that can be applied are located inside a *bounded contact cone* at each contact.

The set of all the possible resultant wrenches produced by the fingers on the object is called the *grasp wrench space*. With the notations of the previous chapter, i.e. if $G$ is the grasp matrix and $f$ is the column vector of the contact forces $f_1, \dots, f_{n_c}$, with $n_c$ the number of contacts, and if we suppose that the magnitude of each contact force is limited by simply bounding the norm of the force, the grasp wrench space $GWS$ would be defined by:

$$GWS = \{G\,f,\ f_i \text{ contact force and } \|f_i\| \leq f_{i,max},\ \forall\, i \in [|1, n_c|]\}$$

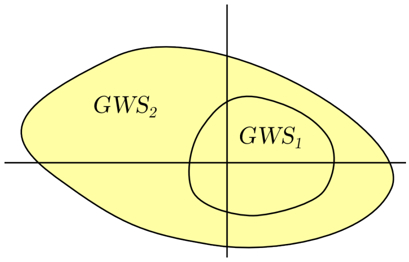
A more algebraic, coordinate-free [4] definition is to say that the grasp wrench space is the sum of the bounded contact cones (Minkowski sum).

Of course, the grasp wrench space contains the zero wrench, so it is a subset of the wrench space located around the origin $0_{6,1}$. It is a convex set, because each bounded contact cone is a convex set, and a sum of convex sets is a convex set. Also, the grasp wrench space defines how good a grasp is: the bigger the space, the better the grasp. Indeed, if two different grasps have $GWS_1$ and $GWS_2$ such that $GWS_1 \subset GWS_2$, then the second one is able to produce more wrenches on the object than the first one, so it is “better”. Not all grasps are that easy to compare though, as illustrated on figure 6.2. Hence the research on grasp quality measures (see section 6.1.2).

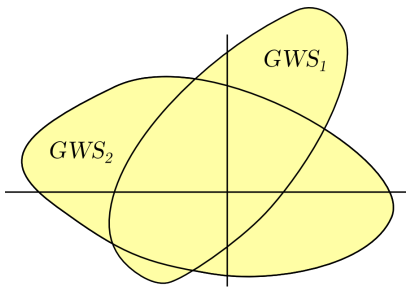
Since a grasp can produce only certain wrenches, it can also withstand only certain wrenches: those for which it can generate the opposite wrench. That makes it possible to define the *space of admissible external wrenches*, or *space of resisted disturbance wrenches*, as the opposite of the grasp wrench space: $-GWS$, see figure 6.3. The disturbances that are not in this space are not admissible, that is to say there are no contact forces in the bounded contact cones that can resist them. Therefore, whatever the contact forces are, the total wrench applied on the object is non-zero, hence an unwanted motion of the object [5]: at best, some sliding, at worst, contacts can break and the object might escape the grip.

4. Speaking of a grasp matrix automatically implies the definition of object and contact frames, since the grasp matrix adds the contact forces at the center of the object, in the object frame: see section 6.1.3. Also, more generally, the grasp matrix is the line concatenation of the co-adjoint matrices between the object frame and the contact frames: see section 5.1.6 in chapter 5.

5. If the object was in static equilibrium. If it was already in motion because of a manipulation, then the total wrench applied on the object is not the one required by the manipulation, and the same outcome happens: an unwanted and unintentional motion of the object.



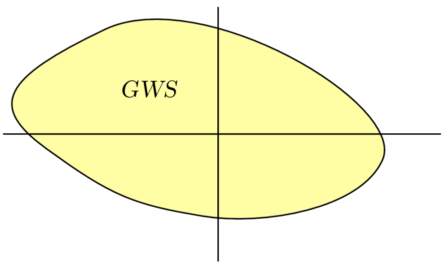

(a) The second grasp is better than the first one.



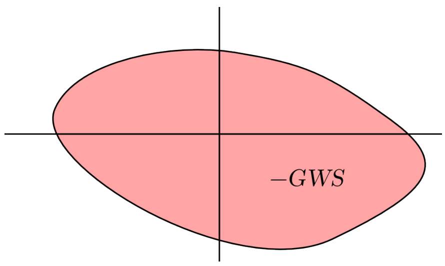

(b) Which grasp is better? It depends on the direction of the wrench space.

Disclaimer: these drawings are two-dimensional depictions of six-dimensional spaces.

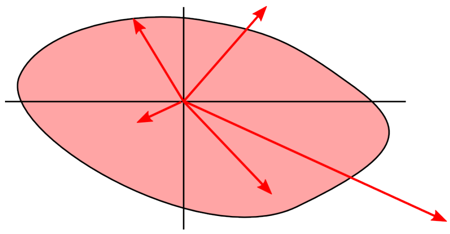
Figure 6.2 – Comparison of grasps by their grasp wrench spaces




(a) Grasp wrench space




(b) Admissible disturbance wrench space



(c) Various disturbances: three are admissible, two cannot be withstood.

Figure 6.3 – Grasp wrench space and admissible disturbances

### Robustness

Among all the disturbances that a grasp can withstand, one is the largest and one is the smallest, in terms of magnitude [6]. These two particular admissible disturbances are illustrated in figure 6.4; of course, the smallest one is the zero wrench.

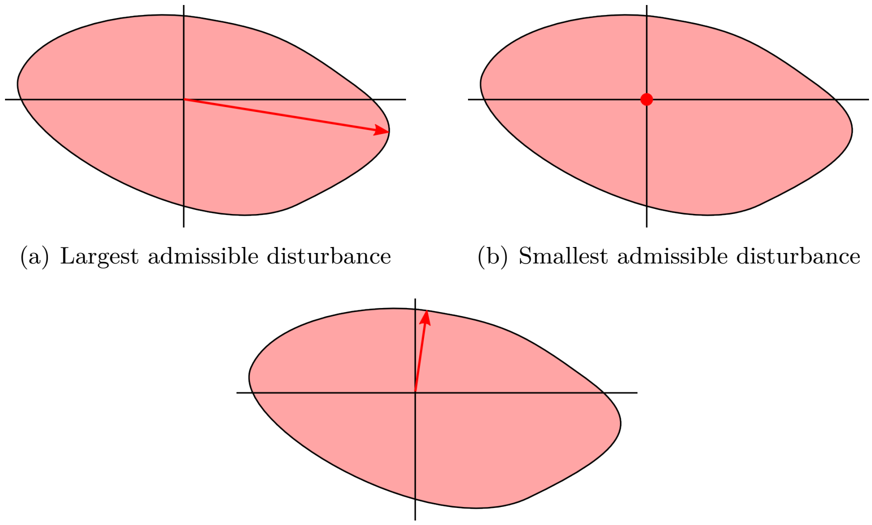
6. The definition of a norm on the wrench space $se_3^*(\mathbb{R})$ is not straightforward. First, the moment in a wrench depends on the point of expression of the wrench. So using the euclidian norm of $\mathbb{R}^6$ on the coordinates of the wrench is a bit pointless: it yields a norm which depends on the expression point, i.e. the same wrench can have many different norms. To alleviate this problem, it is possible to choose one particular point for the expression of the wrenches, when dealing with norms. A second problem comes from the fact that the moment and the resultant of a wrench are not physically comparable: they are in different units, so we should treat them differently in the computation of the norm for the result to be physically consistent. At least, we should multiply the force by a constant length, or divide the moment by a constant length, so that both components of the wrench are in the same unit. In this chapter, we overlooked all these problems and used the usual euclidian norm of $\mathbb{R}^6$. To add a touch of rigor though, we can say that we divide the moment component by 1 m and choose the center of mass of the object to be the wrench expression point, whenever there is a norm.

Another disturbance of interest is the largest disturbance wrench that the grasp is able to withstand, in the direction of the wrench space for which this wrench is the smallest:

$$\min_{w \text{ direction}} \max_{\rho \text{ intensity}} \{\rho w \quad \text{s.t. } \rho w \in -GWS\}$$

This wrench is called the *largest-minimum* resisted disturbance wrench (Suárez, Roa, and Cornellà 2006, page 10). It is illustrated in figure 6.4 too. In contrast, the largest resisted disturbance wrench has the following definition:

$$\max_{w \text{ direction}} \max_{\rho \text{ intensity}} \{\rho w \quad \text{s.t. } \rho w \in -GWS\}$$



(a) Largest admissible disturbance

(b) Smallest admissible disturbance

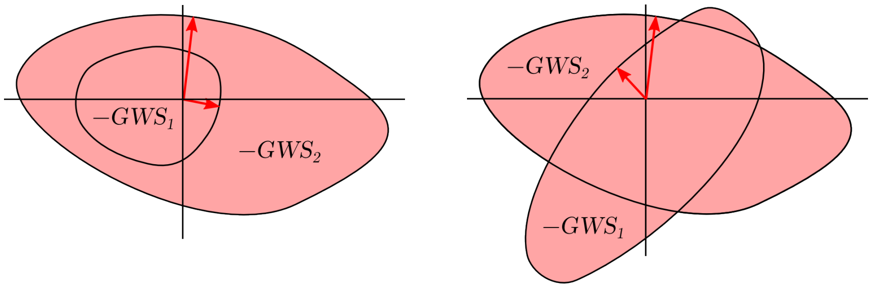
(c) Largest-minimum admissible disturbance

Figure 6.4 – Three particular disturbance wrenches

So the largest and largest-minimum admissible disturbance wrenches are respectively, by definition, upper and lower bounds on the grasp's maximal robustness, which is indicated by the boundary of the admissible disturbance wrench space. Consequently, a way to quantify the robustness of a grasp is to find those two particular wrenches.

Actually, one can argue that the largest-minimum resisted wrench is a better measure of the grasp's robustness than the largest resisted wrench. Indeed, the grasp is known to withstand *all* wrenches smaller than the largest-minimum resisted wrench, irrespective of the direction, whereas nothing very useful concerning the robustness in other directions can be infered from the largest resisted wrench. In other words, let $W_{dist}$ denote some disturbance: if we know for certain that $W_{dist}$ is smaller than the largest-minimum admissible disturbance wrench, then we can conclude that it is admissible too; whereas if we only know that $W_{dist}$ is smaller than the largest admissible disturbance wrench, we have not enough information to conclude whether or not it is admissible.

So, the largest-minimum admissible disturbance wrench qualifies as a valid, physically-founded way to quantify the robustness of a grasp. Or in other words: indicate the size of the admissible disturbance wrench space. Or in other words again: assess the quality of a grasp. It is actually a better way to measure the quality of a grasp, and compare two different grasps, than the inclusion of grasp wrench spaces illustrated in figure 6.2, because it does not leave out the equivocal case of one grasp wrench space being not totally included in the other [7]. Figure 6.5 illustrates how the grasps of figure 6.2 compare in the sense of the quality measure of the largest-minimum admissible disturbance wrench (also called *criteria of the residual ball* and *criteria of the largest ball*, see section 6.1.2).




(a) The second grasp is better than the first one.

(b) Here again, the second grasp is better than the first one.

Figure 6.5 – Comparison of grasps by their largest-minimum resisted disturbance wrenches

A last remark about the largest and largest-minimum resisted wrenches is that in addition to their intensities quantifying (bounding) the grasp's maximal robustness, they indicate, respectively, the "best" and "worst" directions of the wrench space for a disturbance to happen. Disturbances that happen in the "best" direction are the most likely to be resisted by the grasp, whereas disturbances that happen in the "worst" direction are the least likely to be resisted.

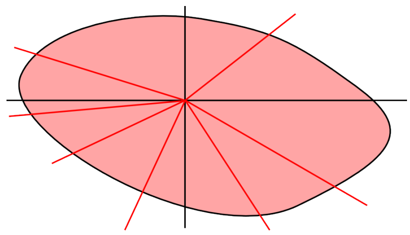
More generally now, any wrench on the boundary of the admissible disturbance wrench space is a measure of the grasp's maximal robustness, because it indicates the largest wrench that the grasp can resist in that particular direction. So, a complete description of the grasp's maximal robustness should include not only the largest and largest-minimum resisted wrenches, but also all the other wrenches on the boundary of the admissible disturbance wrench space.

The complete description of this boundary may not be easy to do: in the general case, the admissible disturbance wrench space is not straightforward to describe and not light to compute. Thankfully, in practical applications, it may not be necessary to have such a detailled knowledge of the grasp's maximal robustness. For instance, if the manipulation task only requires robustness to disturbances in such and such directions of the wrench space, then it is unnecessary to investigate the grasp's robustness elsewhere. Also, depending on the situation, we may consider to have a sufficient knowledge of the grasp's maximal robustness, if we are able to quantify it in a sufficient number of directions. The convexity of the admissible disturbance wrench space then helps a lot: from the known resisted disturbance wrenches on the boundary, we get immediately a polytope included in the admissible disturbance wrench space. This polytope is an approximation of the whole space, and therefore an approximation of the robustness in all the directions of the wrench space, and it is much easier to describe than the original exact convex form.

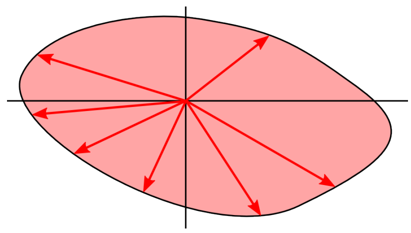
7. Thanks to $\leq$ being a total order on the set of real numbers, whereas $\subset$ is not a total order on the set of all subsets of the wrench space.

This idea of investigating the robustness in certain directions of the wrench space only is the basis of several methods for finding approximations of things that are difficult to find exactly: the largest and/or largest-minimum resisted disturbance wrenches, as well as the whole admissible disturbance wrench space. The approximated values we can find with these methods enable us to quantify the maximal robustness of a grasp, approximately and relatively to a set of disturbance directions indeed, but with moderately complex algorithms at least.

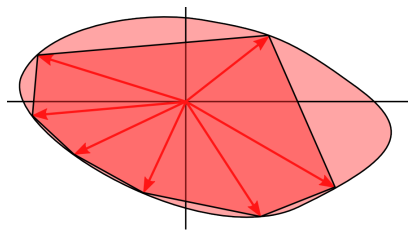
We present two of these methods in figures 6.6 and 6.7, because they are much easier to explain with pictures. The second one is the idea behind a grasp quality measure proposed by Zhu, Ding, and J. Wang (2003), a variation of the method of the largest ball (see section 6.1.2). However, the actual computation of this quality measure, as proposed by these authors, relies more on the approach of the figure 6.6. As for us, our approach to robustness and to tightening determination is more like figure 6.7.



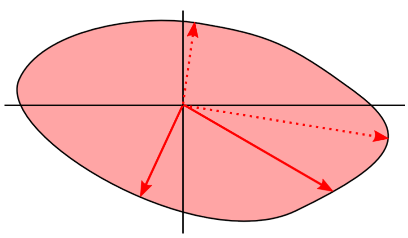
Step 1: we choose directions in the wrench space, possibly according to the task. We will study the grasp's maximal robustness along these directions.



Step 2: we calculate the largest resisted wrench along each of these directions (not necessarily easy).



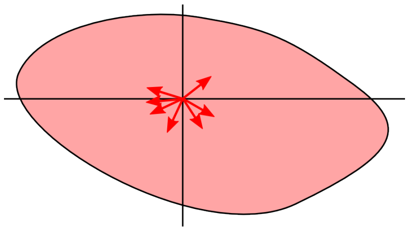
Step 3: the resulting polytope is an approximation of the admissible disturbance wrench space.



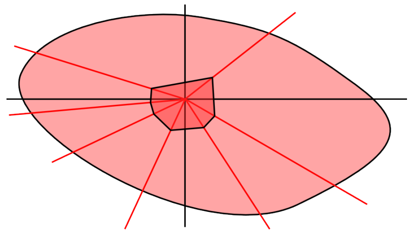
Of course, we don't necessarily get good approximations of the largest and largest-minimum resisted disturbance wrenches! The dotted wrenches are their exact values, the plain ones are the values we get. We see that there may be differences in their intensities and/or directions.

But what is important is that we find the largest and largest-minimum resisted disturbance wrenches for our chosen set of directions: by choosing relevant directions for our manipulation problem, we can find relevant largest and largest-minimum resisted disturbance wrenches.

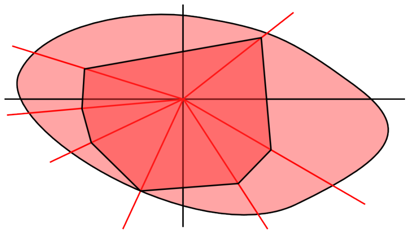
Figure 6.6 – How to describe the maximal robustness of a grasp without calculating the whole boundary of the admissible disturbance wrench space: a first approximation method



Step 1: we choose unit wrenches in the wrench space, possibly according to the task since they indicate directions. We will study the grasp's maximal robustness along these directions.

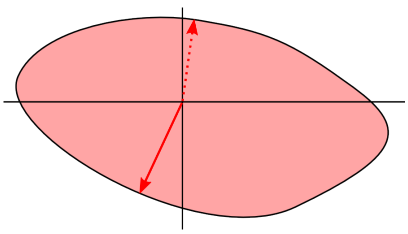


Step 2: the unit wrenches don't only indicate disturbance directions, but also a unit disturbance polytope.



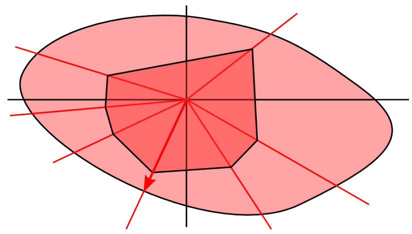
Step 3: we make this polytope grow until it touches the boundary of the admissible disturbance wrench space (not necessarily easy). The resulting polytope is an approximation of the admissible disturbance wrench space.

In comparison with the method explained in figure 6.6, this method is somehow more efficient, because it involves only one calculation (the maximization of the polytope), whereas the other method requires one calculation per disturbance direction (in step 2). On the other hand, the approximation of the admissible disturbance wrench space is worse, since the polytope stops growing when the first vertex touches the boundary.



The point where the polytope touches the boundary of the admissible disturbance wrench space is the largest-minimum resisted disturbance wrench for the chosen set of directions. The method does not return the largest resisted wrench (for the chosen set of directions, again), but it doesn't matter much because as we explained previously, the largest-minimum one is a better measure of grasp robustness than the largest one.

Figure 6.7 – How to describe the maximal robustness of a grasp without calculating the whole boundary of the admissible disturbance wrench space: a second approximation method



The approximation method explained in figure 6.7 has made it possible to describe the grasp's maximal robustness by computing the largest-minimum admissible disturbance wrench for a chosen set of disturbance directions.

To describe a lesser robustness, we scale down the polytope of resisted disturbances used in this method by a desired ratio. For instance, the smaller polytope illustrated here describes a robustness of about 75% of the maximal robustness, for the chosen set of disturbance directions.

Figure 6.8 – How to describe a lesser robustness than the maximal robustness of a grasp, once this maximal robustness has been identified: an addendum to the second approximation method

Once we have found (an approximation of) the maximal robustness thanks to these methods, it is easy to describe a lesser robustness, by scaling down the polytope. Figure 6.8 illustrates this last step; in fact, it illustrates exactly how we specify a robustness objective for our research of tightening contact forces. As mentioned in the introduction of this chapter, this objective is specified in two parts:

**Some directions in the wrench space** They indicate along which directions the grasp is desired to withstand the disturbances that might happen.

**A percentage of a sort of maximal robustness** Namely, a percentage of the magnitude of the largest-minimum admissible disturbance wrench.

To conclude this introductory section 6.1.1, we sum up the outline of our approach to the problem of tightening determination:

1. We want the grasp to tighten the object according to a certain robustness objective. This robustness objective is expressed in terms of disturbances to withstand, coming from certain directions, and having intensity up to a fraction of the largest-minimum admissible disturbance wrench.

   So at the beginning of the problem we know:

   a) Information about the grasp: the grasp configuration and the bounded contact cones.

   b) Information about the object: its equations of motion.

   c) Information about the desired robustness: some directions in the wrench space and a percentage.

   And we look for contact forces.

2. The first thing to do is to calculate the largest-minimum admissible disturbance wrench for the chosen directions, in order to complete the characterization of the desired robustness [8]. This is done with a method based on the approach of figure 6.7: we maximize the polytope defined by unit disturbances along the chosen disturbance directions.

   Our method is only "based on" the approach of figure 6.7, insofar as it does not exactly return the maximal robustness, but an approximation of it, plus appropriate tightening and opposing forces. More precisely, we find:

8. Because we have the percentage of the maximal robustness, but not the maximal robustness itself. . .

a) A lower-bound approximation of the largest-minimum admissible disturbance wrench for the chosen directions [9]. Although it is an approximation, it still quantifies the grasp robustness, i.e. it is a grasp quality measure, and an approximation of the one by Zhu, Ding, and J. Wang (2003).

b) Contact forces associated with this approximated maximal robustness. When looking for them, we take care to distinguishing between tightening forces and opposing forces, see figure 6.1. Also, we mimimize the variations between tightening forces and opposing forces, as explained at the beginning of this section.

The tightening forces and the approximation of the largest-minimum admissible disturbance wrench are found by solving one optimization problem, a linear programming problem, in section 6.3.1 (equations 6.18 to 6.23). The minimal variations are found by solving as many quadratic programming problems as disturbance directions, but very simple ones, without inequality constraints: see section 6.3.1 again (equations 6.16 and 6.17). So, although we are not very much interested in the opposing forces, we can find them from the tightening forces and the minimal variations.

Conclusion: at the end of this first step, we have quantified the maximal robustness of the grasp (in the chosen directions) and found tightening forces suited to this maximal robustness.

3. The second step is to find tightening forces for the lesser robustness defined by the chosen percentage of the maximal robustness, as in figure 6.8. We do this by re-solving the linear programming problem that enabled us to compute the maximal robustness and associated tightening forces, but we change a couple of things:

a) The maximal robustness is no longer an unknown, so we use the desired scaling of the polytope instead of looking for its maximal scaling.

b) The tightening forces are the only unknowns, so we change the objective function so that it is about them only.

We obtain a quadratic programming problem whose solution is the minimal tightening forces suited to the lesser robustness: see section 6.3.2 (equation 6.24).

Conclusion: at the end of the second step, we have found tightening forces for the desired robustness. We can use them as desired contact forces in any control scheme of dextrous manipulation, as explained in section 6.3.3.

### 6.1.2 Related work and contribution

The problem we investigate is closely related to what is known as the force optimization problem, and to the problem of measuring the quality of a grasp, but it is different from them, so in this section we briefly review these two problems and the differences with our tightening problem.

9. Yes, the largest-minimum admissible disturbance wrench for the chosen directions is itself an upper-bound approximation of the actual largest-minimum admissible disturbance wrench (for all directions), see figure 6.7. So what we find is a lower-bound approximation of an upper-bound approximation. At least the errors add up with opposite signs.

### Force optimization problem

The force optimization problem is the problem of finding optimal contact forces against some known external wrench applied on the grasped object: for instance its weight or some other loading wrench. For this problem, optimality often means minimality, although not always; when it does, the force optimization problem is finally finding the smallest contact forces that cancel a given external load, in other words the smallest opposing forces (figure 6.1).

The force optimization problem has been extensively studied, and solved by a variety of techniques. All of them employ some sort of mathematical optimization, since the goal is to find contact forces that are optimal in some sense. For instance, early works to solve this problem were based on linear programming formulations, with linearized friction constraints (i.e. discretized contact cones, see section 5.1.4 in chapter 5). A typical example of this approach is found in a well-known paper by Kerr and Roth (1986) about internal force determination. In this work, static equilibrium against the external wrench forms the linear equality constraints, contact cones are linearized using four-sided pyramids, joint torque limits yield linear inequality constraints on the contact forces, and in the end internal forces are chosen by solving a linear programming problem such that the contact forces are as far as possible from violating any friction or joint torque limit constraint [10]. So the opposing contact forces found using this method are optimal in the sense of maximizing the distance to the optimization constraints, not optimal in the sense of minimality of their intensities.

Another notable linear programming approach to the force optimization problem is the "compact-dual" linear programming method of F.-T. Cheng and Orin (1989, 1990). Acknowledging that solving the force optimization problem using the simplex algorithm was, at that time, "very computationally intensive", F.-T. Cheng and Orin proceeded to reduce its size by obtaining the general solution of the linear equality constraints (which are the force balance equations), in order to eliminate them from the problem. Interestingly enough, they solve these linear equality constraints by transforming the underdetermined matrix into row-reduced echelon form, not by the traditional method of the pseudo-inverse solution and kernel of the grasp matrix [11]. Either way, the resulting "reduced" problem is smaller in size; besides, a linear programming problem without equality constraints can be solved more efficiently than one with equality constraints. In order to further reduce the size and improve the computational efficiency, F.-T. Cheng and Orin applied the duality theory of linear programming before the final step of solving the linear programming problem (in that case, using the simplex algorithm on the resulting dual problem). In this last step, their optimization criteria is the minimization of the sum of the magnitudes of the normal components of the contact forces (F.-T. Cheng and Orin 1990, equations 59 and 60).

The method proposed by Y.-H. Liu and M. Wang (Y.-H. Liu and M. Wang 1998; Y.-H. Liu 1999) makes use of linear programming too, but results from a very different approach of computational geometry. In short, using a decomposition of the contact forces along the edges of the discretized contact cones rather than along the vectors of the contact frames, they demonstrate that the problem of minimizing the $L_1$

10. We give a little more detail about the approach of Kerr and Roth (1986) in section 5.2.3 of chapter 5, when discussing internal force determination for hybrid force/position control of multifingered hands.

11. See section 5.2.3 of chapter 5 for more about this method.

norm of the contact forces balancing a given external wrench can be transfered to a ray-shooting problem in the wrench space (detecting the intersection between a line and a set). This problem is well-known in computational geometry to be dual to a linear programming problem with inequality constraints only, thus efficiently solved. The resulting contact forces have minimal $L_1$ norm, which does not mean that they have minimal $L_2$ norm too, but at least these norms are related by a double inequality since all norms on a finite-dimensional real vector space are equivalent: in the case of contact forces $f_1, \ldots, f_{n_c}$ in $\mathbb{R}^3$, the column vector of the contact forces $f$ is in $\mathbb{R}^{3n_c}$ and therefore $\frac{1}{\sqrt{3n_c}} \|f\|_1 \leq \|f\|_2 \leq \|f\|_1$. In less mathematical terms, one can say that the smaller the $L_1$ norm is, the smaller the contact forces are, and so the less power is used by the actuators.

More recently, Gazeau, Zeghloul, and Ramirez (2005) and Saut, Remond, Perdereau, and Drouin (2005) proposed methods based on quadratic programming: the force optimization problem is formulated as a quadratic programming problem under inequality constraints only, because the equality constraints, which are the force balance equations, are "eliminated" from the problem by solving them with the traditional method of the pseudo-inverse solution and kernel of the grasp matrix (they don't really disappear of course: their solution triggers a change of variable from the contact forces to the internal forces in the objective function and inequality constraints, i.e. they are integrated in these equations). Using quadratic programming to search for optimal contact forces has a straightforward physical interpretation, contrary to linear programming, because the relation with the $L_2$ norm is immediate. For instance, if the optimization criteria is an unweighted $\min_f(f^T f)$ as in the study of Saut, Remond, Perdereau, and Drouin (2005), the optimal contact forces are those of minimal euclidian norms: $f^T f = \|f\|_2^2 = \|f_1\|_2^2 + \cdots + \|f_{n_c}\|_2^2$.

In the late 1990s, exact formulations of the force optimization problem were obtained by several researchers by expressing the problem as a convex optimization problem involving matrix inequalities. "Exact" means that the friction constraints are not linearized, and therefore non-linear programming methods have to be used to solve these problems (mainly quadratically constrained quadratic programming, second-order cone programming and more generally semi-definite programming).

An important study relevant to this approach is the work conducted by Buss, H. Hashimoto, and J. Moore (1995, 1996), based on the observation that the friction constraints and force balancing constraints are equivalent to the positive-definiteness of a certain symmetric matrix subject to linear constraints. This observation made it possible for the authors to formulate the force optimization problem as a convex optimization problem on a smooth manifold of linearly constrained positive-definite matrices. For this kind of problems, gradient flow methods are known to provide globally exponentially convergent solutions. Buss, H. Hashimoto, and J. Moore proposed an interior-point gradient flow method using a barrier function to constrain the gradient flow to the smooth manifold of interest. They also developed discrete-time versions of this method for numerical implementation (Buss, H. Hashimoto, and J. Moore 1995, 1996; Buss, Faybusovich, and J. Moore 1997, 1998).

Their study was a breakthrough in the field of grasp force optimization, because the few non-linear programming methods that had been previously proposed were considered unsuitable to real-time applicability with then-available computing resources. In fact, even linear programming methods were mostly off-line at that time. In comparison, the discretized gradient flow methods of Buss, H. Hashimoto, and

J. Moore (1995, 1996) were a huge improvement, proving even faster in an experiment than the compact-dual linear programming method of F.-T. Cheng and Orin (1989, 1990), yet at the top of computational efficiency. The performance of these methods further improved with refinements brought by Z. Li, Qin, Jiang, and Han (1998), who splitted the computation into an off-line component and an on-line component, and explored block matrix inversion techniques with sparse matrices. With these improvements, the computation time for a simple two-fingered manipulation with rolling contacts was reduced to a value small enough to consider the possibility of using these algorithms in control structures, where they would compute the desired contact forces to balance the external load applied on the object. Real-time capability for resolution of the force optimization problem is indeed very important in the case of time-varying contacts such as rolling contacts, because the change in the grasp configuration makes it necessary to refresh the contact force objective very often in order to keep cancelling the external load; also, if the load itself changes with time, in orientation or magnitude, fast refresh of the contact force objective is necessary. Therefore, the time required to solve a force optimization problem must be close to, and ideally less than the time step of the control loop [12].

By analyzing the structure of the symmetric positive-definite matrices arising from the friction constraints in the formulation of Buss, H. Hashimoto, and J. Moore (1995, 1996), Han, Trinkle, and Z. Li (1999, 2000) found out that these friction constraints could be further casted into linear matrix inequalities [13], and that the grasping force optimization problem could be formulated as a convex optimization problem involving linear matrix inequalities. These latter problems had been recently extensively studied by researchers in mathematical optimization and control theory, and very efficient interior-point methods with polynomial time complexity had been made available in the early 1990s. G. Liu and Z. Li (2004) pointed out that the only major downside of all these approaches (Buss, H. Hashimoto, and J. Moore 1996; Z. Li, Qin, Jiang, and Han 1998; Han, Trinkle, and Z. Li 2000) is that the recursive optimization algorithms need an initial condition satisfying both the friction constraints and the force balance equation; they cannot start anywhere in the space of the optimization variable. Methods for finding these valid initial forces for general grasps are given by Han, Trinkle, and Z. Li (2000) and G. Liu and Z. Li (2004).

Last but not least in the field of grasp force optimization, Boyd and Wegbreit, as well as, independently, Cornellà, Suárez, Carloni, and Melchiorri, proposed recently approaches based on the duality theory of non-linear programming. The study of Cornellà, Suárez, Carloni, and Melchiorri (2006, 2008) deals with a very classic quadratic formulation of the force optimization problem: the minimization of the $L_2$ norm of the internal force, constrained by the linear inequalities coming from the linearized friction cone constraints, and no equality constraints (the external force

12. Boyd and Wegbreit (2007) note that nowadays, "a typical force optimization problem, with five contact points and one external wrench, can be solved in well under a second, on the order of 100 ms on a current typical desktop computer", with general-purpose optimization solvers. This may still not be fast enough, especially with less powerful embedded control systems and non quasi-static manipulations. Thankfully, custom algorithms designed specifically for the force optimization problem, such as those by Buss, Faybusovich, and J. Moore (1998) and particularly Boyd and Wegbreit (2007), can be much faster.

13. In convex optimization, linear matrix inequalities are equations of the form $\mathrm{LMI}(y) = A_0 + y_1 A_1 + \cdots + y_m A_m \geq 0$, where $y = (y_1, \ldots, y_m) \in \mathbb{R}^m$ is the variable, $A_0, A_1, \ldots, A_m \in \mathbb{R}^{m \times m}$ are symmetric matrices, and $\geq 0$ means "is a positive semi-definite matrix". Strict linear matrix inequalities have $> 0$ in place of $\geq 0$, meaning "is a positive-definite matrix".

balance equations are classically eliminated by solving them with pseudo-inversion and the kernel of the grasp matrix). The resulting quadratic programming problem is then solved with very general concepts of non-linear programming: Karush, Kuhn, and Tucker optimality conditions, dual theorem of non-linear programming, and gradient flow with optimal step size.

In contrast, Boyd and Wegbreit (2007, 2008) work on the exact formulation of the force optimization problem, with convex inequality constraints for the contact cones and linear equality constraints for the equilibrium against the external wrench. The optimality of the solution is measured by the maximum magnitude of the contact forces, that is to say, the optimization criteria is to minimize the following objective function: $\max\{\|f_1\|, \ldots, \|f_{n_c}\|\}$. The resolution method is based on non-linear dual programming too, but with a custom interior-point algorithm "exploiting special structure in the force optimization problem to compute the search direction in each iteration". It has "a complexity that is linear in the number of contact forces, whereas methods based on generic semi-definite programming or second-order cone programming have a complexity that is cubic in the number of contact forces". But it is also much faster, even for small problems: for a typical grasping problem with five contact points, it solves the force optimization problem in around 400 µs, on a 3 GHz single-core desktop central processing unit, "with a not particularly optimized C++ implementation". That is, "many hundreds of times faster than generic semi-definite programming or second-order cone programming solvers". Thanks to this huge efficiency, the method of Boyd and Wegbreit is a perfect candidate in situations where many related force optimization problems must be solved: manipulation with time-varying contacts, as explained before, but also certain grasp analysis and grasp planning problems such as "choosing contact points on an object so as to minimize the required contact forces" holding the object in equilibrium (a problem known as grasp synthesis). As a matter of fact, Boyd and Wegbreit even propose "methods for obtaining even more efficiency when solving a family of related force optimization problems".

#### Grasp quality measures

Like the optimization of contact forces, the assessment of grasp quality is a classical problem in multifingered grasping and manipulation. As a matter of fact, it was one of the first issues to be investigated in the history of multifingered grasping, starting in the late 1970s and early 1980s, that is to say at the same time as the first robot hands. At that time, studies on grasp quality focused especially on restrain analysis, using the century-old notions of form closure and force closure, traditionally used in mechanical engineering for the analysis and design of mechanisms of all sorts. Let's remind that when applied to multifingered hands, form closure means that the grasp geometry ensures the total restrain of the object, whereas force closure means that contact forces ensure the equilibrium of the object against any external wrench. By "grasp", these notions only mean the position of the contact points and contact normals on the object (the hand is not taken into account), and as for the "contact forces", they are limited by the friction cone constraints but can be as large as desired (which makes force close grasps theoretical descriptions rather than physical realities). Classical references about these concepts include the works of Reuleaux (1875), Somov (1897, 1900), Lakshminarayana (1978), Dizioğlu and Lakshminarayana (1984), Mishra, J. Schwartz, and Sharir (1986, 1987), Markenscoff, Ni, and Papadimitriou (1990) on form closure, and Reuleaux (1875), Nguyen (1985a, 1986c,a,b, 1987a, 1988) on force closure.

Since they indicate whether the in-hand object is totally restrained, form closure and force closure are *qualitative* measures of grasp quality: a grasp is form close or not, it is force close or not. Later in the 1980s, and during the following decades, various *quantitative* measures of grasp quality were developped by roboticists in order to assess how good a grasp is, compare grasps to decide which one should be preferred because it is better, and determine the optimal location of the contact points on an object, in the sense that it maximizes some quality measure (this is grasp synthesis, a problem of grasp planning). As a result, there is now a wide repertoire of grasp quality measures, or grasp metrics as they are sometimes called, and research in this field keeps going (Y. Zheng and Qian 2008). Most of them are related to the position of the contact points on the object, and possibly to the contact forces. For instance, the volume of the polytope whose vertices are the contact points is a possible quality measure (it indicates the span of the grasp), and so are the distance between the centroid of that polytope and the center of mass of the object (it indicates how well-centered the object is in the grasp), or the smallest singular value of the grasp matrix (it indicates the distance to singular configurations), or the largest-minimum admissible external wrench, introduced in section 6.1.1 (it indicates the capability of the grasp to equilibrate the worst-case external wrench, see figure 6.5). There are also a couple of grasp quality measures related to the hand configuration, such as the smallest singular value of the hand jacobian (it indicates the distance to singular configurations) or the deviation of the articular coordinates from their middle-range values (it indicates the proximity to the physical limits of the joints). For more information, Suárez, Roa, and Cornellà have recently reviewed these numerous quality measures and their mathematical properties, in a survey that is worth reading (Suárez, Roa, and Cornellà 2006; Roa, Suárez, and Cornellà 2008).

The most common, well-known, and popular grasp quality measure is probably the criteria of the residual ball, or criteria of the largest ball. It was introduced by Kirkpatrick, Mishra, and Yap (1990, 1992) and by Ferrari and Canny (1992), and then further discussed by Mishra and Teichmann (Mishra 1995; Teichmann 1996; Teichmann and Mishra 1997). It has been used in several works, often about grasp analysis and grasp planning, and it still keeps being used today (Roa and Suárez 2009), or analyzed (Y. Zheng and Qian 2009). In short, the criteria of the residual ball measures the magnitude of the largest-minimum resisted external wrench, introduced in section 6.1.1, so in a certain sense it measures the size of the grasp wrench space (see figures 6.2 and 6.5). Let's remind here that the grasp wrench space is the set of all the possible resultant wrenches produced by the fingers on the object, the magnitude of the contact forces being somehow limited. For instance, with $G$ being the grasp matrix, $f$ the vector of the contact forces $f_1, \dots, f_{n_c}$, and each contact force being limited in norm:

$$GWS = \{G\,f,\ f_i \text{ contact force and } \|f_i\| \leq f_{i,max},\ \forall\, i \in [|1, n_c|]\}$$

Given that, the criteria of the residual ball states that the quality of the grasp is the residual radius of the grasp wrench space, that is to say, the radius of the largest origin-centered $L_2$ ball [14] of the wrench space $se_3^*(\mathbb{R})$ that is fully contained in $GWS$:

$$\text{ball of radius } r \text{ centered on } 0_{6,1}\text{: } B(r) = \{W \in se_3^*(\mathbb{R}),\ \|W\| \leq r\}$$

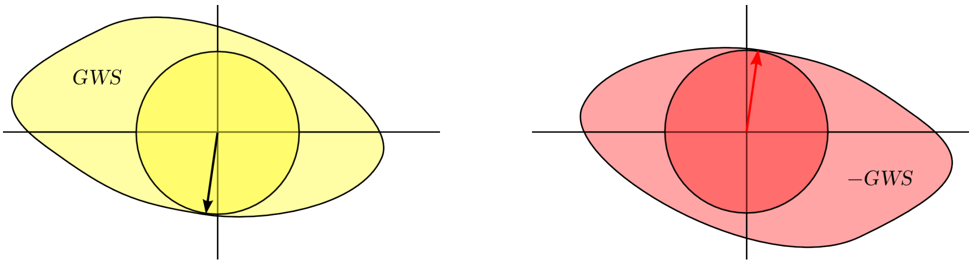
$$\text{grasp quality measure: } \max\{r \ \text{ s.t. } B(r) \subset GWS\}$$

14. See the remark in section 6.1.1 about the difficulty of defining a norm on the wrench space.

By definition, the residual ball "touches" the boundary of $GWS$ where it is the closest to the origin $0_{6,1}$, see figure 6.9(a). That is to say, it gives an indication of the size of $GWS$ by pointing out the largest produced wrench in the direction of the wrench space for which this wrench is the smallest:

$$\min_{w \text{ direction}} \max_{\rho \text{ intensity}} \{\rho w \ \text{ s.t. } \rho w \in GWS\}$$

This particular wrench is called the *largest-minimum* wrench that the grasp can produce on the object. It is the opposite of the largest-minimum admissible disturbance wrench, introduced in section 6.1.1: the largest wrench that the grasp can resist, in the direction of the wrench space for which this wrench is the smallest (the "worst" direction). Indeed, we remind that the set of wrenches that the grasp can resist is just the opposite of the set of wrenches that it can produce: $-GWS$, see figure 6.3 and 6.9(b).




(a) Residual radius of the grasp wrench space

(b) Residual radius of the admissible disturbance wrench space

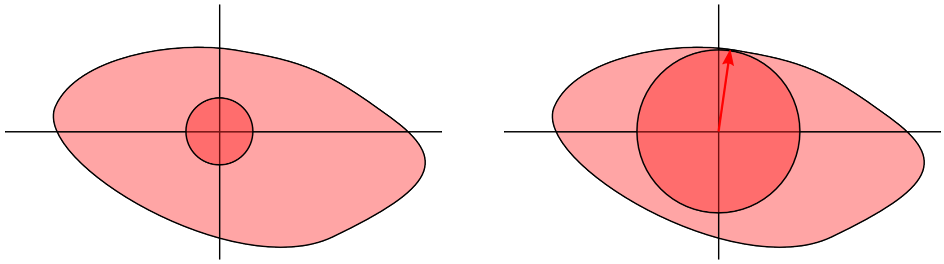
Figure 6.9 – A grasp quality measure, the criteria of the largest ball. It is the magnitude of the largest-minimum resisted external wrench.

Recently, the criteria of the largest ball was thoroughly investigated by Y. Zheng and Qian (2009), in a study based on an algebraic construction of the grasp wrench space from the exact, non-linearized bounded contact cones. Y. Zheng and Qian proved that the quality measure of the criteria of the largest ball was equal to the maximum, on the unit sphere of $\mathbb{R}^6$, of the minimum, on a certain discrete set, of a particular distance function from $\mathbb{R}^6$ into $\mathbb{R}$, which happens to be very easy to evaluate. So the calculation of this grasp quality measure appears as the maximization of a non-linear function over $\mathbb{R}^6$. This objective function is not differentiable, but it is at least Lipschitz continuous, and therefore differentiable almost everywhere [15], which is sufficient for practical usability of gradient-based algorithms. As a matter of fact, computing the quality measure of a grasp using this method happens to be surprisingly efficient, according to the authors: the number of operations involved in one iteration of a gradient descent is much smaller than if the friction cones were linearized.

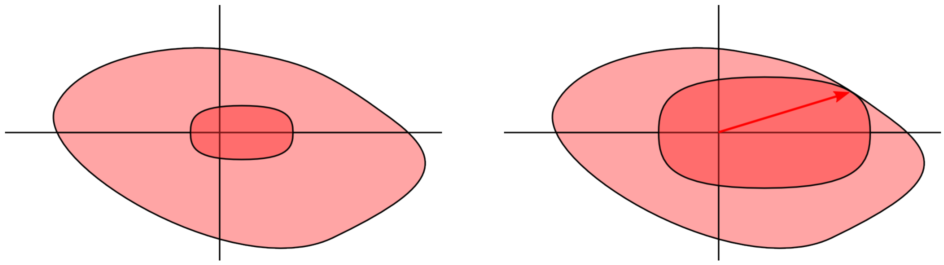
There are several variations of the criteria of the largest ball. One of them may be called the criteria of the largest convex set, or the criteria of the largest convex polytope. It was introduced in articles by Zhu, Ding, and H. Li (2001) and Zhu, Ding, and J. Wang (2003). As the name suggests, it uses a convex set of $se_3^*(\mathbb{R})$ (including the origin) instead of a ball, and in numerical implementation, it uses a

15. That is to say, the set of points of $\mathbb{R}^6$ at which the objective function is not differentiable is of Lebesgue measure zero.

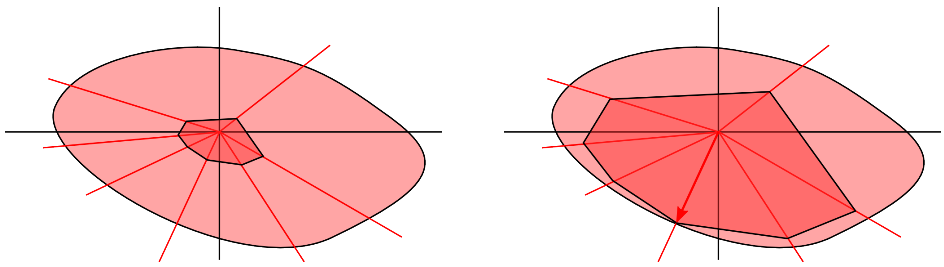
convex polytope. In both cases, the convex set represents expected disturbances, or at least disturbances the hand is supposed to resist. The quality index is defined as the largest scale factor that makes this set of expected disturbances fully contained in the admissible disturbance wrench space, $-GWS$. It measures the largest-minimum disturbance wrench that the grasp can resist in the directions indicated by the convex set, whereas a ball is isotropic. This quality measure is illustrated in figure 6.10.



(a) When the convex set is a ball, we get the criteria of the largest ball, and the scale factor is proportional to the magnitude of the largest-minimum resisted disturbance wrench.



(b) In the general case, when disturbances are considered in specific directions, the defined grasp quality measure is related to the largest-minimum resisted disturbance wrench "in the directions of interest".



(c) When a polytope is used, the grasp quality measure that is found is related to the largest-minimum resisted disturbance wrench in the directions indicated by the vertices.

Figure 6.10 – A variation of the criteria of the largest ball. The quality measure is the scale factor between the chosen convex set, on the left, and the maximal homothetic one, on the right.

Zhu, Ding, and J. Wang (2003) propose a simple method to compute this quality measure, in the case that a polytope is used. This method is actually along the lines of figure 6.6, even though the presentation in terms of scale factors and growing polytopes makes it look like figure 6.7 and 6.10 at first glance. In essence:

1. For each disturbance direction i.e. for each vertex, the largest resisted wrench is computed, by maximizing the scale factor along that direction.

2. The smallest of these maximal scale factors i.e. the smallest of the largest resisted wrenches is chosen as the quality measure. It indicates the largest-minimum resisted wrench in the considered directions.

So there are as many optimization problems as disturbance directions, which explains why using a generic convex set instead of a polytope is impractical. Let $\lambda$ denote a positive real number, $w_{dist}^1, \ldots, w_{dist}^{n_d}$ denote the vertices of the polytope (disturbances), and $f_1, \ldots, f_{n_c}$ denote contact forces. The optimization problem proposed by Zhu, Ding, and J. Wang is, for the vertex $w_{dist}^j$:

$$\max_{f_1,\ldots,f_{n_c},\lambda} (\lambda) \text{ subject to the constraints:}$$
$$\begin{cases} \text{static equilibrium: } \lambda\, w_{dist}^j = \displaystyle\sum_{i=1}^{n_c} f_i \\ \text{friction cone constraints} \\ \text{limited contact forces} \end{cases}$$

So for each vertex, the solution of the optimization problems yields the maximum scale factor in the vertex direction, $\lambda^{sol,j}$, the maximum resisted wrench, $\lambda^{sol,j}\, w_{dist}^j$, and opposing contact forces balancing this wrench, $f_1^{sol,j}, \ldots, f_{n_c}^{sol,j}$. Then, the grasp quality measure is simply: $\min\{\lambda^{sol,1}, \ldots, \lambda^{sol,n_d}\}$. Even though it is not obtained by scaling the polytope as a whole, but by scaling its vertices one after another, it still is the scale factor described in figure 6.10(c).

As an end remark, let us note that the objective function and the equality constraint being linear, the linearity of the maximization problems depends on the inequality constraints. Zhu, Ding, and J. Wang report that these constraints are linear when the contacts are frictionless, when the grasp is two-dimensional, or when the contact cones are linearized. In those three cases, the optimization problem is a linear programming problem.

### Contribution

From the description of the problem we are interested in, in section 6.1.1, and from the review of the related research, here in section 6.1.2, the things in common and the differences appear quite clearly.

In short, our approach has a look of both the classical problems of contact force optimization and grasp quality evaluation, because if borrows elements from both. But there are important differences:

**Relatively to the force optimization problem** We are looking for optimal contact forces too, but tightening forces, not opposing forces. The contact forces we want are not related to only one external wrench, known in magnitude and direction. They are related to a certain robustness against a set of perturbations of unknown intensity, and embody a notion of pre-strain that is not found in the force optimization problem.

As far as we know, this problem of optimal tightening determination had not been investigated in robotic dextrous manipulation before we became interested in it (Michalec and Micaelli 2009b); at least, not in the sense of contact forces in relation with an objective of robustness to disturbances.

**Relatively to the grasp quality measures** In the formulation of the robustness objective, the largest-minimum admissible disturbance wrench plays a pivotal role: it describes what we call the maximal robustness of the grasp. Our method requires the determination of its magnitude (more exactly an approximation). So we get a measure of the quality of the grasp, but contrary to traditional grasp quality evaluation, this was not the purpose: our goal remains the tightening contact forces, and the quality index is merely a by-product of the calculations.

Tightening is very valuable for a grasp to withstand a disturbance more easily, because it facilitates the role of friction in keeping hold of the object: the larger the normal component of a contact force, the more freedom there is in the magnitude of the tangential component, before the contact force lands on the surface of the contact cone. It also reflects what many physiologists have experimentally observed in human grasps: when the occurence of a disturbance can be foreseen, grip forces increase before it, not only after (e.g. Turrell, F.-X. Li, and Wing 1999).

From a control point of view, it is not worth computing opposing forces to a disturbance, nor setting them as desired contact forces. Only tightening forces are worth it. Indeed, opposing forces to a certain disturbance cannot even be computed by the control scheme, since a disturbance is by definition unknown. But even if it were possible, it would be pointless: by the time the disturbance is detected and somehow measured by the hand's sensors, and by the time the control algorithms have come up with opposing forces, the disturbance is likely over, and there isn't any force to oppose any longer. So the force optimization problem is relevant in cases where the external force is known, but it is of no use for disturbances, and tightening determination must be preferred.

Another interesting difference between our approach and the pre-existing research is the relative independence on the number of disturbance directions. When they compute their quality measure, Zhu, Ding, and J. Wang (2003) use $n_d$ optimization problems with a variable in $\mathbb{R}^{3n_c+1}$, $n_c$ being the number of contacts and $n_d$ the number of investigated disturbance directions. The way we compute the tightening forces associated to the maximal robustness is similar in essence to solving all the optimization problems of Zhu, Ding, and J. Wang at the same time: our mathematical formulation of the problem of tightening determination, in equations (6.14) and (6.15), is a linear programming problem with a variable in $\mathbb{R}^{3n_c(1+n_d)+1}$, which is quite large. To reduce the dimension of this problem, we pre-compute the force variations that turn the tightening forces into opposing forces, by solving an auxiliary optimization problem for each disturbance (6.16). It is there, by the way, that we ensure that these force variations are minimal, and therefore tightening is optimal. The resulting linear programming problem, in equations (6.18) to (6.23), has a variable in $\mathbb{R}^{3n_c+1}$. The dependence on the number of disturbances has disappeared in the resolution of the $n_d$ auxiliary problems, which happens to be very easy since the problems are quadratic programming problems without inequality constraints: the analytical expression of their solution is readily available (6.17). All this means that eventually, a large number of disturbance directions may be considered simultaneously without significant decrease in the computing efficiency.

Last but not least, our approach takes the dynamics of the object into account, whereas the force optimization problem is always considered at static equilibrium, and the quality measure of a grasp is also always evaluated at static equilibrium. We consider fully-fledged equations of motion instead of balancing equations, and can find tightening forces associated to a robustness objective and compatible with the motion of the object. This makes robust manipulation possible, not just robust grasping.

### 6.1.3 Notations and definitions

Now that we have described in detail our method and its physical interpretation (section 6.1.1), and that we have explained how it relates to grasp force optimization and grasp quality evaluation (section 6.1.2), we will translate it into mathematical terms (sections 6.2 and 6.3). To this aim, we introduce in this section the physical quantities and the notations that we use to study grasp robustness. Most of them have already been used to study manipulation control in the previous chapter, and some of them have been used informally in the previous two sections. We remind them here anyway, in order to make this chapter self-contained and well-defined, but this reminder is voluntarily kept limited in detail.

For more information, the reader is invited to refer to section 5.1 in chapter 5; it describes the modeling of dextrous manipulation much more thoroughly. Besides, in the present chapter, the hand itself is not considered in full, only its grasp is studied, that is to say, the contact frames and the contact forces. Therefore, in the section 5.1 of chapter 5, only the subsections on contact modeling and object modeling are relevant, not those on hand modeling: that is to say, mainly, the subsections 5.1.4 and 5.1.6.

#### Basic notations

We let $n_c \geq 2$ denote the number of contacts in the grasp and $i$ denote the index of a contact: $i \in [|1, n_c|]$ [16]. The different frames are illustrated on figure 6.11: *ref* is an inertial reference frame, *obj* is the frame of the object being manipulated, and $c_i$ denotes both the $i$-th contact point and the $i$-th contact frame $(t_i^1, t_i^2, n_i)$, with the vector $n_i$ outward and normal to the object's surface.

We remind that all these frames are direct orthonormal, that the object body frame *obj* is rigidly linked to the object and usually attached to its center of mass, and that it is not the case of the contact frames, which move with the contact points.

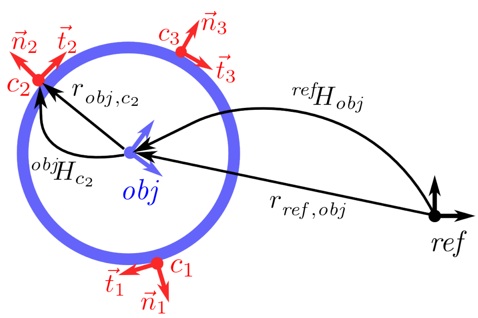



Figure 6.11 – Frames and rigid transformations

The modeling framework is still that of rigid body mechanics, like in chapter 5. Therefore, all the concepts, definitions and notations of chapter 4 apply: rigid transformations between frames, twists and wrenches, adjoint and co-adjoint matrices,

16. This notation is for an integer interval: $[|1, n|] = \{1, \ldots, n\}$.

and so on. We remind that homogeneous matrices represent rigid transformations, which locate frames relative to each other, for instance:

$$^{ref}H_{obj} = \begin{pmatrix} ^{ref}R_{obj} & r^{ref}_{ref,obj} \\ 0_{1,3} & 1 \end{pmatrix} \in SE_3(\mathbb{R})$$

locates the object relatively to *ref* through the rotation $^{ref}R_{obj} \in SO_3(\mathbb{R})$ between the bases of the frames and the translation $r^{ref}_{ref,obj} \in \mathbb{R}^3$ from the origin of *ref* to the origin of *obj*, this vector being written in *ref* coordinates.

### Contact modeling

Contacts between the fingers and the object are modeled as rigid point contacts with friction, and the friction model is, very classicaly, the Coulomb friction model. That is to say, only forces, no moments, can be transmitted between the fingers and the object at a contact point, and the tangential and normal components of a contact force, in the corresponding contact frame, are related by a conical constraint. For more about this contact model and this friction model, see section 5.1.4 in chapter 5.

The forces $f_1, \ldots, f_{n_c} \in \mathbb{R}^3$ applied by the fingers on the object are assumed written in their respective contact frames $c_1, \ldots, c_{n_c}$, in other words $f_i = f_i^{c_i}$, and we define $f$ the column vector of contact forces:

$$f = \begin{pmatrix} f_1 \\ \vdots \\ f_{n_c} \end{pmatrix}$$

By definition, contact forces are unilateral, from the finger to the object. Given the choice of an outward-pointing normal in the contact frames, the normal component of each contact force satisfies the following inequality:

$$f_{i,n} \leq 0 \qquad \forall\, i \in [|1, n_c|]$$

Also, the Coulomb friction conditions result in the following relationship between the tangential and normal components:

$$\|f_{i,t}\| \leq \mu \, \|f_{i,n}\| \qquad \forall\, i \in [|1, n_c|]$$

with $\mu$ the dry friction coefficient. This inequality constraint describes the Coulomb contact cone (figure 6.12). We remind that when the contact is sliding, this inequality is an equality, and that when it is not sliding, the inequality remains a "less than or equal to", it does not become a strict inequality. The treatment of robustness presented in this chapter does not need any assumption on the non-sliding of contacts.

It is well-known that the Coulomb friction constraints may be linearized by approximating the contact cone with a multi-faceted cone, as shown in figure 6.12. Besides, it so happens that the resulting linear equations also account for unilaterality. That is to say, we may find matrices $C$ and $d$ such that the friction and unilaterality constraints read:

$$Cf + d \leq 0_{n_c \times n_e, 1} \tag{6.1}$$

$C$ is $(n_c \times n_e, 3n_c)$ in size, $n_e$ being the number of edges in the cone discretization; $d$ is a vector with $n_c \times n_e$ lines. Their expressions are given in chapter 5, at the end of section 5.1.4.

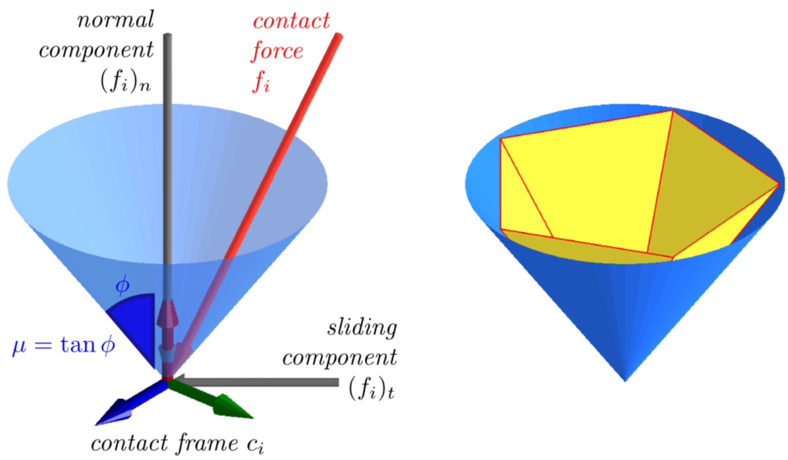



Figure 6.12 – A non-sliding contact, its exact contact cone, and a linearized contact cone

### Object dynamics and grasp matrix

We let $V_{obj}$ denote the absolute twist of the object and $W_{f\to obj}$ denote the net wrench applied on the object by the fingers, both written in the frame of the object:

$$V_{obj} = \begin{pmatrix} v_{obj} = v^{obj}_{obj/ref} \\ \omega_{obj} = \omega^{obj}_{obj/ref} \end{pmatrix} \qquad W_{f\to obj} = \begin{pmatrix} f_f = f^{obj}_{f\to obj} \\ m_f = m^{obj}_{f\to obj} \end{pmatrix}$$

$v_{obj}$ is the velocity of the origin of the frame $obj$ (usually the center of mass), $\omega_{obj}$ is the angular velocity of the object; both velocities are relative to the reference frame. $f_f$ is the net force applied by the fingers on the object, $m_f$ is the net moment applied by the fingers on the object, at the origin of the frame $obj$. All four quantities are written in the basis of the object frame.

We let $m_{obj}$ denote the mass of the object and $[I]_{obj}$ denote its inertia tensor, written in the object frame. Both quantities are arranged into the object's generalized mass matrix, written in the object frame as follows:

$$M_{obj} = \begin{pmatrix} m_{obj} I_3 & 0_{3,3} \\ 0_{3,3} & [I]_{obj} \end{pmatrix}$$

The object dynamics has been presented in the section 5.1.6 of chapter 5, it is:

$$M_{obj}\,(\dot{V}_{obj} - g) + N_{obj} V_{obj} = W_{f\to obj} \tag{6.2}$$

where $N_{obj}V_{obj}$ are the Coriolis and centrifugal forces, and all the quantities are written in object coordinates. In particular, the gravity wrench $M_{obj}\,g$ and the resultant wrench applied by the fingers are:

$$M_{obj}\,g = \begin{pmatrix} m_{obj} I_3 & 0_{3,3} \\ 0_{3,3} & [I]_{obj} \end{pmatrix} \begin{pmatrix} {}^{obj}R_{ref} \begin{pmatrix} 0 \\ 0 \\ -9.81 \end{pmatrix} \\ 0_{3,1} \end{pmatrix} = m_{obj}\,g \tag{6.3}$$

$$\begin{aligned} W_{f\to obj} = \sum_{i=1}^{n_c} W^{obj}_{f_i\to obj} &= \sum_{i=1}^{n_c} {}^{obj}Ad^{-T}_{c_i} W^{c_i}_{f_i\to obj} \\ &= \sum_{i=1}^{n_c} \begin{pmatrix} {}^{obj}R_{c_i} & 0_{3,3} \\ \hat{r}^{obj}_{obj,c_i}\,{}^{obj}R_{c_i} & {}^{obj}R_{c_i} \end{pmatrix} \begin{pmatrix} f_i \\ 0_{3,1} \end{pmatrix} \end{aligned} \tag{6.4}$$

where $W^{c_i}_{f_i \to obj} = \begin{pmatrix} f_i \\ 0_{3,1} \end{pmatrix}$ is the wrench applied at the contact $i$ and ${}^{obj}Ad^{-T}_{c_i}$ is the co-adjoint matrix of ${}^{obj}H_{c_i}$, with $\hat{}$ the operation that returns a skew-symmetric matrix for left-wise cross-product by the input vector: $\hat{r}u = r \times u$ (see sections 4.2.2 and 4.A in chapter 4). In the end, we get for the resultant wrench:

$$\begin{aligned} W_{f \to obj} &= \begin{pmatrix} {}^{obj}R_{c_1} & \dots & {}^{obj}R_{c_{n_c}} \\ \hat{r}^{obj}_{obj,c_1} \, {}^{obj}R_{c_1} & \dots & \hat{r}^{obj}_{obj,c_{n_c}} \, {}^{obj}R_{c_{n_c}} \end{pmatrix} \begin{pmatrix} f_1 \\ \vdots \\ f_{n_c} \end{pmatrix} \\ &\stackrel{\text{def}}{=} G\, f \end{aligned} \tag{6.5}$$

The matrix $G$ is called the *grasp matrix* of the grip; more information about it is given in chapter 5, section 5.1.6.

#### Disturbances

When a disturbing wrench is applied on the object, the equations of motion (6.2) feature an additional wrench, next to the contact wrench in the right-hand side:

$$M_{obj}\,(\dot{V}_{obj} - g) + N_{obj} V_{obj} = W_{f \to obj} + W_{dist}$$

We let $W_{dist} \in se^*_3(\mathbb{R})$ denote a disturbance on the object, written in the object frame $obj$, and $W^1_{dist}, \dots, W^{n_d}_{dist} \in se^*_3(\mathbb{R})$ denote a set of such disturbances, that may happen and that we want the grasp to be able to withstand. We remind that the wrench space $se^*_3(\mathbb{R})$ is the dual space of the twist space $se_3(\mathbb{R})$, hence the notation. $j$ denotes the index of a disturbance: $j \in [|1, n_d|]$.

## 6.2 Grasp robustness to expected disturbance wrenches

In this section, we consider the preliminary problem of robustness to a set of expected disturbance wrenches, that is to say, we suppose that the disturbances are known in direction and magnitude. It is a preparatory study to the problem of robustness to a set of expected disturbance directions, that will be investigated in the next section. In other words, here the robustness objective is a given polytope in wrench space, whereas in the next section it will be directions in wrench space and a fraction of the maximal robustness.

Under this assumption, we write in section 6.2.1 the equations of the problem of tightening determination, and some remarks about them. Then we describe the linearization of this problem in section 6.2.2, and how to get optimal tightening forces (not just random tightening forces) in section 6.2.3.

### 6.2.1 Statement of the problem of grasp robustness

Let $W^1_{dist}, \dots, W^{n_d}_{dist} \in se^*_3(\mathbb{R})$ be the expected disturbances wrenches, $n_d \geq 1$. They are liable to happen and be applied on the object. We would like the grasp to withstand them with opposing contact forces resulting from deviations of tightening contact forces; i.e. one set of opposing forces per disturbance and one set of tightening forces for all the disturbances.

To this aim, we define the problem of grasp robustness to the expected disturbances as follows: find forces $f^1_0, \dots, f^{n_c}_0 \in \mathbb{R}^3$ such that, at the current time:

1. In the absence of any disturbance:
   - The forces $f_0^1, \dots, f_0^{n_c}$ are contact forces, that is to say they are unilateral and respect the friction limit constraints.
   - Their intensities remain below a certain admissible threshold.
   - The object's equations of motion, with these contact forces, are satisfied:

$$M_{obj}\,(\dot{V}_{obj} - g) + N_{obj} V_{obj} = W_{f_0 \to obj} \tag{6.6}$$

2. $\forall\, j \in [|1, n_d|]$, $\exists\, \delta f_j^1, \dots, \delta f_j^{n_c} \in \mathbb{R}^3$ such that, if we suppose that the object is subject to the disturbance $W_{dist}^j$:
   - The forces $f_0^1 + \delta f_j^1, \dots, f_0^{n_c} + \delta f_j^{n_c}$ are contact forces too, that is to say they are unilateral and respect the friction limit constraints.
   - Their intensities remain below the same admissible threshold.
   - The object's equations of motion are still satisfied, but with these new contact forces and the disturbance $W_{dist}^j$:

$$M_{obj}\,(\dot{V}_{obj} - g) + N_{obj} V_{obj} = W_{(f_0 + \delta f_j) \to obj} + W_{dist}^j \tag{6.7}$$

By doing so, we make sure that the grasp just has to apply the force variations $\delta f_j^1, \dots, \delta f_j^{n_c}$ to the contact forces $f_0^1, \dots, f_0^{n_c}$ in order to withstand the disturbance $W_{dist}^j$, if this disturbance really happens. This makes the grasp able to withstand all the expected disturbances $W_{dist}^1, \dots, W_{dist}^{n_d}$ from a common tightening. We say it is robust to these disturbances.

In the rest of this chapter, $f_0$ and $\delta f_j$ denote the column vectors of the corresponding forces:

$$f_0 = \begin{pmatrix} f_0^1 \\ \vdots \\ f_0^{n_c} \end{pmatrix} \in \mathbb{R}^{3n_c} \qquad\qquad \delta f_j = \begin{pmatrix} \delta f_j^1 \\ \vdots \\ \delta f_j^{n_c} \end{pmatrix} \in \mathbb{R}^{3n_c} \quad \forall\, j \in [|1, n_d|]$$

Of course, these forces are supposed written in their respective contact frames. With $G$ the grasp matrix:

$$W_{f_0 \to obj} = G\, f_0 \qquad\qquad W_{(f_0 + \delta f_j) \to obj} = G\,(f_0 + \delta f_j) = W_{f_0 \to obj} + G\, \delta f_j$$

By the way, we also remind that to ensure the consistency of the equations of motion, the disturbances $W_{dist}^j$ are supposed to be written in the object frame.

**Remark**

It is visible from the equations of motion, with and without disturbance, that we consider that the disturbing effect of $W_{dist}^j$ is perfectly canceled by the contact force variations: by combining (6.6) and (6.7):

$$G\, \delta f_j = -W_{dist}^j \quad \forall\, j \in [|1, n_d|]$$

Therefore, the contact forces from the undisturbed case, $f_0^1, \dots, f_0^{n_c}$, are able to manipulate the object during a disturbance as if there was no disturbance: since the disturbance is entirely absorbed by the force variations, it does not affect $\dot{V}_{obj}$, and consequently the motion of the object remains the same. In short, the contact forces $f_0$ ensure manipulation and tightening of the object, and the contact forces $f_0 + \delta f_j$ ensure the same manipulation and tightening, plus withstanding to the disturbance $W^j_{dist}$.

Of course, it is very unrealistic that a grasp withstands disturbances so perfectly that the motion of the object in grasp is not even affected. From a control point of view, there are two objections:

1. First of all, the disturbances are unknown to the control scheme, so it is impossible for it to compute force variations that could cancel them.
2. Besides, even if it were possible, the force variations would have to be applied by the fingers at the exact same time that the disturbance happens. This is not possible for reasons of causality: the hand's controller first has to know that a disturbance happens before it can react with force variations.

These objections explain why we are interested in the manipulation and tightening forces $f_0$ of the undisturbed case rather than in the opposing forces $f_0 + \delta f^j$ of the disturbed cases: only $f_0$ is exploitable in a control scheme of dextrous manipulation, as the desired value of the contact forces. In contrast, the contact forces $f_0 + \delta f_j$ that withstand $W^j_{dist}$ are not really worth bothering, because there is no point servoing the hand to them: to be effective against $W^j_{dist}$, they have to be applied at the same time as the disturbance, which is not possible, and moreover this disturbance must be measured precisely to compute the variations $\delta f_j$, which is at least difficult. In practical application, by the time the control algorithms of a robot hand can find from the sensor values that there is a disturbance, that this disturbance is $W^j_{dist}$, and that $f_0 + \delta f_j$ are therefore to be applied, the disturbance is long gone.

### Non-linear expression of the problem of grasp robustness

We translate into equations the problem of grasp robustness to the expected $W^1_{dist}, \ldots, W^{n_d}_{dist}$, from its full-text definition at the beginning of this section:

$$\text{Find } f_0 \in \mathbb{R}^{3n_c} \text{ s.t. } \exists\, \delta f_1, \ldots, \delta f_{n_d} \in \mathbb{R}^{3n_c} \text{ s.t.}$$
$$\left\{\begin{array}{l}
\text{equations of motion:} \\
\quad M_{obj}(\dot{V}_{obj} - g) + N_{obj} V_{obj} = G\, f_0 \\
\quad M_{obj}(\dot{V}_{obj} - g) + N_{obj} V_{obj} = G\,(f_0 + \delta f_j) + W^j_{dist} \qquad \forall\, j \in [|1, n_d|] \\
\text{friction constraints:} \\
\quad \|(f_0)_t\| \le \mu\ \|(f_0)_n\| \\
\quad \left\|(f_0 + \delta f_j)_t\right\| \le \mu\ \left\|(f_0 + \delta f_j)_n\right\| \qquad \forall\, j \in [|1, n_d|] \\
\text{unilateral contact forces:} \\
\quad (f_0)_n \le 0_{n_c,1} \\
\quad (f_0 + \delta f_j)_n \le 0_{n_c,1} \qquad \forall\, j \in [|1, n_d|] \\
\text{limited contact forces:} \\
\quad \|f_0\| \le f_{max} \\
\quad \left\|f_0 + \delta f_j\right\| \le f_{max} \qquad \forall\, j \in [|1, n_d|]
\end{array}\right. \tag{6.8}$$

The notations $()_t$ and $()_n$ are for the tangential and normal components of course, and the notation $\| \ \|$ means the column vector of the norms:

$$\|f_0\| = \begin{pmatrix} \|f_0^1\| \\ \vdots \\ \|f_0^{n_c}\| \end{pmatrix} \in \mathbb{R}^{n_c} \qquad \|(f_0)_{n,t}\| = \begin{pmatrix} \|(f_0^1)_{n,t}\| \\ \vdots \\ \|(f_0^{n_c})_{n,t}\| \end{pmatrix} \in \mathbb{R}^{n_c}$$

In a similar way, $f_{max}$ is a vector of $n_c$ positive elements.

### Remarks

**Convexity** The tightening forces $f_0$ are the basis for opposing forces withstanding the expected disturbances $W^1_{dist}, \dots, W^{n_d}_{dist}$, but not only: all the disturbances in the wrench polytope of vertices $W^1_{dist}, \dots, W^{n_d}_{dist}$ can be resisted from $f_0$, not just the vertices themselves. This is because the problem (6.8) is obviously convex:

- The equality constraints are linear, so if $f_0 + \delta f_{j_1}$ balances $W^{j_1}_{dist}$ and $f_0 + \delta f_{j_2}$ balances $W^{j_2}_{dist}$, then $f_0 + [\alpha \delta f_{j_1} + (1-\alpha)\delta f_{j_2}]$ balances $\alpha W^{j_1}_{dist} + (1-\alpha) W^{j_2}_{dist}$, $0 \le \alpha \le 1$.
- The inequality constraints describe bounded contact cones which are convex, so if the forces $f_0 + \delta f_{j_1}$ and $f_0 + \delta f_{j_2}$ are in these contact cones, then the forces $f_0 + [\alpha \delta f_{j_1} + (1-\alpha)\delta f_{j_2}]$ are in them too.

**Optimality** The idea behind our statement of the problem is that the variations $\delta f_j$ are small, for all $j \in [|1, n_d|]$, and the robustness comes primarily from the tightening. In some way, $f_0$ should represent a compromise between all the $f_0 + \delta f_j$, as opposed to little tightening and large force variations (see the paragraph about tightening forces at the beginning of section 6.1.1). We enforce this aspect latter, in section 6.2.3, via adequate weighting of the $\delta f_j$ relatively to $f_0$, in a minimization problem.

**Admissibility** The problem of robustness to expected disturbances makes sense only if these disturbances can be resisted. Indeed, if one of them, say $W^j_{dist}$, is not admissible, i.e. if it is not in the opposite of the grasp wrench space, then there is no $f_0 + \delta f_j$ that the grasp can produce to withstand it, thus the problem (6.8) does not have any solution.

So in the rest of this section (sections 6.2.2 and 6.2.3), we suppose that the expected disturbances are admissible.

**Motion and equilibrium** Studies about the force optimization problem are always formulated at static equilibrium of the object ($V_{obj} = 0_{6,1}$, $\dot{V}_{obj} = 0_{6,1}$) and look for optimal contact forces balancing a given external wrench and therefore keeping the object at equilibrium. It would be however possible to take a dynamic motion of the object into account, merely by writing the equations of motion rather than the equations of static equilibrium. That would result in force optimization problems were optimal forces balancing an external wrench *during motion* are searched.

In our study about tightening, we take the dynamics of the object into account, and therefore look for tightening forces associated to a robustness objective *and* compatible with the motion of the object. So the grasp will be robust even during a manipulation, not just at static equilibrium.

Of course, if the motion is quasi-static, or at least if $M_{obj}\dot{V}_{obj}$ and $N_{obj}V_{obj}$ are negligible with respect to the contact forces, the gravitational forces, and the disturbances, then the right-hand sides of the equations of motion in (6.8) are reduced to $-M_{obj}\,g$ i.e. $-m_{obj}\,g$ (see equation 6.3), and we fall back to the equations of equilibrium.

### 6.2.2 Linearization of the problem of grasp robustness

To solve (6.8), the first step we can take is to simplify it by linearization. In particular, the linearization of the contact cones done in equation (6.1) yields immediately:

$$
\begin{aligned}
&\text{friction constraints and unilateral forces:}\\
&\quad C f_0 + d \leq 0_{n_c \times n_e, 1}\\
&\quad C(f_0 + \delta f_j) + d \leq 0_{n_c \times n_e, 1} \qquad \forall\, j \in [|1, n_d|]
\end{aligned}
\tag{6.9}
$$

The constraints which set an upper bound on the contact forces may be approximated by linear constraints too. For instance, we can write:

$$\|f_0\| \approx \|(f_0)_n\| = -(f_0)_n$$

This approximation is a bit rough, but it is acceptable when the friction cones are not too wide, i.e. when the friction coefficient is not too large. It means that the admissible region for the contact force $f_0^i$ is its friction cone truncated by a plane at $f_{max}$ level along the axis, i.e. the bounded contact cone is approximated by a truncated contact cone. There are other ways to linearize this constraint, though, for instance the “bounded” part of the cone could be approximated by a multi-faceted pyramid like the rest of the cone.

Keeping the rough approximation, we define a matrix $E$ as a $(n_c, 3n_c)$ block-diagonal matrix of $\begin{pmatrix} 0 & 0 & 1 \end{pmatrix}$ blocks:

$$E = \begin{pmatrix} 0 & 0 & 1 & & & \\ & & & \ddots & & \\ & & & 0 & 0 & 1 \end{pmatrix}$$

This matrix is such that $Ef_0 = (f_0)_n$. Therefore, the linearized constraints about the upper bound on the contact forces are:

$$
\begin{aligned}
&\text{limited forces:}\\
&\quad - E f_0 \leq f_{max}\\
&\quad - E(f_0 + \delta f_j) \leq f_{max} \qquad \forall\, j \in [|1, n_d|]
\end{aligned}
\tag{6.10}
$$

If we had chosen another approximation, we would just have got another matrix $E$ (as long as the approximation is linear of course).

So after these linearizations (6.9) and (6.10), the grasp robustness problem (6.8) becomes the following problem:

$$
\text{Find } f_0 \in \mathbb{R}^{3n_c} \text{ s.t. } \exists\, \delta f_1, \dots, \delta f_{n_d} \in \mathbb{R}^{3n_c} \text{ s.t.}
$$
$$
\begin{cases}
\text{equations of motion:} \\
\quad G\, f_0 = M_{obj}(\dot{V}_{obj} - g) + N_{obj} V_{obj} \\
\quad G\, \delta f_j = -W^j_{dist} \qquad \forall\, j \in [|1, n_d|] \\
\text{friction constraints and unilateral forces:} \\
\quad C f_0 \leq -d \\
\quad C(f_0 + \delta f_j) \leq -d \qquad \forall\, j \in [|1, n_d|] \\
\text{limited forces:} \\
\quad -E f_0 \leq f_{max} \\
\quad -E(f_0 + \delta f_j) \leq f_{max} \qquad \forall\, j \in [|1, n_d|]
\end{cases}
\tag{6.11}
$$

Of course we cannot claim (6.8) $\Leftrightarrow$ (6.11) but only (6.11) $\Rightarrow$ (6.8). That is to say, if $f_0$ (and $\delta f_1, \dots, \delta f_{n_d}$) is a solution of the linearized robustness problem, it is also a solution of the general robustness problem.

Let $x$ denote the unknown of (6.11):

$$
x = \begin{pmatrix} f_0 \\ \delta f_1 \\ \vdots \\ \delta f_{n_d} \end{pmatrix}
$$

This problem (6.11) is a system of linear equations and inequations in $x$. The dimension of the unknown may be quite large, though not untractable: $x \in \mathbb{R}^{3n_c(1+n_d)}$. We will see further, section 6.3.1, equation (6.16), how it can be much reduced. For now, the system to be solved is:

$$
\begin{cases}
\overline{G}\, x = \overline{M}_{obj}(\dot{\overline{V}}_{obj} - \overline{g}) + \overline{N}_{obj} \overline{V}_{obj} - \overline{W}_{dist} \\
\overline{C}\, x \leq -\overline{d} \\
-\overline{E}\, x \leq \overline{f}_{max}
\end{cases}
\tag{6.12}
$$

$$
\overline{G} = \begin{pmatrix} G & & & \\ & G & & \\ & & \ddots & \\ & & & G \end{pmatrix}
\qquad
\overline{g} = \begin{pmatrix} g \\ 0_{6,1} \\ \vdots \\ 0_{6,1} \end{pmatrix}
\qquad
\overline{W}_{dist} = \begin{pmatrix} 0_{6,1} \\ W^1_{dist} \\ \vdots \\ W^{n_d}_{dist} \end{pmatrix}
$$

$$
\overline{M}_{obj} = \begin{pmatrix} M_{obj} & & & \\ & 0_{6,6} & & \\ & & \ddots & \\ & & & 0_{6,6} \end{pmatrix}
\qquad
\overline{N}_{obj} = \begin{pmatrix} N_{obj} & & & \\ & 0_{6,6} & & \\ & & \ddots & \\ & & & 0_{6,6} \end{pmatrix}
$$

$$
\overline{V}_{obj} = \begin{pmatrix} V_{obj} \\ 0_{6,1} \\ \vdots \\ 0_{6,1} \end{pmatrix}
\qquad
\overline{C} = \begin{pmatrix} C & & & \\ C & C & & \\ \vdots & & \ddots & \\ C & & & C \end{pmatrix}
\qquad
\overline{d} = \begin{pmatrix} d \\ d \\ \vdots \\ d \end{pmatrix}
$$

$$\overline{E} = \begin{pmatrix} E & & & \\ E & E & & \\ \vdots & & \ddots & \\ E & & & E \end{pmatrix} \qquad \overline{f}_{max} = \begin{pmatrix} f_{max} \\ f_{max} \\ \vdots \\ f_{max} \end{pmatrix}$$

### 6.2.3 Optimal tightening forces

The system of linear equations in (6.12) is underdetermined, so we add an objective function to choose from its possible solutions. It is physically sensible to minimize the $L_2$ norms of the forces, because it makes it possible to get tightening contact forces which satisfy the desired robustness objective without too much energy consumption: a kind of "least-effort" robust grasp. But we must also be careful not to choose tightening contact forces $f_0$ that are too low, because then the force variations $\delta f_j$ could be too high, and this is the opposite of what we want: as explained in section 6.2.1, we want the variations $\delta f_j$ to be small and the contact forces $f_0$ to be a non-negligible amount of tightening. This can be realized by an appropriate weighting of the norms of the forces.

More precisely, we define symmetric, positive-definite weight matrices $Q_0, Q_1, \ldots, Q_{n_d}$ for the contact forces $f_0$ and the force variations $\delta f_1, \ldots, \delta f_{n_d}$. All these matrices are $(3n_c, 3n_c)$ in size and we put them together in the following block-diagonal matrix:

$$\overline{Q} = \begin{pmatrix} Q_0 & & & \\ & Q_1 & & \\ & & \ddots & \\ & & & Q_{n_d} \end{pmatrix}$$

Then, we choose to minimize the norm of $x$ weighted by this symmetric, positive-definite matrix $\overline{Q}$, that is to say we choose to minimize:

$$\begin{aligned} \|x\|^2_{\overline{Q}} &= x^T \overline{Q} x \\ &= f_0^T Q_0 f_0 + \delta f_1^T Q_1 \delta f_1 + \cdots + \delta f_{n_d}^T Q_{n_d} \delta f_{n_d} \\ &= \|f_0\|^2_{Q_0} + \|\delta f_1\|^2_{Q_1} + \cdots + \left\|\delta f_{n_d}\right\|^2_{Q_{n_d}} \end{aligned}$$

A good choice of weighting is therefore when the matrices $Q_1, \ldots, Q_{n_d}$ relative to $\delta f_1, \ldots, \delta f_{n_d}$ are much larger than the matrix $Q_0$ relative to $f_0$. By doing so, the norms of $\delta f_1, \ldots, \delta f_{n_d}$ have priority over the norm of $f_0$ in the minimization of the norm of $x$, which means that we get the smallest $\delta f_1, \ldots, \delta f_{n_d}$ possible, even if it means that $f_0$ is not small. Consequently, $f_0$ results in a sort of compromise between the different $f_0 + \delta f_j$.

So, eventually, we get the following problem:

$$\begin{cases} \min\limits_x \dfrac{1}{2} x^T \overline{Q} x \\ \overline{G}\, x = \overline{M}_{obj}(\dot{\overline{V}}_{obj} - \overline{g}) + \overline{N}_{obj} \overline{V}_{obj} - \overline{W}_{dist} \\ \overline{C}\, x \leq -\overline{d} \\ -\overline{E}\, x \leq \overline{f}_{max} \end{cases} \tag{6.13}$$

When we solve this quadratic programming problem, we find optimal tightening forces $f_0$ that realize a robust grasp against the expected disturbances $W^1_{dist}, \ldots, W^{n_d}_{dist}$, and against all the disturbances in the wrench polytope defined by these disturbances. The optimality is in the sense of $\overline{Q}$-weighted minimality, that is to say the tightening forces can turn into opposing forces against $W_{dist}^1, \ldots, W_{dist}^{n_d}$ by the smallest possible force variations, and if any freedom remains in their choice, then they are chosen as being of minimal euclidian norm too.

## 6.3 Grasp robustness to expected disturbance directions

Now we don't have a set of expected disturbances any more, but only expected disturbance directions, in the wrench space. In section 6.3.1, we determine the maximal robustness of the grasp, defined by its largest-minimum resisted wrench, and we calculate optimal tightening contact forces at the same time, in relation to this maximal robustness. We remind that by "largest-minimum resisted wrench" we mean the largest resisted wrench in the direction of the wrench space for which this wrench is the smallest (also known as the "worst" direction for the grasp to be subject to a disturbance):

$$\min_{w \text{ direction}} \max_{\rho \text{ intensity}} \{\rho w \;\; \text{s.t. } \rho w \in -GWS\}$$

Then, in section 6.3.2, we show how to get optimal tightening forces for a lesser robustness, expressed as a fraction of the maximal robustness. And we explain in section 6.3.3 how to integrate this robust behavior into control schemes for multifingered dextrous manipulation.

As a matter of fact, this section translates into equations the outline of our approach to the problem of tightening determination given in words at the end of section 6.1.1, and in drawings in figures 6.7 and 6.8.

### 6.3.1 Maximal robustness and associated optimal tightening forces

#### Problem statement

We suppose that we have a set of unit disturbances $W_{dist}^1, \ldots, W_{dist}^{n_d} \in se_3^*(\mathbb{R})$, $n_d \geq 1$. They indicate directions of expected disturbances, and also form a unit polytope in wrench space (see figure 6.7 in section 6.1.1).

We are interested in knowing the largest scale factor $\lambda \geq 0$ such that the grasp can withstand all the disturbances in the scaled polytope. This is the problem of finding the maximal robustness of the grasp, for the considered set of disturbance directions.

We are also interested in knowing tightening contact forces $f_0$ such that opposing contact forces $f_0 + \delta f_1, \ldots, f_0 + \delta f_{n_d}$ can be found, with minimal $\delta f_1, \ldots, \delta f_{n_d}$, for each disturbance $\lambda W_{dist}^1, \ldots, \lambda W_{dist}^{n_d}$ at a vertex of the scaled polytope. This is the problem of finding optimal tightening forces for the maximal robustness.

We write these two problems together as follows:

$$\text{Find } f_0 \in \mathbb{R}^{3n_c} \text{ and maximum } \lambda \geq 0 \text{ s.t. } \exists\, \delta f_1, \ldots, \delta f_{n_d} \in \mathbb{R}^{3n_c} \text{ s.t.}$$

$$\begin{cases} \text{equations of motion:} \\ \quad M_{obj}(\dot{V}_{obj} - g) + N_{obj} V_{obj} = G\, f_0 \\ \quad M_{obj}(\dot{V}_{obj} - g) + N_{obj} V_{obj} = G\,(f_0 + \delta f_j) + \lambda W_{dist}^{j} \quad \forall\, j \in [|1, n_d|] \\ \text{friction constraints:} \\ \quad \|(f_0)_t\| \leq \mu\, \|(f_0)_n\| \\ \quad \left\|(f_0 + \delta f_j)_t\right\| \leq \mu\, \left\|(f_0 + \delta f_j)_n\right\| \quad \forall\, j \in [|1, n_d|] \\ \text{unilateral forces:} \\ \quad (f_0)_n \leq 0_{n_c,1} \\ \quad (f_0 + \delta f_j)_n \leq 0_{n_c,1} \quad \forall\, j \in [|1, n_d|] \\ \text{limited forces:} \\ \quad \|f_0\| \leq f_{max} \\ \quad \left\|f_0 + \delta f_j\right\| \leq f_{max} \quad \forall\, j \in [|1, n_d|] \end{cases} \tag{6.14}$$

This is basically the same problem as (6.8), except that the disturbances are no longer fixed in intensity (since we "grow" the polytope) and that the scale parameter $\lambda$ is looked for together with the robust forces.

### Two remarks

Like (6.8), this problem is convex, so the fact that the grasp is desired to withstand the disturbances $\lambda W_{dist}^1, \ldots, \lambda W_{dist}^{n_d}$ only (second line of the "equations of motion" paragraph) is not restrictive at all: the convexity makes sure that if the grasp can withstand these "vertex" disturbances, then it is able to withstand all the disturbances in the scaled-by-$\lambda$ polytope.

It is also noteworthy that the disturbances $W_{dist}^1, \ldots, W_{dist}^{n_d}$ need actually not be unit wrenches, for the same reason that the polytope they describe needs not be a regular polytope. On the contrary, if a specific task to realize makes some disturbance directions and/or intensities more relevant than others, it is judicious to adapt the shape of the polytope according to the shape of this task wrench space: it provides better exploration of the relevant directions of the wrench space during the scaling of the polytope, and results in task-oriented robustness.

### Linearization

The optimization problem (6.14) may be linearized in the same way as (6.8) was linearized in section 6.2.2. We get:

$$
\max_{f_0,\delta f_j,\lambda}(\lambda) \text{ subject to the constraints:}
$$

$$
\begin{cases}
\text{equations of motion:} \\
\quad G\, f_0 = M_{obj}(\dot{V}_{obj} - g) + N_{obj}V_{obj} \\
\quad G\, \delta f_j = -\lambda W^j_{dist} \qquad \forall\, j \in [|1, n_d|] \\
\text{friction constraints and unilateral forces:} \\
\quad C f_0 \leq -d \\
\quad C(f_0 + \delta f_j) \leq -d \qquad \forall\, j \in [|1, n_d|] \\
\text{limited forces:} \\
\quad -E f_0 \leq f_{max} \\
\quad -E(f_0 + \delta f_j) \leq f_{max} \qquad \forall\, j \in [|1, n_d|] \\
\text{and also:} \\
\quad \lambda \geq 0
\end{cases}
\tag{6.15}
$$

### Optimal tightening forces

The unknowns of this problem are $f_0$, $\delta f_1, \ldots, \delta f_{n_d}$ and $\lambda$. We reduce the dimension of the problem by considering that the variables $\delta f_1, \ldots, \delta f_{n_d}$ are those of minimum norm that balance the disturbances $\lambda W^1_{dist}, \ldots, \lambda W^{n_d}_{dist}$ (second line of the "equations of motion" conditions). That is to say, we first solve the following $n_d$ auxiliary quadratic programming problems:

$$
\begin{cases}
\min\limits_{\delta f_j} \dfrac{1}{2}\, \delta f_j^T Q_j\, \delta f_j \\
G\, \delta f_j = -\lambda W^j_{dist}
\end{cases}
\tag{6.16}
$$

The physical interpretation of this approach is a lot like the physical interpretation of the minimization problem (6.13) in section 6.2.3: we are looking for tightening forces $f_0$ which have a certain intensity and force variations $\delta f_1, \ldots, \delta f_{n_d}$ which are as small as possible. In that section, we realized this discrepancy by appropriate weighting of $f_0, \delta f_1, \ldots, \delta f_{n_d}$ in the minimization (6.13) of their norms. Here, we choose directly the minimal force variation $\delta f_j$ that makes the grasp withstand the disturbance $\lambda W^j_{dist}$; that is to say, $\delta f_j$ is just the required amount of force variation to counteract the disturbance. Of course, since $\lambda$ is a variable of (6.15), the $\delta f_1, \ldots, \delta f_{n_d}$ found in the resolution of (6.16) will be function of it, i.e. they won't be fixed amounts of force variation, they will depend on how scaled the disturbance polytope is. As for the weight matrices $Q_j$, they are here to define a weighting of $\delta f^1_j, \ldots \delta f^{n_f}_j$ in the norm of $\delta f_j$, if relevant.

It is easy to prove, from the usual first-order optimality conditions of (6.16) (gradient of the lagrangian with respect to $\delta f_j$ and equality constraint), that the solution of (6.16) is:

$$
\begin{aligned}
&\delta f_j = -\lambda\, G^*_j\, W^j_{dist} \\
&\text{with } G^*_j = Q_j^{-1} G^T [G Q_j^{-1} G^T]^{-1}
\end{aligned}
\tag{6.17}
$$

To get this expression, we write the lagrangian of the problem (6.16):

$$\mathcal{L}_j(\delta f_j, \nu) = \frac{1}{2}\delta f_j^T Q_j \delta f_j + \nu^T (G\delta f_j + \lambda W_{dist}^j)$$

$$\begin{aligned}
\frac{\partial \mathcal{L}_j}{\partial \delta f_j} = 0 &\Rightarrow Q_j \delta f_j + G^T \nu = 0 \\
&\Rightarrow \delta f_j = -Q_j^{-1} G^T \nu \qquad (\star) \\
&\Rightarrow G\delta f_j = -GQ_j^{-1} G^T \nu \\
&\Rightarrow \nu = -[GQ_j^{-1} G^T]^{-1} G\delta f_j
\end{aligned}$$

yet $G\delta f_j = -\lambda W_{dist}^j$ (6.16) so $\nu = \lambda\,[GQ_j^{-1}G^T]^{-1} W_{dist}^j$. Using ($\star$) we deduce:

$$\begin{aligned}
\delta f_j &= -\lambda\, Q_j^{-1} G^T [GQ_j^{-1}G^T]^{-1} W_{dist}^j \\
&\overset{\text{def}}{=} -\lambda\, G_j^* \, W_{dist}^j
\end{aligned}$$

The expression of $G_j^*$ is to be compared with the expression of the pseudo-inverse of the grasp matrix, $G^+ = G^T[GG^T]^{-1}$ (see section 5.2.3 in chapter 5). It appears that $G_j^*$ is a weighted pseudo-inverse of $G$, which reduces to $G^+$ if $Q_j$ is the identity matrix or a diagonal matrix proportional to the identity matrix.

We use (6.17) to make (6.15) become:

$$\max_{f_0,\lambda} (\lambda) \text{ subject to the constraints:}$$
$$\begin{cases}
\text{equation of motion:} \\
\quad G f_0 = M_{obj}(\dot{V}_{obj} - g) + N_{obj} V_{obj} \\
\text{friction constraints and unilateral forces:} \\
\quad C f_0 \leq -d \\
\quad C f_0 - C G_j^* W_{dist}^j \lambda \leq -d \qquad \forall\, j \in [|1, n_d|] \\
\text{limited forces:} \\
\quad -E f_0 \leq f_{max} \\
\quad -E f_0 + E G_j^* W_{dist}^j \lambda \leq f_{max} \qquad \forall\, j \in [|1, n_d|] \\
\text{and also:} \\
\quad \lambda \geq 0
\end{cases} \tag{6.18}$$

### Reduction of the number of constraints

Then, we compact the $n_d + 1$ vector constraints about physical consistency of the contact forces (friction constraints and unilateral forces), as follows:

$$\begin{aligned}
&\begin{cases}
C f_0 \leq -d \\
C f_0 - C G_j^* W_{dist}^j \lambda \leq -d \qquad \forall\, j \in [|1, n_d|]
\end{cases} \\
&\Leftarrow C f_0 + \max\,(0_{n_c \times n_e, 1}, -C G_1^* W_{dist}^1 \lambda, \ldots, -C G_{n_d}^* W_{dist}^{n_d} \lambda) \leq -d \\
&\Leftrightarrow C f_0 - \min\,(0_{n_c \times n_e, 1}, C G_1^* W_{dist}^1, \ldots, C G_{n_d}^* W_{dist}^{n_d}) \lambda \leq -d
\end{aligned}$$

where max (respectively min) is a vector whose $k$-th line is the maximum (respectively minimum) element of the $k$-th lines of its argument vectors.

We may similarly compact the $n_d + 1$ vector constraints about the limits on the contact forces:

$$\begin{cases} -Ef_0 \leq f_{max} \\ -Ef_0 + EG_j^* W_{dist}^j \lambda \leq f_{max} \quad \forall\, j \in [|1, n_d|] \end{cases}$$
$$\Leftarrow -Ef_0 + \max\left(0_{n_c,1}, EG_1^* W_{dist}^1 \lambda, \ldots, EG_{n_d}^* W_{dist}^{n_d} \lambda\right) \leq f_{max}$$
$$\Leftrightarrow -Ef_0 + \max\left(0_{n_c,1}, EG_1^* W_{dist}^1, \ldots, EG_{n_d}^* W_{dist}^{n_d}\right)\lambda \leq f_{max}$$

In the end, if we define:

$$S_1 = \min\left(0_{n_c \times n_e,1}, CG_1^* W_{dist}^1, \ldots, CG_{n_d}^* W_{dist}^{n_d}\right) \tag{6.19}$$
$$S_2 = \max\left(0_{n_c,1}, EG_1^* W_{dist}^1, \ldots, EG_{n_d}^* W_{dist}^{n_d}\right) \tag{6.20}$$

we may write the following simplified problem from (6.18), (6.19) and (6.20):

$$\max_{f_0,\lambda} (\lambda) \text{ subject to the constraints:}$$
$$\begin{cases} \text{equation of motion:} \\ \quad Gf_0 = M_{obj}(\dot{V}_{obj} - g) + N_{obj} V_{obj} \\ \text{friction constraints and unilateral forces:} \\ \quad Cf_0 - S_1\, \lambda \leq -d \\ \text{limited forces:} \\ \quad -Ef_0 + S_2\, \lambda \leq f_{max} \\ \text{and also:} \\ \quad \lambda \geq 0 \end{cases} \tag{6.21}$$

The reductions (6.19) and (6.20) are "worst-case" reductions, on each of the components of the argument vectors of the max and min in $S_1$ and $S_2$. Because of this and the previous simplifications, the solution sets of (6.21), (6.18), (6.15), and (6.14) are *strictly* included in each other (they are not equal). If we let $\mathcal{S}$ denote a solution set, we have:

$$\mathcal{S}(6.21) \subsetneq \mathcal{S}(6.18) \subsetneq \mathcal{S}(6.15) \subsetneq \mathcal{S}(6.14)$$

### Conclusion

The dimension of the unknown has been much reduced when enforcing minimal force variations (equations 6.16 to 6.18), and then the number of constraints has been much reduced too (equations 6.19 to 6.21). We define this new unknown, $x \in \mathbb{R}^{3n_c+1}$ and a companion vector $c$:

$$x = \begin{pmatrix} f_0 \\ \lambda \end{pmatrix} \qquad c = \begin{pmatrix} 0_{3n_c,1} \\ 1 \end{pmatrix} \qquad \lambda = c^T x \tag{6.22}$$

Eventually, we rewrite (6.21) as the following linear programming problem:

$$\begin{cases} \min_x (-c^T x) \\ A_{eq}\, x = b_{eq} \\ A_{neq}\, x \leq b_{neq} \end{cases} \tag{6.23}$$

$$A_{eq} = \begin{pmatrix} G & 0_{6,1} \end{pmatrix} \qquad b_{eq} = M_{obj}(\dot{V}_{obj} - g) + N_{obj}V_{obj}$$
$$A_{neq} = \begin{pmatrix} C & -S_1 \\ -E & S_2 \\ & -c^T \end{pmatrix} \qquad b_{neq} = \begin{pmatrix} -d \\ f_{max} \\ 0 \end{pmatrix}$$

This problem can be solved efficiently by a variety of algorithms. We get:

$$x^{sol} = \begin{pmatrix} f_0^{sol} \\ \lambda^{sol} \end{pmatrix}$$

As explained in section 6.1, figure 6.7 or 6.10(c) for instance, the maximum scale factor $\lambda^{sol}$ is an indication of the size of the set of disturbances that the grasp is able to withstand, in other words an indication of the maximal robustness. It measures the magnitude of the largest-minimum resisted wrench in the investigated directions. It is of course extremely similar to the grasp quality measure of Zhu, Ding, and J. Wang (2003), presented in section 6.1.2.

The solution $f_0^{sol}$ is the optimal tightening forces to apply on the object to realize a robust grasp against all the disturbances in the scaled-by-$\lambda$ disturbance polytope.

So, at the end of this section, we have quantified the maximal robustness of the grasp (in the chosen directions) and found optimal tightening forces for this maximal robustness (optimality being in the sense of minimal variations between the tightening forces and the opposing forces).

#### Grasp quality measure

As we explained in section 6.1.2, Zhu, Ding, and J. Wang (2003) calculate their quality measure with as many linear programming problems in $\mathbb{R}^{3n_c+1}$ as disturbance directions, in a method along the lines of figure 6.6. Contact forces balancing each largest resisted disturbance, in these directions, are also computed as by-products of these linear programs. We remind here the differences between their method and ours, if ours was considered as a method to get a quality measure (as opposed to a method to get optimal tightening forces).

1. We only need one linear programming problem in $\mathbb{R}^{3n_c+1}$ to get our quality measure, in a method along the lines of figure 6.7. It is worth noting that:

   - Because of the successive linearizations (6.15), dimension reduction (6.16 to 6.18) and constraint combinations (6.19 to 6.21), this measure is not exactly the magnitude of the largest-minimum resisted wrench in the investigated directions, as it would if we had solved (6.14) rather than (6.23), but an approximation of it.

   - The dimension of our linear program does not depend on the number of disturbances, $n_d$. Therefore, the polytope of disturbance directions may have a complex shape, with a lot of vertices, without impairing the computational cost other than what is needed for the computation of $S_1$ and $S_2$ (6.19 and 6.20). In contrast, solving $n_d$ linear programs in $\mathbb{R}^{3n_c+1}$ may pose a problem if $n_d$ is too large.

2. We take both known wrenches (gravity, but other external loads may be considered along) and unknown wrenches (disturbances) into account.

3. We distinguish between the forces that are applied in the absence of any disturbance ($f_0$) and those that are applied during a disturbance ($f_0 + \delta f_j m$). In contrast, the forces computed by Zhu, Ding, and J. Wang (2003) are opposing forces only, there is no notion of tightening. This difference comes of course from the fact that the purpose of their method is not tightening determination.

   Because we make this difference, our robustness/quality problem (6.14) has more constraints than the one of Zhu, Ding, and J. Wang (2003). Namely, we have extra constraints, those on $f_0$ alone. As a result, our problem is conservative with respect to theirs, and the quality measure we define is a lower bound of theirs: the more constraints, the more underestimated the grasp ability to resist disturbances.

### 6.3.2 Lesser robustness and associated optimal tightening forces

Once we have solved the problem of finding the maximum robustness of the grasp, (6.23), we are able to specify a variety of robustness objectives by considering the scaled-by-$\lambda$ polytope, $\lambda \in [0, \lambda^{sol}]$, as illustrated in figure 6.8 of section 6.1.1. This is the problem described at the beginning of this chapter: its robustness objective is made of directions in the wrench space and a fraction of the maximal robustness.

The vertices of the scaled-by-$\lambda$ disturbance polytope are known and admissible: $\lambda W^1_{dist}, \ldots, \lambda W^{n_d}_{dist}$, $\lambda \in [0, \lambda^{sol}]$. So, the problem of finding optimal tightening forces for them is exactly a problem of grasp robustness to expected disturbance wrenches, as defined and investigated in section 6.2. Its expression is of the form of (6.8), the only difference being the presence of $\lambda$:

$$\text{Find } f_0 \in \mathbb{R}^{3n_c} \text{ s.t. } \exists\, \delta f_1, \ldots, \delta f_{n_d} \in \mathbb{R}^{3n_c} \text{ s.t.}$$

$$\begin{cases} \text{equations of motion:} \\ \quad M_{obj}(\dot{V}_{obj} - g) + N_{obj} V_{obj} = G\, f_0 \\ \quad M_{obj}(\dot{V}_{obj} - g) + N_{obj} V_{obj} = G\,(f_0 + \delta f_j) + \lambda W^j_{dist} \qquad \forall\, j \in [|1, n_d|] \\ \text{friction constraints:} \\ \quad \|(f_0)_t\| \leq \mu\ \|(f_0)_n\| \\ \quad \left\|(f_0 + \delta f_j)_t\right\| \leq \mu\ \left\|(f_0 + \delta f_j)_n\right\| \qquad \forall\, j \in [|1, n_d|] \\ \text{unilateral contact forces:} \\ \quad (f_0)_n \leq 0_{n_c,1} \\ \quad (f_0 + \delta f_j)_n \leq 0_{n_c,1} \qquad \forall\, j \in [|1, n_d|] \\ \text{limited contact forces:} \\ \quad \|f_0\| \leq f_{max} \\ \quad \left\|f_0 + \delta f_j\right\| \leq f_{max} \qquad \forall\, j \in [|1, n_d|] \end{cases}$$

We can solve this problem as in sections 6.2.2 and 6.2.3: linearization of the bounded friction cones, followed by adding an objective function to choose from the possible solutions of the underdetermined system of linear equations. We get the quadratic programming problem (6.13), the only difference being $\lambda \overline{W}_{dist}$ instead of $\overline{W}_{dist}$.

Instead of ensuring the minimality of the force variations $\delta f_j$ via adequate weighting in the quadratic objective function of (6.13), we can also ensure it via the auxiliary quadratic programming problems (6.16), for the chosen $\lambda \in [|0,1|]$. We can also reduce the number of constraints by combining them as in section 6.3.1, equations (6.19) and (6.20). We obtain the following quadratic programming problem, which is much like (6.21), except with a different objective function and a fixed, given $\lambda$:

$$\min_{f_0} \; \frac{1}{2} \, f_0^T Q_0 f_0 \text{ subject to the constraints:}$$
$$\begin{cases} \text{equation of motion:} \\ \quad G f_0 = M_{obj}(\dot{V}_{obj} - g) + N_{obj} V_{obj} \\ \text{friction constraints and unilateral forces:} \\ \quad C f_0 \leq -d + \lambda S_1 \\ \text{limited forces:} \\ \quad - E f_0 \leq f_{max} - \lambda S_2 \end{cases}$$

In other terms:

$$\begin{cases} \min_{f_0} \; \frac{1}{2} \, f_0^T Q_0 f_0 \\ A'_{eq} \, f_0 = b'_{eq} \\ A'_{neq} \, f_0 \leq b'_{neq} \end{cases} \tag{6.24}$$
$$A'_{eq} = G \qquad\qquad b'_{eq} = M_{obj}(\dot{V}_{obj} - g) + N_{obj} V_{obj}$$
$$A'_{neq} = \begin{pmatrix} C \\ -E \end{pmatrix} \qquad\qquad b'_{neq} = \begin{pmatrix} -d + \lambda S_1 \\ f_{max} - \lambda S_2 \end{pmatrix}$$

### 6.3.3 Integration in control frameworks

The integration of tightening abilities into control schemes of dextrous manipulation is easy. There are basically two cases, depending on whether the control scheme makes use of internal forces or not.

#### Desired internal forces

In most control schemes [17], the desired contact forces $f^{[d]}$ are split into desired internal forces $f_I^{[d]}$ and desired forces $f_P^{[d]}$ that are solution of $W_{f\to obj}^{[d]} = G f_P^{[d]}$, where $W_{f\to obj}^{[d]}$ is the desired total contact wrench applied by the hand on the object, for manipulation purposes. The $^{[d]}$ superscript is for "desired" of course; $_P$ is for a "particular solution" of the equation $W_{f\to obj}^{[d]} = G f_P^{[d]}$.

Very often, this separation of the contact forces is done with the help of the pseudo-inverse of the grasp matrix. The internal forces are in the kernel of the grasp matrix, which means that they cannot participate to the resultant wrench on the object, for instance they cannot produce any motion of the object. In short:

$$W_{f\to obj}^{[d]} = G \, f^{[d]}$$
$$f^{[d]} = f_P^{[d]} + f_I^{[d]}$$
$$G \, f_P^{[d]} = W_{f\to obj}^{[d]} \qquad\qquad G \, f_I^{[d]} = 0_{6,1}$$

17. See section 5.2.3 in chapter 5 for a review of multifingered dextrous manipulation control.

In these control schemes, the forces $f_P^{[d]}$ are computed first and deal with the manipulation objectives of the control: motion of the object and/or force between the object and the environment, for hybrid force/position control; impedance of the object, for impedance control. So the only freedom left in the choice of the contact forces is in the internal forces $f_I^{[d]}$. This is where we can integrate tightening abilities in relation to a robustness objective.

For instance, a crude way to proceed is to put all the tightening into the internal forces, like that:

$$f_I^{[d]} = f_0^{sol}$$

with $f_0^{sol}$ either the optimal tightening forces associated with the maximal robustness (section 6.3.1, equation 6.23) or the optimal tightening forces of a less robust grasp (section 6.3.2, equation 6.24). It is important to note that since the forces $f_0^{sol}$ will be set as desired internal forces, they must be in the kernel of the grasp matrix, so they must be computed with the right-hand sides of the "equations of motion" constraints set to $0_{6,1}$, so that they result in $Gf_0^{sol} = 0_{6,1}$. In the above-cited problems (6.23) and (6.24), that just means that $b_{eq} = 0_{6,1}$ and $b'_{eq} = 0_{6,1}$ instead of $M_{obj}(\dot{V}_{obj} - g) + N_{obj}V_{obj}$. In other words, there is no need to worry about the motion of the object since it is taken care of by $f_P^{[d]}$.

But this is not a very good way to proceed: there are two flaws in this method.

1. Tightening is not under exclusive control of the internal forces $f_I$, but shared between them and the forces $f_P$. That is to say, $f_P$ are not necessarily only about moving the object; in the general case they include a component in the kernel of the grasp matrix too, unless explicitely chosen not to. So, the "tightening part" of $f_P$ interferes with $f_I$ and the robustness objective is not realized as planned.

2. The problems (6.23) and (6.24) ensure that the tightening forces that are found as optimal solutions are physically consistent, that is to say they respect the friction cone and unilaterality constraints. So if $f_I^{[d]} = f_0^{sol}$, then the internal forces are physically consistent, but there is not the slightest guarantee that the contact forces $f^{[d]} = f_P^{[d]} + f_I^{[d]}$ will be too. And servoing the hand to desired contact forces that are not physically consistent is for sure an unfortunate decision.

It is possible to overcome these difficulties by separating the contact forces $f$ into $f_P$ and $f_I$ directly in the problems (6.23) and (6.24). For instance the problem (6.24) would become as follows, all simplifications made. $f_{0,P}^{[d]}$ is a given parameter, since it is chosen to realize $W_{f\to obj}^{[d]}$, and $f_{0,I}$ is the new variable:

$$\begin{cases} \min\limits_{f_{0,I}} \ \dfrac{1}{2}\, f_{0,I}^T\, Q_0\, f_{0,I} + f_{0,I}^T\, Q_0\, f_{0,P}^{[d]} \\ A''_{eq}\, f_{0,I} = b''_{eq} \\ A''_{neq}\, f_{0,I} \leq b''_{neq} \end{cases}$$

$$A''_{eq} = G \qquad\qquad b''_{eq} = M_{obj}(\dot{V}_{obj} - g) + N_{obj}V_{obj} - Gf_{0,P}^{[d]}$$

$$A''_{neq} = \begin{pmatrix} C \\ -E \end{pmatrix} \qquad\qquad b''_{neq} = \begin{pmatrix} -d + \lambda S_1 - Cf_{0,P}^{[d]} \\ f_{max} - \lambda S_2 + Ef_{0,P}^{[d]} \end{pmatrix}$$

Solving this problem returns internal forces $f_{0,I}^{sol}$ such that the whole contact forces $f_0^{sol} = f_{0,P}^{[d]} + f_{0,I}^{sol}$ ensure a tightening related to the robustness objective, are physically consistent, and also respect the limitations imposed on their magnitude. So we take these forces as desired internal forces in the control scheme:

$$f_I^{[d]} = f_{0,I}^{sol}$$

#### Desired contact forces

The optimization-based control scheme that we proposed in chapter 5 doesn't use internal forces; it works entirely with contact forces instead. To take robustness into account in this control scheme, we simply define the following contact force objective:

$$f^{[d]} = f_0^{sol}$$

with $f_0^{sol}$ either the optimal tightening forces associated with the maximal robustness (section 6.3.1, equation 6.23) or the optimal tightening forces for a lesser robustness (section 6.3.2, equation 6.24).

We also define an associated weight matrix. Indeed, our control strategy tries to realize a lot of different control objectives, and sometimes some of them are incompatible with each other, so it needs weights on each of them to realize a trade-off between those that are incompatible (to have a look at the control objectives, see table 5.2 in section 5.3 of chapter 5).

Once $f^{[d]}$ is defined with its associated weight matrix, the optimization nature of our control strategy combines this desired value with all the other control objectives, in particular with the one on the contact forces $f$ that results from the desired motion of the object. And robust manipulation ensues.

## 6.4 Simulation-based validation

In this section, we demonstrate the tightening abilities that our robustness study brings to the optimization-based control law we described in chapter 5. The example is a four-fingered hand keeping hold of an object in the presence of disturbances. It is tested in dynamic simulation with Arboris, an open-source dynamical engine for the simulation of articulated rigid body mechanics, written in Matlab programming language at CEA/LIST [18] and UPMC/ISIR [19] (Micaelli and Barthélémy 2006–2010). This physical engine and how we use it have been described in chapter 5, sections 5.1.1 and 5.4, as well as the computer implementations of the hand model and of its control.

### 6.4.1 Grasp robustness in static equilibrium

The robustness objective is as follows: the grasp should be able to withstand disturbances in any of the six force directions along the $x$, $y$ and $z$ axes of the reference

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19. *Université Pierre et Marie Curie, Institut des Systèmes Intelligents et de Robotique*: Pierre and Marie Curie University, Institute for Intelligent Systems and Robotics (Paris, France).

frame, up to 75% of the largest-minimum resisted wrench. That is to say, we consider the following six disturbance directions, written in *ref*:

$$W^{\pm x} = \begin{pmatrix} \pm 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad W^{\pm y} = \begin{pmatrix} 0 \\ \pm 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad W^{\pm z} = \begin{pmatrix} 0 \\ 0 \\ \pm 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

At each time step, after the necessary changes of frames (in our equations, the wrenches are supposed to be written in *obj*), we solve (6.23), section 6.3.1: we get the quality measure $\lambda^{sol}$ indicating the maximal robustness, and appropriate optimal contact forces for a grasp with maximal robustness. Then we solve (6.24), section 6.3.2, for $\lambda = 0.75\,\lambda^{sol}$: we get appropriate optimal contact forces $f_0^{sol}$. Eventually, we set the desired contact forces at $f^{[d]} = f_0^{sol}$ in our control scheme, as explained in section 6.3.3.

The desired object motion is to remain at rest at the object's initial position. Gravity is set to zero for simplicity. We use discretized contact cones with eight faces and a friction coefficient $\mu = 0.8$. The programming problems (6.23) and (6.24) are solved with a constraint $f_{max} = 2\,\mathrm{N}$ for each finger force norm.

Disturbances are applied on the object successively in each of the six directions. Their intensity is about 75% of the intensity of the largest-minimum resisted wrench, that is to say, $\left\| W_{dist}^{\pm x,y,z} \right\| \lessapprox 0.75\,\lambda^{sol}$. They last 0.1 s each. The grasp withstands all six disturbances; two of them are illustrated on figure 6.13.

On the contrary, if the same disturbances happen when the control of the hand does not provide any robustness (as in the simulations presented in section 5.4.1, chapter 5), it is no wonder that they result in the hand losing grip, figure 6.14. In this figure, the same manipulation was executed with the tightening objective emulated with desired normal contact forces accounting for some light tightening: $f_{i,n}^{[d]} = 0.5\,\mathrm{N}$, $\forall\, i \in [|1, 4|]$. As explained in section 5.4.1 of chapter 5, it is not possible to increase this objective very much because it is not neutral with respect to the static equilibrium of the object (it produces a non-zero net wrench on the object): a larger objective provides more tightening but hinders static equilibrium. In contrast, the tightening forces we design in this chapter from a robustness objective have the significant advantage of taking into account the object's equation of motion (or static equilibrium, in this case).

### 6.4.2 Grasp robustness in dynamic motion

Now the same four-fingered hand is subject to gravity and supposed to translate the object 2 cm backwards, along $-y$, from $t = 1\,\mathrm{s}$ to $t = 3\,\mathrm{s}$. This desired object motion is plotted in black on figure 6.15.

During the motion, a disturbance along $+x$ happens at $t = 2\,\mathrm{s}$. Except the motion and gravity, everything remains the same as previously, in particular the robustness objective and the intensity and duration of the disturbance.

The grasp withstands the disturbance and completes successfully its motion objective. Figure 6.15 shows plots indicating the position of the center of the object during the disturbed motion.

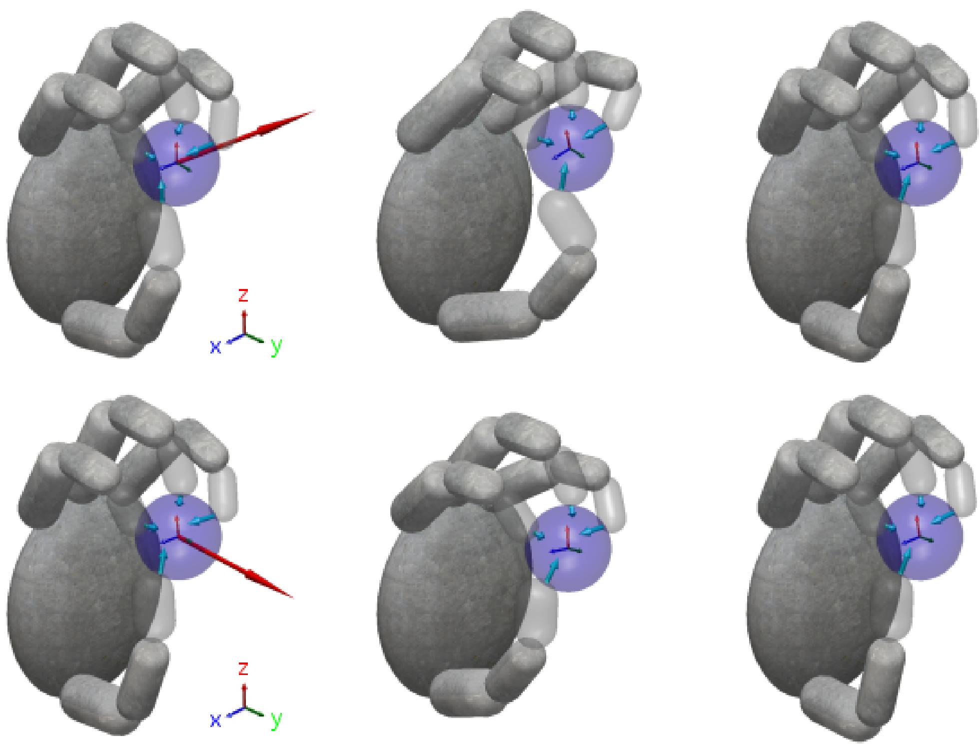



Figure 6.13 – Two disturbances (red arrows, left images) are withstood by the hand (center images), which then returns to equilibrium (because of its position control, right images).

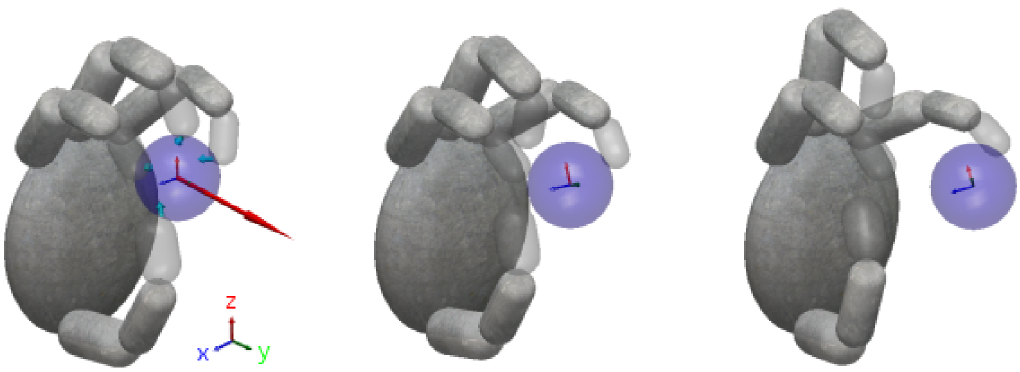
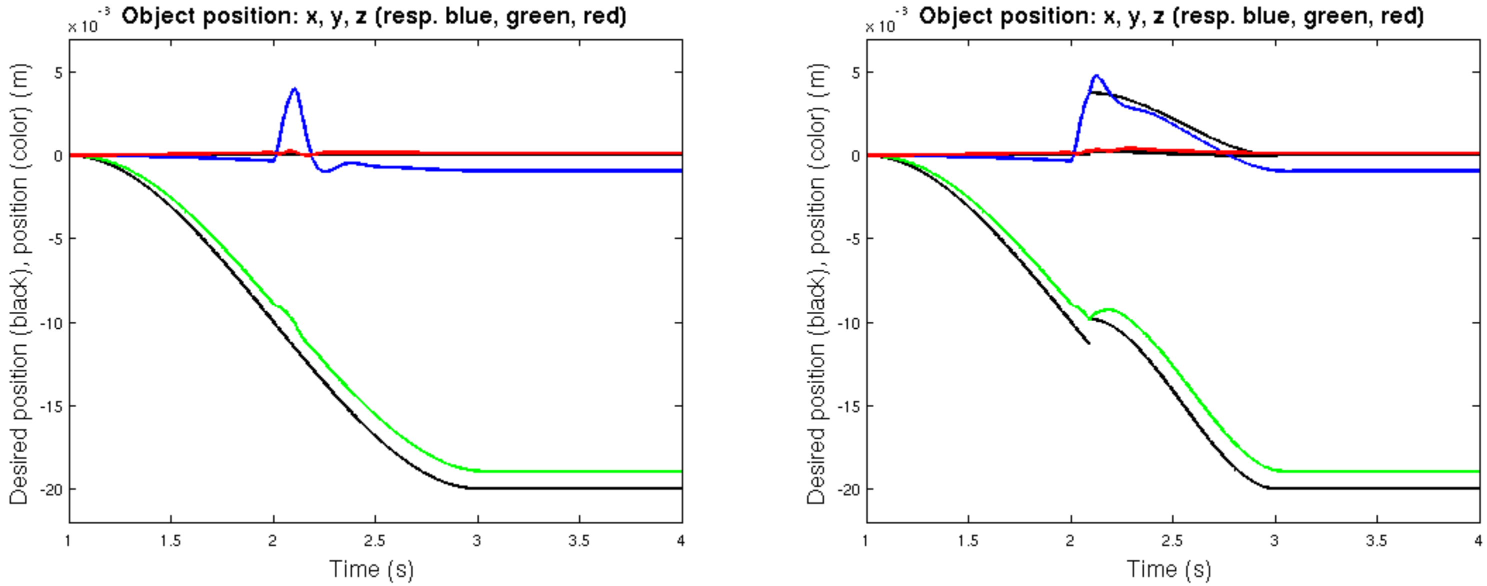



Figure 6.14 – No robustness objective results in poor grasp in face of disturbances




(a) The motion of the grasped object is disturbed along $+x$ but the robustness objective ensures that the hand does not lose its grip on the object, enabling the control to complete the motion.

(b) In this plot, the desired trajectory of the object is recomputed after the disturbance is detected, giving the hand a more human-like response time than in the previous plot.

Figure 6.15 – Withstanding disturbances during a manipulation

## 6.5 Conclusion

### 6.5.1 Summary

In this chapter, we proposed a method for calculating tightening contact forces for a multifingered grasp, according to a certain robustness objective against disturbances.

The robustness objective is expressed in terms of directions of expected disturbance in wrench space, and a percentage of the maximal robustness of the grasp, defined by the magnitude of its largest-minimum resisted disturbance wrench. These two elements form a polytope in wrench space, representing expected, admissible disturbance wrenches, and we want our tightening forces to be "optimal" in relation to this polytope, in the sense that the force variations between the tightening forces, on the one hand, and the opposing forces for each disturbance at a vertex of the polytope, on the other hand, are minimal.

Our method of determining those optimal tightening forces somehow merges elements of the problems of grasp quality measure and contact force optimization. It involves the resolution of a linear programming problem and a consecutive quadratic programming problem, both of reasonable dimensions and with no dependence on the number of expected disturbance directions. The first optimization problem computes an approximation of the above-mentioned maximal robustness, i.e. an approximation of the magnitude of the largest-minimum admissible disturbance; it also computes optimal tightening forces for this maximal robustness. The approximation of the maximal robustness is a lower-bound approximation of the quality measure of Zhu, Ding, and J. Wang (2003). The second optimization problem computes optimal tightening forces for a lesser grasp robustness, that is to say according to the wrench polytope defined as robustness objective in the first place (directions of expected disturbance and percentage of the maximal robustness).

Once the optimal tightening forces have been determined, we can integrate them into control schemes of multifingered dextrous manipulation, in particular into our own optimization-based control strategy, presented in chapter 5. We treat those optimal tightening forces as desired values for the contact forces. Because the motion of the object is taken into account in their determination, they are compatible with it, that is to say they do not hinder a manipulation of the object. This achieves robust manipulation.

### 6.5.2 Future work

A limitation of our study is that it implicitly assumes that the grasp is infinitely rigid, with fixed contacts and fingers so stiff that we do not have to take them into account. However, during a disturbance, it is definitively not the case: the fingers move and the contact points move too. Future work should model the compliance of the fingers and of the grasp, and see how it is possible to be closer to the reality when working with disturbances and grasps able to withstand them.

From a mathematical point of view, our approach is somewhat unsophisticated in its determination of the optimal tightening forces. It linearizes the bounded contact cones and uses a lot of approximations. In the end, the problem we solve is quite degraded in comparison to its original, exact formulation, and the maximal robustness is underestimated. Better this than the other way round, of course: overestimating the robustness of the grasp leads to unsafe grasps, thought to be robust to such and such disturbance but possibly not in fact. Still, when compared with the mathematically exact, computationally efficient methods for solving the force optimization problem that have been proposed since the end of the 1990s (see section 6.1.2), our method for determining optimal tightening forces looks a least dated. We should take inspiration from these state-of-the-art approaches to find more elegant and more efficient ways of computing tightening contact forces than this first draft.

Also, it is worth noting that contact forces are not the only solution to keep hold of an object in face of disturbances. The geometry of the grasp can be used, too: this is what happens in power grasps. Also, the stiffness of the grasp can provide some robustness: a hand whose fingers have little compliance is likely to keep hold of an object more easily than a hand with high compliance. In our own hands, stiffness of the fingers and contact forces are highly coupled because of the intricacy of the muscle and tendon actuation system: it is not possible to apply large contact forces without stiffening the fingers (whereas it is possible to stiffen the fingers without applying any contact force). For a robot hand, things are usually simpler. Finger stiffness and contact forces are usually two different things: the first one is function of the servo gains in the joints, the second one is function of the motor power outputted by the actuators. Therefore, finger stiffness can be used as a means to bring some kind of robustness to a grasp, too. The following chapter is about this topic: it investigates grasp stiffness, with the intention of stiffness control of dextrous manipulation.

# 7

# Stiffness modeling for grasping with rolling contacts

## Contents



In the previous chapters, we have been concerned with problems related to motion and force control of dextrous manipulation. Here, we address an issue related to stiffness control, or compliance control as it is called too (compliance is the inverse of stiffness). In dextrous manipulation, stiffness control means producing an elastic behavior of the grasped object around some position of reference, in translation and rotation, by adjusting the elastic behavior of the fingers themselves. In other words, it is the control of the stiffness of the object by the stiffness of the fingers. It is an indirect control strategy, that is to say it is not meant to achieve a given, explicit motion or force objective, but to ensure a desired dynamic behavior of the object.

The anatomical equivalent is co-contraction of the muscles in our forearms and in the proximal part of our hands (this is where the muscles moving our fingers are located, see the section 2.1.2 about muscle and tendon anatomy, in chapter 2). By contracting simultaneously agonist and antagonist muscles, we stiffen the fingers, and if an object is in grasp, it stiffens on its current position too, in the sense that it is less easy to move with the other hand than it was before co-contraction. By adjusting the intensity of the co-contraction, we can produce grasps that are more or less compliant, i.e. the object is more or less easy to move with the other hand. Yet, at the same time, no increase in the contact forces is applied, so this change in the dynamic behavior of the object comes solely from the change in the stiffness of the fingers.

In a humanoid robot hand, muscle co-contraction can be emulated by co-actuation of the flexor and extensor tendons, if the fingers are tendon-driven, or adjustment of the servo gains of the actuators, if the fingers are torque-driven. For instance, let say for simplicity sake that each joint is torque-controlled by a trivial proportional regulator, $\tau = k\,(q^{[d]} - q)$: the servo gain $k$ represents the stiffness of the joint around the desired articular position $q^{[d]}$. So, stiffness control of an object grasped by a multifingered robot hand is choosing the servo gains in order to achieve a desired stiffness of the object around some desired cartesian position.

This control problem requires modeling the elastic behavior of the object, that is to say finding the relation betwen the stiffness of the object and the stiffness of the fingers. Because of the presence of rolling motion at the contacts between the fingers and the object, such modeling happens to be a non-trivial issue, very different from the case of simpler parallel manipulators such as those formed by coordinated manipulators grasping a common workpiece by fixtures. In this chapter, we provide an expression of the cartesian stiffness produced on the object by the fingers, as a function of the cartesian stiffness of the fingers, in the case that the contacts are non-sliding point contacts that can freely roll (on the tangent plane) and twist (around the contact normal). We show that this object-level cartesian stiffness depends not only on the finger stiffness, and of course on the grasp configuration (location of the contact points), but also on the contact forces and on the local geometries of the contacting surfaces. This result was first proven in an article presented at the IEEE/RAS International Conference on Humanoid Robots in 2010 (Michalec and Micaelli 2010), and this chapter is adapted from it.

We begin by presenting the different stiffness relationships of a multifingered grasp, in section 7.1. We also describe our approach to the modeling of grasp stiffness, define our notations and our model, state its hypotheses, and investigate the kinematics of rolling contacts. Once all the equations we need are in place, we calculate in section 7.2 the stiffness produced on the object by the fingers, as a function of the stiffness of the fingers. Section 7.3 confirms this relationship with numerical simulations, and section 7.4 concludes the chapter. An appendix proves a property of rigid body mechanics, used twice in the calculations of section 7.2.

## 7.1 Introduction

### 7.1.1 Problem statement and contribution

#### Joint stiffness

In a robotic multifingered hand, each joint of each finger may have a certain stiffness, characteristic of its elastic behavior. This stiffness is termed passive when it arises from structural reasons and active when it results from motor control.

**Passive stiffness** results from a wide range of mechanical reasons, such as actuator compliance, elasticity in the transmission chain, and fingertip materials. It also stems from structural properties such as couplings between joints or between fingers, through underactuation for instance. It cannot be easily modified, at least not when the hand is in operation.

**Active stiffness** on the other hand can be changed much more easily. As explained above, it results from the servo gains used by the control scheme. So to adjust it, we just need to make sure that the control algorithms in the hand's embedded electronics can specify arbitrarily the gains they use.

The stiffnesses of the joints of a finger may be put together in a characteristic joint stiffness matrix for each finger. Let $K_{art,i}$ denote this stiffness matrix for the $i$-th finger of the hand. It is a square $(n_{dof,i}, n_{dof,i})$ symmetric definite-positive matrix, with $n_{dof,i}$ the number of degrees of freedom of the $i$-th finger. Its diagonal terms are the principal stiffness coefficients of the joints, and its off-diagonal terms, if any, are stiffness couplings between the joints. For a finger with no couplings, $K_{art,i}$ would be the following diagonal matrix:

$$K_{art,i} = \begin{pmatrix} k_1^i & & \\ & \ddots & \\ & & k_{n_{dof,i}}^i \end{pmatrix}$$

The definition of a joint stiffness matrix is actually as follows: let $q^i = (q_1^i, \ldots, q_{n_{dof,i}}^i) \in \mathbb{R}^{n_{dof,i}}$ denote the articular coordinates of the $i$-th finger, and $\tau^i = (\tau_1^i, \ldots, \tau_{n_{dof,i}}^i) \in \mathbb{R}^{n_{dof,i}}$ denote the joint torques of that finger, then:

$$K_{art,i} \stackrel{\text{def}}{=} -\frac{d\tau^i}{dq^i}$$

For the above-mentioned finger with no couplings, this boils down to a classical Hooke-like relationship in the joints:

$$d\tau_p^i = -k_p^i \, dq_p^i \qquad \forall\, p \in \{1, \ldots, n_{dof,i}\}$$

In the general case, both passive and active components are present in $K_{art,i}$, and we can only act on the active one:

$$K_{art,i} = K_{art,i}^{passive} + K_{art,i}^{active}$$

but sometimes the passive component may be negligible in comparison with the active component.

### Cartesian finger stiffness

The joint stiffness of the $i$-th finger results in an equivalent stiffness in the cartesian space, at distal phalanx level, that is to say at end-effector level. We let $K_{dp_i}$ denote the $(6, 6)$ matrix of this cartesian stiffness, written in the frame of the distal phalanx:

$$K_{dp_i} = \begin{pmatrix} K_{tr}^i & K_{cpl}^i \\ K_{cpl}^i & K_{rot}^i \end{pmatrix}$$

This matrix represents the elastic behavior of a generalized spring, working in translation and rotation in the cartesian space at phalanx level (figure 7.1). The $(3,3)$ blocks $K^i_{tr}$ and $K^i_{rot}$ are the linear and angular stiffness matrices of this generalized spring, and the two $K^i_{cpl}$ are possible couplings between these directions (not necessarily the same despite the notation). The whole matrix makes the connection between the infinitesimal change in the linear and angular positions of the distal phalanx and the infinitesimal change in the force and the moment that the distal phalanx applies in response to this change of position:

$$dF_i = -K_{dp_i}\,\delta X_{dp_i} \qquad \text{with } dF_i = \begin{pmatrix} df_i \\ dm_i \end{pmatrix} \text{ and } \delta X_{dp_i} = \begin{pmatrix} \delta x_{dp_i} \\ \delta\theta_{dp_i} \end{pmatrix}$$

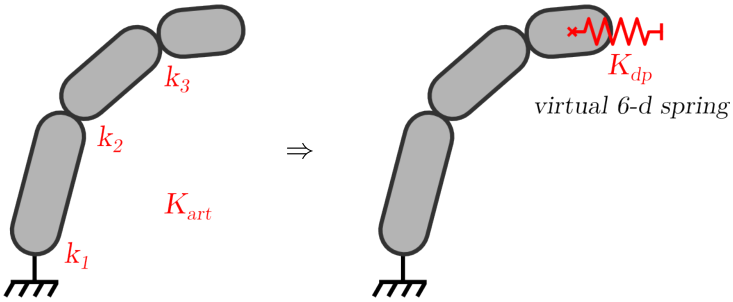



Figure 7.1 – Joint stiffness and cartesian stiffness of a finger

The relationship between $K_{art,i}$ and $K_{dp_i}$ was first given by Salisbury (1980) as a standard change-of-frame formula between joint coordinates and cartesian coordinates:

$$K_{art,i} = J_i^T K_{dp_i} J_i$$

with $J_i$ the jacobian matrix of the $i$-th finger. Salisbury actually proposed this relationship for the general case of a standard serial manipulator. It was generally accepted and applied in studies on stiffness control, but it is in fact incomplete. Indeed, it so happens that the loading of the end-effector, i.e. the contact forces, and the changes in the configuration of the joints as they move under the effect of this loading, i.e. the differential of the jacobian, both contribute to the cartesian stiffness of the finger. Salisbury's original relationship misses a term to account for this contribution. It was corrected by S.-F. Chen and Kao (1999, 2000a):

$$K_{art,i} - K_{g,i} = J_i^T K_{dp_i} J_i$$

The additional term $K_{g,i}$ depends on the changes in the geometry of the finger as it moves under the effect of the contact force $f_i$, and also on the value of this contact force.

Figure 7.2 sums up the stiffness relationships in a finger, in joint space and in cartesian space at phalanx level.

### Cartesian object stiffness

When an object is grasped, the finger stiffnesses induce a total resulting stiffness at object level, in the cartesian space (figure 7.3). We let $K_{obj}$ denote the $(6,6)$ cartesian stiffness matrix, at object level, written in the frame of the object. It is of the same form as $K_{dp_i}$, that is to say two $(3,3)$ blocks for linear and angular stiffnesses and

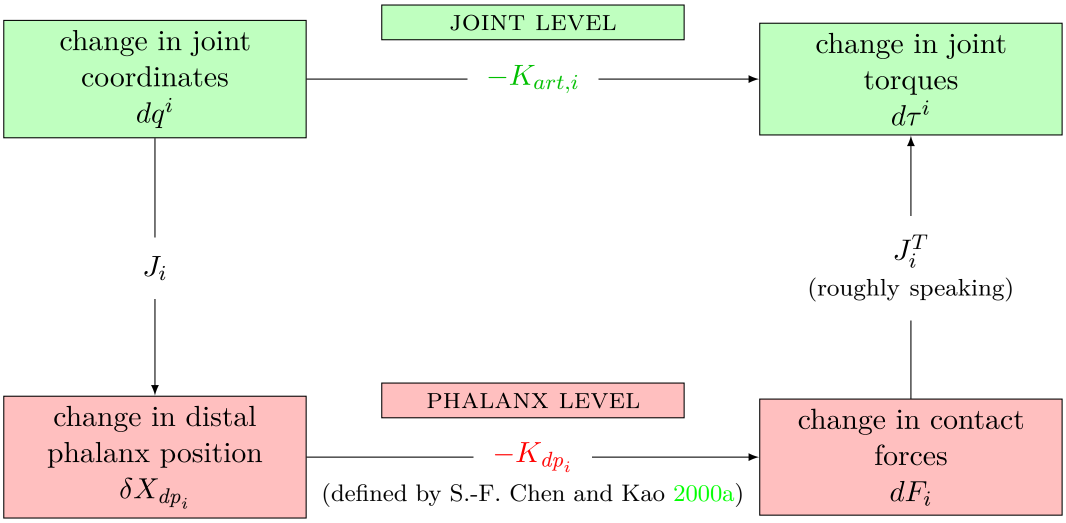



Figure 7.2 – Stiffness mappings at joint and phalanx level, for the $i$-th finger. An arrow from $a$ to $b$ with the matrix $M$ on it means $b = Ma$. "Roughly speaking" means that there is more to it than just a matrix (in the present case, $\tau^i = J_i^T F_i \Rightarrow d\tau^i = J_i^T dF_i + d(J_i^T)F_i$).

two $(3,3)$ blocks for couplings, and it also represents the dynamic behavior of a generalized spring:

$$dF_{obj} = -K_{obj}\,\delta X_{obj} \qquad \text{with } dF_{obj} = \begin{pmatrix} df_{obj} \\ dm_{obj} \end{pmatrix} \text{ and } \delta X_{obj} = \begin{pmatrix} \delta x_{obj} \\ \delta\theta_{obj} \end{pmatrix}$$

$\delta X_{obj}$ represents the infinitesimal changes in the linear and angular positions of the object and $dF_{obj}$ represents the infinitesimal changes in the total contact force and the total contact moment (we voluntarily keep the notations and the formalism simple in this introductory section, but all these quantities will be defined in full precision further in the text).

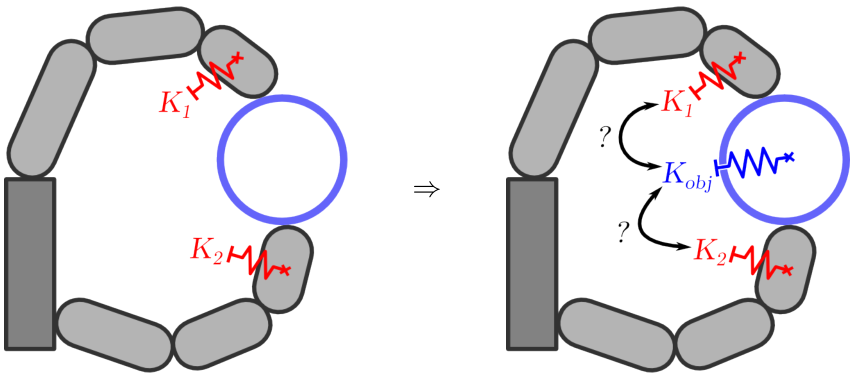



Figure 7.3 – Cartesian finger stiffness and cartesian object stiffness. We look for the relationship represented by the question marks.

The resulting cartesian stiffness $K_{obj}$ produced on the object by the fingers is usually considered equal to the sum of the finger cartesian stiffnesses $K_{dp_i}$, after some change of frame since $K_{obj}$ is typically written in object coordinates and $K_{dp_i}$ in distal phalanx coordinates. That is to say, something like this (see e.g. Kao and Cutkosky 1992, equation 11):

$$K_{obj} = \sum_{i=1}^{n_f} {}^{obj}Ad_{dp_i}^{-T} K_{dp_i} \, {}^{dp_i}Ad_{obj}$$

where $n_f$ is the number of fingers, and ${}^{dp_i}Ad_{obj}$ and ${}^{obj}Ad_{dp_i}^{-T}$ are appropriate change-of-frame matrices. It is clear that if the contacts are fixtures, as happens in cooperative manipulation, then this simple summation formula is true. Examples of works that use this relationship are papers by S. Huang and Schimmels (2001, equation 7) and Pashkevich, Klimchik, Chablat, and Wenger (2009, end of section 3). In the first reference, the stiffnesses to add describe simple, one-dimensional springs; in the second one, they are more general.

In humanoid robot hands, fingertips are generally not fixed on the object, there is some amount of relative motion. If the fingertips are round, they may roll on the surface of the object, and they probably *will* roll in the course of most motions. Fingertips may slide too, although we will assume in this chapter that it is not the case. When relative motion happens, the simple summation formula written above is very incomplete: we prove in this chapter that in the case of non-sliding contacts that can freely roll (on the tangent plane) and twist (around the contact normal), the relationship between $K_{obj}$ and the various $K_{dp_i}$ includes terms that are function of the contact forces between the object and the fingers, and of the curvatures of the surfaces in contact.

We prove this fact constructively, by deriving the whole relationship between $K_{obj}$ and $K_{dp_i}$. As far as we know, this relationship, in the case that the contacts are not fixtures, was unknown or at least undocumented before we investigated it (Michalec and Micaelli 2010). Yet it is of valuable interest for stiffness control.

Figure 7.4 completes figure 7.2 with the stiffness relationship related to the object. It also makes clear what is already known and what we are looking for.

### Contributions

As explained above, we address the problem of modeling the total stiffness resulting at object level from the stiffness of the fingers, in the case of rolling contacts. We do this in two steps, in sections 7.2.1 and 7.2.2 respectively:

1. We calculate the relationship between the infinitesimal change in linear and angular positions of the object, $\delta X_{obj}$, and the infinitesimal changes in linear and angular positions of the distal phalanges, $\delta X_{dp_i}$. This relationship is indicated with a question mark in figure 7.4. We prove that it is linear: there exist a matrix $M^i$, function of the cartesian finger stiffness $K_{dp_i}$, of the generalized contact force $F_i$, and of the relative curvature $\Gamma_{rel,i}$ of the surfaces in contact at the $i$-th contact point, such that:

   $$\delta X_{dp_i} = M^i(\Gamma_{rel,i}, F_i, K_{dp_i}) \, \delta X_{obj}$$

   The explicit expression of this linear map constitutes our first contribution.

2. Once this relationship is known, it becomes easy to find $K_{obj}$ as a function of the various $K_{dp_i}$. By combining the relationships found along the orange arrow in figure 7.5, we get an expression of the object cartesian stiffness $K_{obj}$ as a function of the finger cartesian stiffnesses $K_{dp_i}$, of the contact forces, and of the local geometries of the contacting surfaces.

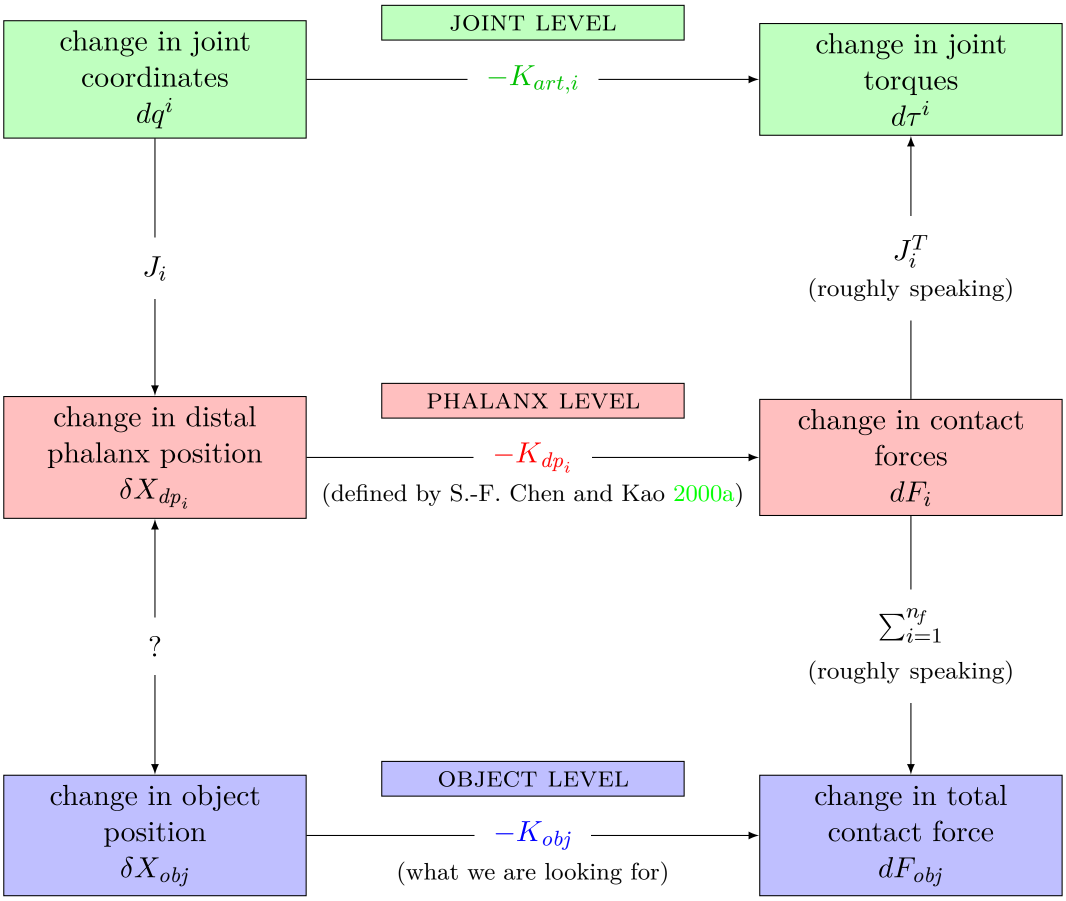



Figure 7.4 – Stiffness mappings at joint, phalanx, and object level. The relationship indicated with a question mark is not trivial to find, contrary to the other relationships in this diagram. We are looking for $K_{obj}$ as a function of $K_{dp_i}$ (and of anything else that will be necessary).

> This expression constitutes our second contribution. Unfortunately, it is far from the elegant simplicity of the congruence transformation that relates the joint stiffness and cartesian stiffness of only one finger.

Those two results are valid under the following model hypotheses: all the bodies are rigid bodies, the contacts are non-sliding point contacts with friction, rolling and twisting of the contacts are possible, and the contacts never break. We will also need to assume the invertibility of a certain matrix.

It is also worth noting that we present a study entirely formulated in the cartesian space: we work at object and phalanx level, but not at joint level, as illustrated in figure 7.5. As a result we get $K_{obj}$ as a function of $K_{dp_i}$, not $K_{art,i}$. For control purposes, it would be better to have this second relationship, though. But it is more difficult to get, because of inversion issues: the conservative congruence transformation of S.-F. Chen and Kao (2000a) expresses $K_{art,i}$ as a function of $K_{dp_i}$, while we would rather have $K_{dp_i}$ as a function of $K_{art,i}$; and the inversion of this relation is not straightforward. Those inversion issues are also visible in figure 7.5, in the direction of the arrows between the quantities at joint level and phalanx level (green and red boxes). These arrows "point the wrong way" to chain easily the relationships with an orange arrow, which should go from $\delta X_{obj}$ to $\delta X_{dp_i}$ to $dq^i$ to $d\tau^i$ to $dF_i$ to $dF_{obj}$, i.e.

it should pass through $K_{art,i}$ rather than $K_{dp_i}$. Reversing these arrows would mean writing $J_i^{-1}$ and $J_i^{-T}$ on them instead of $J_i$ and $J_i^T$, and that is not possible because the jacobian matrix is not invertible (it isn't even a square matrix, generally).

So, in this chapter, we remain at object and distal phalanx level, and we leave the extension to joint level to further research.

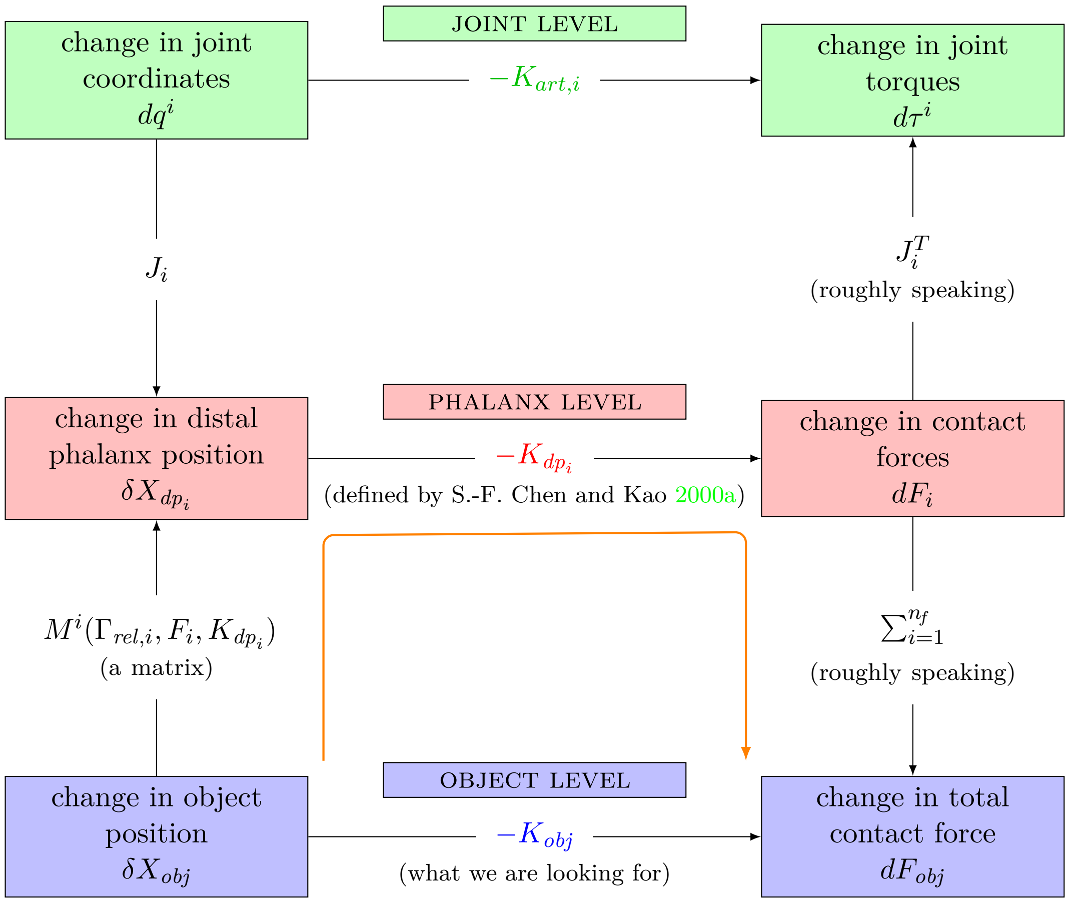



Figure 7.5 – Stiffness mappings at joint, phalanx, and object level.
Our method for finding $K_{obj}$ is represented by the orange arrow.

### 7.1.2 Rigid body mechanics: twists and wrenches

The modeling framework of the study presented here is the same as in the previous chapters: rigid body mechanics, with the formalism of screw theory. It has been presented in detail in chapter 4, and most notations used here have already been used in the previous chapters. We still remind them briefly in this section, for the sake of completeness and self-containment. We also introduce a few new notations found only in this chapter: $\widehat{V}^a_{S_2/S_1}$, $\widehat{W}^a_{S_1\to S_2}$, and $\delta X^a_{S_2/S_1}$.

First, we remind that we let $V^a_{S_2/S_1}$ denote the twist, i.e. the generalized velocity, of some rigid body $S_2$ relatively to some other rigid body $S_1$, written in some frame $a$. We also let $W^a_{S_1\to S_2}$ denote the wrench, i.e. the generalized force, applied by the rigid body $S_1$ to the rigid body $S_2$, written in the frame $a$:

$$V^a_{S_2/S_1} = \begin{pmatrix} v^a_{A\in S_2/S_1} \\ \omega^a_{S_2/S_1} \end{pmatrix} \qquad\qquad W^a_{S_1\to S_2} = \begin{pmatrix} f^a_{S_1\to S_2} \\ m^a_{A,S_1\to S_2} \end{pmatrix}$$

In these expressions, $A$ is the origin of the frame $a$, so that $m^a_{A,S_1\to S_2}$ is the moment in $A$ applied by $S_1$ to $S_2$, written in the basis $a$, and $v^a_{A\in S_2/S_1}$ is the velocity of $A$, *considered as a fixed point* of $S_2$, relatively to $S_1$, written in the basis $a$. The other components, $f^a_{S_1\to S_2}$ and $\omega^a_{S_2/S_1}$, are respectively the force applied by $S_1$ to $S_2$ and the angular velocity of $S_2$ relatively to $S_1$, both written in the basis $a$; they do not depend on the point at which the twist or wrench is written. When writing twists, we often omit $S_1$ if it is the reference body, the "world", i.e. for absolute twists: $V^a_{S_2} = V^a_{S_2/ref}$.

In our notations, the frame or basis specified at top-right position is the frame or basis in which the quantity is written, whatever the quantity. To write a twist or a wrench in another frame, we use the following change of frame formulas:

$$V^a_{S_2/S_1} = {}^aAd_b V^b_{S_2/S_1} \qquad\qquad W^a_{S_1\to S_2} = {}^aAd_b^{-T} W^b_{S_1\to S_2}$$

$${}^aAd_b = \begin{pmatrix} {}^aR_b & \hat{r}^a_{a,b}\,{}^aR_b \\ 0_{3,3} & {}^aR_b \end{pmatrix} \qquad\qquad {}^aAd_b^{-T} = \begin{pmatrix} {}^aR_b & 0_{3,3} \\ \hat{r}^a_{a,b}\,{}^aR_b & {}^aR_b \end{pmatrix}$$

${}^aAd_b$ and ${}^aAd_b^{-T}$ are respectively the adjoint and co-adjoint matrices (of the rigid body transformation from frame $a$ to frame $b$). ${}^aR_b$ is the rotation matrix of basis $b$ with respect to basis $a$, $r^a_{a,b} = \overrightarrow{AB}^a$ is the vector between the origins of the frames, written in basis $a$, and $\hat{r}^a_{a,b}$ is the following skew-symmetric matrix, embedding the operation of left-wise cross-product by vector $r_{a,b}$, in $a$ coordinates:

$$r^a_{a,b} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} \quad \mapsto \quad \hat{r}^a_{a,b} = \begin{pmatrix} 0 & -z & y \\ z & 0 & -x \\ -y & x & 0 \end{pmatrix}$$

$$\text{this matrix meets: } \forall\, u \in \mathbb{R}^3,\ \hat{r}^a_{a,b} u^a = r^a_{a,b} \times u^a$$

For more about twists and adjoints, wrenches and co-adjoints, we refer the reader to the sections 4.2 and 4.3 of chapter 4, respectively, and for more about the cross-product matrix, to the section 4.A.

We let $\Pi$ denote a matrix that selects the first component of a twist or a wrench, for instance $v^a_{A\in S_2/S_1} = \Pi V^a_{S_2/S_1}$, and we let $\Pi'$ denote the one that selects the other component, as in $m^a_{A,S_1\to S_2} = \Pi' W^a_{S_1\to S_2}$:

$$\Pi = \begin{pmatrix} I_3 & 0_{3,3} \end{pmatrix} \qquad\qquad \Pi' = \begin{pmatrix} 0_{3,3} & I_3 \end{pmatrix}$$

Similarly to the cross-product matrix $\hat{r}^a_{a,b}$, we define the following two matrices, relative to a twist and a wrench, and by extension we also denote them with hats and refer to them as cross-product matrices:

$$\widehat{V}^a_{S_2/S_1} = \begin{pmatrix} \hat{\omega}^a_{S_2/S_1} & \hat{v}^a_{A\in S_2/S_1} \\ 0_{3,3} & \hat{\omega}^a_{S_2/S_1} \end{pmatrix} \qquad\qquad \widehat{W}^a_{S_1\to S_2} = \begin{pmatrix} 0_{3,3} & \hat{f}^a_{S_1\to S_2} \\ \hat{f}^a_{S_1\to S_2} & \hat{m}^a_{A,S_1\to S_2} \end{pmatrix}$$

It is worth noting that the wrench-relative cross-product matrix is skew-symmetric:

$$(\widehat{W}^a_{S_1\to S_2})^T = \begin{pmatrix} 0_{3,3} & (\hat{f}^a_{S_1\to S_2})^T \\ (\hat{f}^a_{S_1\to S_2})^T & (\hat{m}^a_{A,S_1\to S_2})^T \end{pmatrix} = \begin{pmatrix} 0_{3,3} & -\hat{f}^a_{S_1\to S_2} \\ -\hat{f}^a_{S_1\to S_2} & -\hat{m}^a_{A,S_1\to S_2} \end{pmatrix} = -\widehat{W}^a_{S_1\to S_2}$$

It is not the case of the twist-relative cross-product matrix [1] though.

We also formulate an infinitesimal displacement $\delta X^a_{S_2/S_1}$ of body $S_2$ relatively to body $S_1$, during $dt$, and written in frame $a$, as:

$$\delta X^a_{S_2/S_1} = V^a_{S_2/S_1} dt = \begin{pmatrix} \delta x^a_{A\in S_2/S_1} \\ \delta\theta^a_{S_2/S_1} \end{pmatrix}$$

that is to say, the integral of $V^a_{S_2/S_1}$ over $dt$. The vector $\delta\theta_{S_2/S_1}$ is along the instantaneous axis of rotation of body $S_2$ relatively to body $S_1$, since it is $\omega_{S_2/S_1} dt$.

In the rest of this chapter, as in the previous chapters in fact, some quantities miss a frame specification in the top-right position, for brevity of the expressions. When unspecified, a frame is the most "natural" frame for the quantity. For instance, we have already encountered $K_{dp_i}$ and $K_{obj}$, in section 7.1.1. They are written respectively in the frames of the phalanx and the object, that is to say:

$$K_{dp_i} = K^{dp_i}_{dp_i} \qquad\qquad K_{obj} = K^{obj}_{obj}$$

### 7.1.3 Hand and object models

#### Frames and notations

The robot hand we consider consists of $n_f$ fingers grasping a rigid object in three-dimensional space at $n_f$ point contacts with friction. The $i$-th finger, $i \in [|1, n_f|]$ [2], is illustrated in figure 7.6, together with the various frames we use. We place no restriction on the number of phalanges and joints. Anyway they won't play any role since we only work in the cartesian space at object and distal phalanx level, as explained in section 7.1.1.

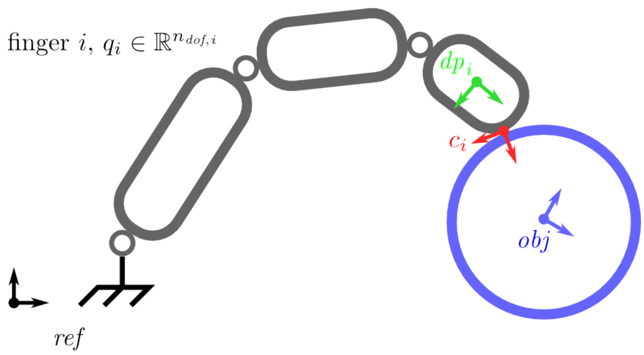



Figure 7.6 – The reference frame, the object, and the $i$-th finger, $i \in [|1, n_f|]$

$dp_i$ denotes both the distal phalanx and its main frame, located at the phalanx center of mass. $ref$ is an inertial reference frame and $obj$ is the object, or its frame. $c_i$ is both the contact point and a contact frame at the interface between the object and the finger, with outward-pointing normal with respect to the distal phalanx. $dp_i$ and

1. This matrix is called the "small adjoint" in many textbooks on differential geometry, and it is denoted $\mathfrak{ad}_b$ (or equivalent notation).

2. This notation is for an integer interval: $[|1, n|] = \{1, \ldots, n\}$.

$obj$ are rigidly linked to their respective rigid bodies, whereas $c_i$ can move on the surface of the object and on the surface of the phalanx.

All those frames were used in chapters 5 and 6. The orientation of the contact normal is the only difference: in the previous chapters, it was pointing out of the object; in this chapter, it points out of the distal phalanx.

**Stiffness relationships**

The stiffness relationships at object and distal phalanx level are as follows:

$$dW_{dp\to obj} = -K_{obj}\,\delta X_{obj} \tag{7.1}$$

$$dW_{dp_i\to obj} = -K_{dp_i}\,\delta X_{dp_i} \qquad \forall\, i \in [|1, n_f|] \tag{7.2}$$

In these equations, $K_{obj}$ is the stiffness matrix whose expression we are looking for, and $K_{dp_i}$ are defined by S.-F. Chen and Kao (2000a) from the joint stiffnesses:

$$J_i^T K_{dp_i} J_i = K_{art,i} - K_{g,i} \qquad \forall\, i \in [|1, n_f|]$$

with $K_{g,i}$ defined by S.-F. Chen and Kao too. $\delta X_{dp_i}$ and $\delta X_{obj}$ are the infinitesimal displacement of the $i$-th distal phalanx and the infinitesimal displacement of the object, relative to the reference frame, and written respectively in $dp_i$ and $obj$:

$$\delta X_{dp_i} = \delta X^{dp_i}_{dp_i/ref} \qquad \delta X_{obj} = \delta X^{obj}_{obj/ref}$$

$dW_{dp_i\to obj}$ and $dW_{dp\to obj}$ are the infinitesimal variation in the contact force applied by the $i$-th finger and the infinitesimal variation in the total contact force, written respectively in $dp_i$ and $obj$:

$$dW_{dp_i\to obj} = dW^{dp_i}_{dp_i\to obj} \qquad dW_{dp\to obj} = dW^{obj}_{dp\to obj}$$

The stiffness relationships (7.1) at object level and (7.2) at distal phalanx level are reported in figure 7.7, which is a more detailed version of figure 7.4. In this figure, the equation (7.3) is the differentiation of $W_{dp\to obj} = \sum_{i=1}^{n_f} W^{obj}_{dp_i\to obj}$ after the change of frame $W^{obj}_{dp_i\to obj} = {}^{obj}\!Ad^{-T}_{dp_i} W^{dp_i}_{dp_i\to obj}$:

$$dW_{dp\to obj} = \sum_{i=1}^{n_f} d({}^{obj}\!Ad^{-T}_{dp_i}) W_{dp_i\to obj} + {}^{obj}\!Ad^{-T}_{dp_i} dW_{dp_i\to obj} \tag{7.3}$$

### 7.1.4 Contact kinematics

In this chapter, we assume that the point contacts are non-sliding and that rolling (on the tangent plane) and twisting (around the contact normal) are free motions. We also assume that the contacts always hold.

We note $V^{c_i}_{dp_i/obj}$ the twist of the relative motion between the $i$-th phalanx and the object, written in the contact frame $c_i$, and $v_{c_i\in dp_i/obj}$ and $\omega_{dp_i/obj}$ the linear and angular velocities of this relative motion:

$$V^{c_i}_{dp_i/obj} = \begin{pmatrix} v^{c_i}_{c_i\in dp_i/obj} \\ \omega^{c_i}_{dp_i/obj} \end{pmatrix} \qquad \forall\, i \in [|1, n_f|] \tag{7.4}$$

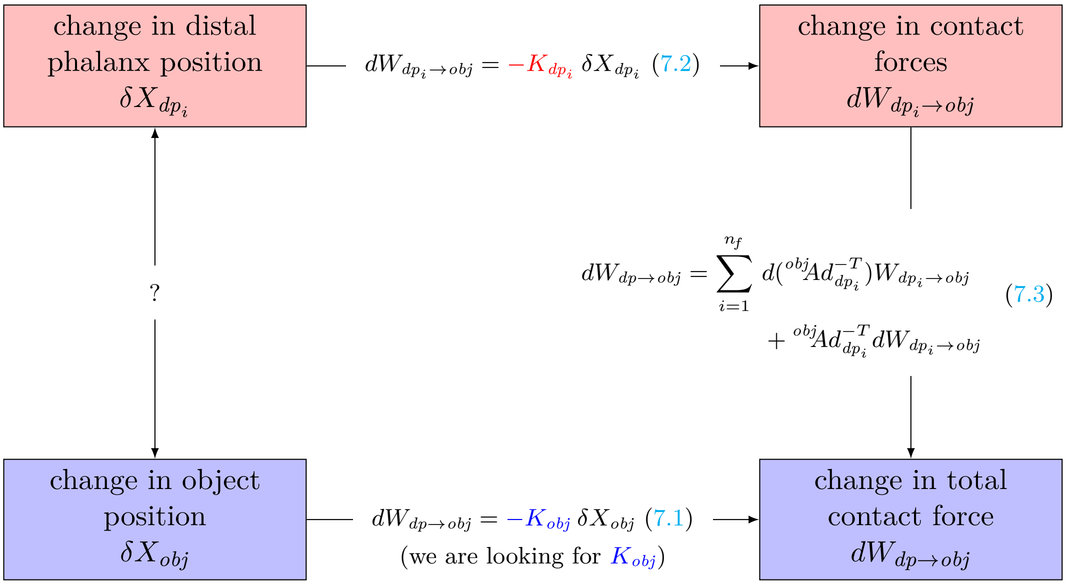



Figure 7.7 – Stiffness mappings in the cartesian space, at phalanx and object levels. Detailed relationships.

This twist may be written as the difference of the absolute twist of the object and the absolute twist of the $i$-th distal phalanx by a mere velocity-addition law, written at the contact point and in $c_i$ coordinates: $V^{c_i}_{dp_i/obj} + V^{c_i}_{obj/ref} = V^{c_i}_{dp_i/ref}$, so for all $i \in [|1, n_f|]$:

$$\begin{aligned} \text{instantaneous formulation: } V^{c_i}_{dp_i/obj} &= V^{c_i}_{dp_i} - V^{c_i}_{obj} \\ \text{in terms of infinitesimal displacements: } \delta X^{c_i}_{dp_i/obj} &= \delta X^{c_i}_{dp_i} - \delta X^{c_i}_{obj} \end{aligned} \tag{7.5}$$

Different components, in $c_i$ coordinates, of the velocities $v_{c_i \in dp_i/obj}$ and $\omega_{dp_i/obj}$ are commonly known as the *sliding*, *rolling*, *twisting* and *breaking* velocities, between the phalanx and the object. Namely:

$$\begin{aligned} (v^{c_i}_{c_i \in dp_i/obj})_{x,y} &= \text{sliding velocity} & (\omega^{c_i}_{dp_i/obj})_{x,y} &= \text{rolling velocity} \\ (v^{c_i}_{c_i \in dp_i/obj})_{z} &= \text{breaking velocity} & (\omega^{c_i}_{dp_i/obj})_{z} &= \text{twisting velocity} \end{aligned}$$

The notations $()_x$, $()_y$, $()_z$, $()_{x,y}$ and so on stand of course for the corresponding coordinates of the vector they enclose. In the case of $c_i$ coordinates, $z$ is the normal vector and $x$, $y$ are the tangent ones.

### Non-sliding and non-breaking

The assumption of non-sliding and the condition of non-breaking combine into:

$$\begin{aligned} v_{c_i \in dp_i/obj} &= 0_{3,1} \\ \text{in other words: } \Pi\, V^{c_i}_{dp_i/obj} &= 0_{3,1} \end{aligned} \tag{7.6}$$

and in terms of infinitesimal displacements:

$$\Pi\, \delta X^{c_i}_{dp_i/obj} = 0_{3,1} \text{ or with (7.5): } \Pi\, \delta X^{c_i}_{dp_i} = \Pi\, \delta X^{c_i}_{obj} \tag{7.7}$$

### Free rolling and free twisting

Free rolling and free twisting imply that no moment can be applied by the finger on the object at the contact point:

$$\begin{gathered} m_{c_i, dp_i \to obj} = 0_{3,1} \\ \text{in other words: } \Pi' \, W^{c_i}_{dp_i \to obj} = 0_{3,1} \end{gathered} \tag{7.8}$$

and an obvious consequence is:

$$\Pi' \, dW^{c_i}_{dp_i \to obj} = 0_{3,1} \tag{7.9}$$

Another consequence is that the contact wrench at the $i$-th contact reads, in matrix form and in $c_i$ coordinates:

$$\widehat{W}^{c_i}_{dp_i \to obj} = \begin{pmatrix} 0_{3,3} & \hat{f}^{c_i}_{dp_i \to obj} \\ \hat{f}^{c_i}_{dp_i \to obj} & 0_{3,3} \end{pmatrix}$$

and thanks to this specific, anti-diagonal form, it meets the following identity (easy to verify):

$$\Pi' \, \widehat{W}^{c_i}_{dp_i \to obj} = \Pi' \, \widehat{W}^{c_i}_{dp_i \to obj} \, \Pi^T \, \Pi \tag{7.10}$$

### Kinematics of rolling contacts

When investigating contact kinematics, it is important to make the distinction between the relative motion of the bodies in contact and the motion of the contact point relatively to each body. The following velocities are not necessarily the same:

$v_{c_i/obj}$ = velocity of the contact point $c_i$ relatively to the object (since the contact point moves on the object)

$v_{c_i/dp_i}$ = velocity of the contact point $c_i$ relatively to the distal phalanx (since the contact point moves on the distal phalanx)

$v_{c_i \in dp_i/obj}$ = velocity of the distal phalanx relatively to the object, measured at the contact point $c_i$

$v_{c_i \in obj/dp_i}$ = velocity of the object relatively to the distal phalanx, measured at the contact point $c_i$

the last two velocities verify: $v_{c_i \in dp_i/obj} = -v_{c_i \in obj/dp_i}$

This important distinction between velocities was emphasized in chapter 4, in the section on twists, 4.2.1, and also in chapter 5, at the beginning of the section on contact modeling, 5.1.4. In short, $v_{c_i \in dp_i/obj}$ is the velocity of the point of the distal phalanx that coincides with the contact point $c_i$ at the current time, it is not the velocity of the contact point itself. This is the meaning of the notation $c_i \in dp_i$, as opposed to just $c_i$. Both points $c_i$ and $c_i \in dp_i$ are at the same place at any given time, but with possibly different velocities. The same difference exists on the object, between the points $c_i$ and $c_i \in obj$, and the associated velocities.

All these velocities are related through kinematic equations proven by Montana (1988). There are four equations, verified by $a$) the velocity of the contact point on the object: $v_{c_i/obj}$; $b$) the velocity of the contact point on the distal phalanx:

$v_{c_i/dp_i}$; and $c$) the sliding, rolling, twisting, and breaking velocities: components of $v_{c_i\in dp_i/obj}$ and $\omega_{dp_i/obj}$. Apart from these velocities, only the *geometric parameters* of the surfaces in contact are involved in these relationships, that is to say the metric tensors, curvature forms, and torsion forms of these surfaces.

We use one of Montana's kinematic equations of contact in the derivation of the relationship between $\delta X_{obj}$ and $\delta X_{dp_i}$, the question mark in figure 7.7. The one we use relates the motion of the contact point across the surface of the distal phalanx, $v_{c_i/dp_i}$, and the sliding and rolling velocities. We will not explain all the notions of differential geometry that are necessary to the total understanding of the kinematic equations of contact, though. That would be too long, however interesting the subject is. They are presented by Montana (1988) in his original study, and can be found in any subsequent reference book on multifingered manipulation that deals with the kinematics of rigid contact, for instance those by Murray, Z. Li, and Sastry (1994, chapter 5, section 6.2, pages 248–253) and by Chiacchio and Chiaverini (1998, chapter 5, section 5.3.6, pages 139–141).

In order to describe the motion of the contact point $c_i$ on the phalanx $dp_i$, we define the following pseudo-twist:

$$V^{c_i}_{c_i/dp_i} = \begin{pmatrix} v^{c_i}_{c_i/dp_i} \\ \omega^{c_i}_{c_i/dp_i} \end{pmatrix} \tag{7.11}$$

We call it a pseudo-twist because it is missing a body: twists represent the motion of some rigid body relatively to another, so here the $c_i$ in "$c_i/dp_i$" is supposed to be a rigid body, yet there is no such rigid body at the interface between the finger and the object, so the pseudo-twist makes only little sense. Besides, formally, the linear velocity should be $v^{c_i}_{c_i\in c_i/dp_i}$, which is hardly intelligible. In fact, it is possible to consider the $c_i$ in "$c_i/dp_i$" as a virtual rigid body to which the frame $c_i$ is rigidly linked. Therefore, the first $c_i$ in $v^{c_i}_{c_i\in c_i/dp_i}$ is the contact point, the second one is the virtual body and the third one is the frame of expression: this velocity is indeed the velocity of the contact point $c_i$ in its motion on the distal phalanx $dp_i$, written in the basis $c_i$, and we rather note it $v^{c_i}_{c_i/dp_i}$. Similarly, $\omega^{c_i}_{c_i/dp_i}$ is the rotational velocity of the contact frame $c_i$ relatively to $dp_i$, written in the basis $c_i$. Thus the pseudo-twist is actually a twist, but for the motion of a virtual body (a frame).

This being clear, it is possible to translate into our notations Montana's kinematic equation of contact relative to $v_{c_i/dp_i}$ (Montana 1988, equation 17):

$$(v^{c_i}_{c_i/dp_i})_{x,y} = (\Gamma^{c_i}_{dp_i} + \Gamma^{c_i}_{obj})^{-1} \left[ \begin{pmatrix} -(\omega^{c_i}_{dp_i/obj})_y \\ (\omega^{c_i}_{dp_i/obj})_x \end{pmatrix} - \Gamma^{c_i}_{obj} \begin{pmatrix} (v^{c_i}_{c_i\in dp_i/obj})_x \\ (v^{c_i}_{c_i\in dp_i/obj})_y \end{pmatrix} \right] \tag{7.12}$$

In this equation, $\Gamma^{c_i}_{dp_i}$ and $\Gamma^{c_i}_{obj}$ denote $(2,2)$ matrices that are the curvature forms of the surfaces, at the point of contact, and relatively to the $x$ and $y$ axes of the contact frame $c_i$ (the ones in the tangent plane). Their sum is called the *relative curvature* form.

The original formulation of (7.12) also involves the metric tensor of the surface of the phalanx, however this tensor is a function of the local parameterization chosen for the surface around the contact point. In our case, we can choose at each time $t$ a convenient, orthonormal local coordinate chart to parameterize the surface of the phalanx around the contact point. This yields a metric tensor equal to the identity matrix $I_2$.

Because of non-sliding, equation (7.6), the kinematic equation of contact (7.12) may be simplified as:

$$(v^{c_i}_{c_i/dp_i})_{x,y} = (\Gamma^{c_i}_{dp_i} + \Gamma^{c_i}_{obj})^{-1} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} (\omega^{c_i}_{dp_i/obj})_{x,y} \tag{7.13}$$

Since the contact point always remains on the surface of the phalanx (!), we have $(v^{c_i}_{c_i/dp_i})_z = 0$, an identity that enables the rewriting of (7.13) as:

$$\begin{aligned} v^{c_i}_{c_i/dp_i} &= \begin{pmatrix} (\Gamma^{c_i}_{dp_i} + \Gamma^{c_i}_{obj})^{-1} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} & 0_{2,1} \\ 0_{1,2} & 0 \end{pmatrix} \omega^{c_i}_{dp_i/obj} \\ &\stackrel{\text{def}}{=} \widehat{\Gamma}_{dp_i,obj}\, \omega^{c_i}_{dp_i/obj} \end{aligned} \tag{7.14}$$

Using the matrices $\Pi$ and $\Pi'$ defined in section 7.1.2, as well as the definitions (7.11) and (7.4) of $V^{c_i}_{c_i/dp_i}$ and $V^{c_i}_{dp_i/obj}$, (7.14) can be rewritten as:

$$\Pi\, V^{c_i}_{c_i/dp_i} = \widehat{\Gamma}_{dp_i,obj}\, \Pi'\, V^{c_i}_{dp_i/obj}$$

Eventually, we multiply by $dt$ and use the velocity-addition law (7.5) to get:

$$\Pi\, \delta X^{c_i}_{c_i/dp_i} = \widehat{\Gamma}_{dp_i,obj}\, \Pi'\, (\delta X^{c_i}_{dp_i} - \delta X^{c_i}_{obj}) \tag{7.15}$$

We use this equation in the derivation of the relationship between $\delta X_{obj}$ and $\delta X_{dp_i}$, in section 7.2.1.

## 7.2 Stiffness modeling

As explained in section 7.1.1, we are interested in the relationship between $K_{obj}$ and $K_{dp_i}$. Namely, we look for $K_{obj}$ as a function of the different $K_{dp_i}$.

To find it, we try to express $dW_{dp \to obj}$ as a linear function of $\delta X_{obj}$, i.e. we try to identify $K_{obj}$ in the relationship (7.1). To this aim, we will need no more than six model equations:

- (7.2) The definition of the finger cartesian stiffness matrices $K_{dp_i}$.
- (7.3) The differentiation of the expression of the total contact wrench as the sum of the contact forces.
- (7.5) A simple velocity-addition law at the contact points, written in terms of infinitesimal displacements.
- (7.6) The equation of non-sliding at the contact points, or more exactly its formulation in terms of infinitesimal displacements (7.7).
- (7.8) The equation of free rolling at the contact points, or more exactly its consequences (7.9) and (7.10).
- (7.12) One of Montana's kinematic equation of contact, or more exactly its consequence (7.15).

These model equations make it possible to find a linear relationship between $dW_{dp \to obj}$ and $\delta X_{obj}$, like (7.1), therefore proving constructively the existence of a cartesian stiffness at object level. At the same time, we get the stiffness matrix $K_{obj}$ as a function of the different stiffness matrices $K_{dp_i}$.

### 7.2.1 The linear relationship between $\delta X_{obj}$ and $\delta X_{dp_i}$

For the moment, we are still no further than the situation depicted by the figure 7.7, with an unknown relationship between the infinitesimal changes in position and orientation of the object and the $i$-th distal phalanx, $\delta X_{obj}$ and $\delta X_{dp_i}$.

So first of all, we use the modeling equations enumerated above [3] to prove the first contribution of this chapter: $\delta X_{obj}$ and $\delta X_{dp_i}$ are linearly dependent one another. We provide an expression of this linear map, in the coordinates of the contact frame, that is to say as a relationship between $\delta X^{c_i}_{obj}$ and $\delta X^{c_i}_{dp_i}$. Only appropriate adjoints are needed to write this linear relationship in other coordinates.

#### An expression of $dW^{c_i}_{dp_i \to obj}$

$W_{dp_i \to obj}$ is the contact wrench applied by the $i$-th finger on the object; its expressions in the contact frame $c_i$ and in the distal phalanx frame $dp_i$ are related through the following change of frame formula:

$$W^{c_i}_{dp_i \to obj} = {}^{c_i}Ad^{-T}_{dp_i} W_{dp_i \to obj}$$

By differentiating this relation, using the definition of phalanx-level stiffness (7.2), and using a simple change of frame formula, we yield successively:

$$\begin{aligned} dW^{c_i}_{dp_i \to obj} &= d({}^{c_i}Ad^{-T}_{dp_i}) W_{dp_i \to obj} - {}^{c_i}Ad^{-T}_{dp_i} dW_{dp_i \to obj} \\ &= d({}^{c_i}Ad^{-T}_{dp_i}) W_{dp_i \to obj} - {}^{c_i}Ad^{-T}_{dp_i} K_{dp_i} \delta X_{dp_i} \\ &= d({}^{c_i}Ad^{-T}_{dp_i}) W_{dp_i \to obj} - {}^{c_i}Ad^{-T}_{dp_i} K_{dp_i} {}^{dp_i}Ad_{c_i} \delta X^{c_i}_{dp_i} \end{aligned} \tag{7.16}$$

Then we use the property (7.29) proven in the appendix of this chapter to rewrite (7.16) as:

$$dW^{c_i}_{dp_i \to obj} = \widehat{W}^{c_i}_{dp_i \to obj} \, \delta X^{c_i}_{c_i/dp_i} - {}^{c_i}Ad^{-T}_{dp_i} K_{dp_i} {}^{dp_i}Ad_{c_i} \delta X^{c_i}_{dp_i} \tag{7.17}$$

In the notation $\delta X^{c_i}_{c_i/dp_i}$, according to (7.29), the $c_i$ in "$c_i/dp_i$" is a rigid body to which the frame $c_i$ is rigidly linked. As we explained previously, there is no such rigid body except a virtual one: the $\delta X^{c_i}_{c_i/dp_i}$ coming from the application of (7.29) is exactly the one we used in section 7.1.4, equations (7.11) and following. Consequently, we are entitled to use (7.15), proven in that section. We will also use the previous developments (7.9) and (7.10).

#### A first relationship between $\delta X^{c_i}_{dp_i}$ and $\delta X^{c_i}_{obj}$

First we pre-multiply (7.17) by $\Pi'$ and use (7.9) to write:

$$0_{3,1} = \Pi' \, \widehat{W}^{c_i}_{dp_i \to obj} \, \delta X^{c_i}_{c_i/dp_i} - \Pi' \, {}^{c_i}Ad^{-T}_{dp_i} K_{dp_i} {}^{dp_i}Ad_{c_i} \, \delta X^{c_i}_{dp_i}$$

Thanks to (7.10), this equation becomes:

$$0_{3,1} = \Pi' \, \widehat{W}^{c_i}_{dp_i \to obj} \, \Pi^T \, \Pi \, \delta X^{c_i}_{c_i/dp_i} - \Pi' \, {}^{c_i}Ad^{-T}_{dp_i} K_{dp_i} {}^{dp_i}Ad_{c_i} \, \delta X^{c_i}_{dp_i}$$

3. Except (7.3) and (7.5) actually, we don't need them in this section, but will use them in the next one.

Then (7.15) yields:

$$0_{3,1} = \Pi' \,\widehat{W}^{c_i}_{dp_i \to obj} \,\Pi^T \,\widehat{\Gamma}_{dp_i,obj} \,\Pi' \,(\delta X^{c_i}_{dp_i} - \delta X^{c_i}_{obj}) - \Pi' \,{}^{c_i}\!Ad^{-T}_{dp_i} K_{dp_i} \,{}^{dp_i}\!Ad_{c_i} \,\delta X^{c_i}_{dp_i}$$

Eventually we group the resulting terms in $\delta X^{c_i}_{dp_i}$ and $\delta X^{c_i}_{obj}$:

$$\begin{aligned} 0_{3,1} = {} & (\Pi' \,\widehat{W}^{c_i}_{dp_i \to obj} \,\Pi^T \,\widehat{\Gamma}_{dp_i,obj} \,\Pi' - \Pi' \,{}^{c_i}\!Ad^{-T}_{dp_i} K_{dp_i} \,{}^{dp_i}\!Ad_{c_i}) \delta X^{c_i}_{dp_i} \\ & - \Pi' \,\widehat{W}^{c_i}_{dp_i \to obj} \,\Pi^T \,\widehat{\Gamma}_{dp_i,obj} \,\Pi' \,\delta X^{c_i}_{obj} \end{aligned} \tag{7.18}$$

#### A second relationship between $\delta X^{c_i}_{dp_i}$ and $\delta X^{c_i}_{obj}$

The equation (7.18) is a system of three scalar linear equations relating the $(6,1)$ vectors $\delta X^{c_i}_{dp_i}$ and $\delta X^{c_i}_{obj}$: it is not sufficient to derive the one as a linear function of the other, three other scalar linear equations are required.

These equations are provided by the equation of non-sliding (7.7), which relates $\delta X^{c_i}_{dp_i}$ and $\delta X^{c_i}_{obj}$ too. We remind it here for convenience:

$$\Pi \,\delta X^{c_i}_{dp_i} = \Pi \,\delta X^{c_i}_{obj} \tag{7.19}$$

#### Conclusion

Eventually, with (7.18) and (7.19) we have a system of six scalar linear equations between $\delta X^{c_i}_{dp_i}$ and $\delta X^{c_i}_{obj}$:

$$\left\{ \begin{aligned} & (\Pi' \,\widehat{W}^{c_i}_{dp_i \to obj} \,\Pi^T \,\widehat{\Gamma}_{dp_i,obj} \,\Pi' - \Pi' \,{}^{c_i}\!Ad^{-T}_{dp_i} K_{dp_i} \,{}^{dp_i}\!Ad_{c_i}) \,\delta X^{c_i}_{dp_i} \\ & \qquad\qquad - \Pi' \,\widehat{W}^{c_i}_{dp_i \to obj} \,\Pi^T \,\widehat{\Gamma}_{dp_i,obj} \,\Pi' \,\delta X^{c_i}_{obj} = 0_{3,1} \\ & \qquad \Pi \,\delta X^{c_i}_{dp_i} - \qquad\qquad \Pi \,\delta X^{c_i}_{obj} = 0_{3,1} \end{aligned} \right. \tag{7.20}$$

We define the following $(6,6)$ matrices:

$$\Xi_{dp_i} = \begin{pmatrix} \Pi' \,\widehat{W}^{c_i}_{dp_i \to obj} \,\Pi^T \,\widehat{\Gamma}_{dp_i,obj} \,\Pi' - \Pi' \,{}^{c_i}\!Ad^{-T}_{dp_i} K_{dp_i} \,{}^{dp_i}\!Ad_{c_i} \\ \Pi \end{pmatrix}$$

$$\Xi_{obj,i} = \begin{pmatrix} \Pi' \,\widehat{W}^{c_i}_{dp_i \to obj} \,\Pi^T \,\widehat{\Gamma}_{dp_i,obj} \,\Pi' \\ \Pi \end{pmatrix}$$

Equation (7.20) may be rewritten as:

$$\Xi_{dp_i} \,\delta X^{c_i}_{dp_i} - \Xi_{obj,i} \,\delta X^{c_i}_{obj} = 0_{6,1} \tag{7.21}$$

To solve this system in the variables $\delta X^{c_i}_{dp_i}$, we assume that the matrix $\Xi_{dp_i}$ is invertible. We get the following expression of $\delta X^{c_i}_{dp_i}$ as a linear function of $\delta X^{c_i}_{obj}$, which is what we were looking for in this section:

$$\delta X^{c_i}_{dp_i} = \Xi^{-1}_{dp_i} \,\Xi_{obj,i} \,\delta X^{c_i}_{obj} \tag{7.22}$$

or in $dp_i$ and $obj$ coordinates instead of $c_i$ coordinates:

$$\delta X_{dp_i} = {}^{dp_i}\!Ad_{c_i} \,\Xi^{-1}_{dp_i} \,\Xi_{obj,i} \,{}^{c_i}\!Ad_{obj} \,\delta X_{obj} \tag{7.23}$$

### 7.2.2 Expression of $K_{obj}$ as a function of $K_{dp_i}$

Now we are in the situation of figure 7.8, with no question mark any more between $\delta X^{c_i}_{dp_i}$ and $\delta X^{c_i}_{obj}$. To find the object cartesian stiffness matrix $K_{obj}$ as a function of finger cartesian stiffness matrices $K_{dp_i}$, we simply combine the relationships found along the orange arrow.

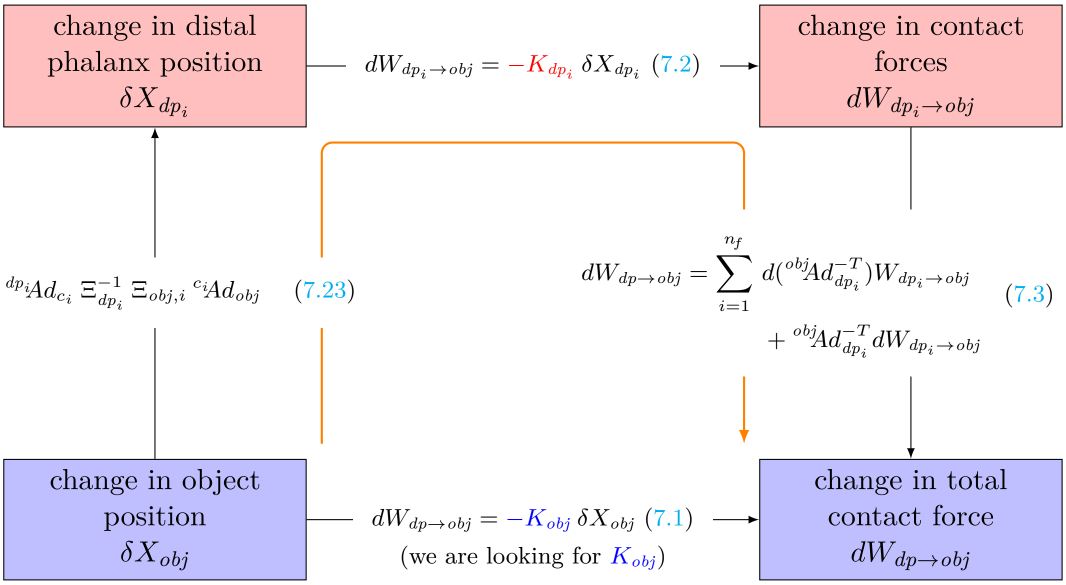



Figure 7.8 – Stiffness mappings in the cartesian space, at phalanx and object levels. Detailed relationships, complete diagram.

#### An expression of $dW_{dp \to obj}$

First we put (7.2) into (7.3) and use a simple change of frame formula to get the following expression of $dW_{dp \to obj}$:

$$dW_{dp \to obj} = \sum_{i=1}^{n_f} d({}^{obj}\!Ad^{-T}_{dp_i}) W_{dp_i \to obj} - {}^{obj}\!Ad^{-T}_{dp_i} K_{dp_i}\, {}^{dp_i}\!Ad_{c_i} \delta X^{c_i}_{dp_i} \tag{7.24}$$

Then we use successively the property (7.29) proven in the appendix, a change of frame formula, and the velocity-addition law (7.5) to rewrite the first term of the right-hand side of (7.24) as follows:

$$\begin{aligned} d({}^{obj}\!Ad^{-T}_{dp_i}) W_{dp_i \to obj} &= \widehat{W}^{obj}_{dp_i \to obj}\, \delta X^{obj}_{obj/dp_i} \\ &= \widehat{W}^{obj}_{dp_i \to obj}\, {}^{obj}\!Ad_{c_i}\, \delta X^{c_i}_{obj/dp_i} \\ &= \widehat{W}^{obj}_{dp_i \to obj}\, {}^{obj}\!Ad_{c_i}\, (\delta X^{c_i}_{obj} - \delta X^{c_i}_{dp_i}) \end{aligned}$$

Consequently, by replacing this expression into (7.24), we see that $dW_{dp \to obj}$ depends linearly on $\delta X^{c_i}_{obj}$ and $\delta X^{c_i}_{dp_i}$:

$$\begin{aligned} dW_{dp \to obj} = \sum_{i=1}^{n_f} & \widehat{W}^{obj}_{dp_i \to obj}\, {}^{obj}\!Ad_{c_i}\, \delta X^{c_i}_{obj} \\ & - ({}^{obj}\!Ad^{-T}_{dp_i} K_{dp_i}\, {}^{dp_i}\!Ad_{c_i} + \widehat{W}^{obj}_{dp_i \to obj}\, {}^{obj}\!Ad_{c_i})\, \delta X^{c_i}_{dp_i} \end{aligned} \tag{7.25}$$

or in $dp_i$ and $obj$ coordinates instead of $c_i$ coordinates:

$$\begin{aligned} dW_{dp\rightarrow obj} = \sum_{i=1}^{n_f} & \widehat{W}^{obj}_{dp_i\rightarrow obj}\,\delta X_{obj} \\ & - \left({}^{obj}\!Ad^{-T}_{dp_i} K_{dp_i}\,{}^{dp_i}\!Ad_{obj} + \widehat{W}^{obj}_{dp_i\rightarrow obj}\right)\,{}^{obj}\!Ad_{dp_i}\,\delta X_{dp_i} \end{aligned} \tag{7.26}$$

#### Conclusion

We replace (7.23) into (7.26) to get:

$$\begin{aligned} dW_{dp\rightarrow obj} = \sum_{i=1}^{n_f} \Big[ & \widehat{W}^{obj}_{dp_i\rightarrow obj} - \left({}^{obj}\!Ad^{-T}_{dp_i} K_{dp_i}\,{}^{dp_i}\!Ad_{obj} + \widehat{W}^{obj}_{dp_i\rightarrow obj}\right)\cdots \\ & \cdots {}^{obj}\!Ad_{c_i}\,\Xi^{-1}_{dp_i}\,\Xi_{obj,i}\,{}^{c_i}\!Ad_{obj}\Big]\,\delta X_{obj} \end{aligned} \tag{7.27}$$

This proves constructively the existence of the stiffness relationship (7.1) in cartesian space, at object level (under the hypotheses of our model and the assumption of invertibility of $\Xi_{dp_i}$). Eventually, we also get $K_{obj}$ as a function of $K_{dp_i}$:

$$\begin{aligned} K_{obj} = \sum_{i=1}^{n_f} \Big[ & \left({}^{obj}\!Ad^{-T}_{dp_i} K_{dp_i}\,{}^{dp_i}\!Ad_{obj} + \widehat{W}^{obj}_{dp_i\rightarrow obj}\right)\cdots \\ & \cdots {}^{obj}\!Ad_{c_i}\,\Xi^{-1}_{dp_i}\,\Xi_{obj,i}\,{}^{c_i}\!Ad_{obj} - \widehat{W}^{obj}_{dp_i\rightarrow obj}\Big] \end{aligned} \tag{7.28}$$

### 7.2.3 Remarks

#### Contributions to the stiffness of the object

We can see in the expression of $K_{obj}$ that it embeds a variety of contributions:

**Finger stiffness** The stiffness of the fingers is of course the most natural contribution. It is represented in (7.28) by the various cartesian stiffness matrices $K_{dp_i}$, present in the main terms ${}^{obj}\!Ad^{-T}_{dp_i} K_{dp_i}\,{}^{dp_i}\!Ad_{obj}$ but also in the matrices $\Xi_{dp_i}$.

These cartesian stiffness matrices $K_{dp_i}$ themselves embed not only the stiffnesses of the joints of the fingers, but also the contributions to stiffness of the contact forces and of the changes in the geometry of the fingers as they move under the effect of the contact forces, as mentioned in section 7.1.1 (and explained by S.-F. Chen and Kao 1999, 2000a).

**Contact forces** The contact forces contribute a second time to $K_{obj}$ through the various $\widehat{W}_{dp_i\rightarrow obj}$. Two of these matrices are visible in (7.28) and two others are hidden in the matrices $\Xi_{dp_i}$ and $\Xi_{obj,i}$.

**Surface curvatures** The relative curvatures, at the contact points, of the surfaces of the fingers and the object, contribute through the terms $\widehat{\Gamma}_{dp_i,obj}$, not visible in (7.28) but present in $\Xi_{dp_i}$ and $\Xi_{obj,i}$.

**Grasp configuration** A number of lever arms, involved in transposing the effects of the contact forces and finger cartesian stiffnesses, from the surface of the object or from the center of the phalanges to the center of mass of the object, also contribute to $K_{obj}$, through the various adjoint and co-adjoint matrices.

### Symmetry and positive-definiteness

Stiffness matrices in robotics are usually defined as symmetric positive-definite matrices, or at least positive semi-definite. If $K_{obj}$ is indeed symmetric positive-definite, then it is not obvious from its expression (7.28); one could even say that it is unlikely to be symmetric positive-definite. Fortunately, there is a case for generally asymmetric[4] stiffness matrices, only a submatrix of which would be positive (semi)-definite.

As a matter of fact, the symmetry and asymmetry properties of cartesian stiffness matrices were investigated before the conservative congruence transformation emerged in the works of S.-F. Chen and Kao (1999, 2000a). Asymmetric cartesian stiffness matrices were introduced and discussed during the 1990s by various researchers, in particular Pigoski, Griffis, and Duffy (Griffis and Duffy 1993; Pigoski, Griffis, and Duffy 1998) and Ciblak and Lipkin (1994). Howard, Žefran, and Kumar also investigated the (a)symmetry properties of cartesian stiffness matrices, in a differential geometry framework (Žefran and Kumar 1996, 1997, 2002; Howard, Žefran, and Kumar 1998). In turn, S.-F. Chen, Y. Li, and Kao exposed in a series of papers why the finger cartesian stiffness matrix $K_{dp_i}$ yielded from the symmetric positive-definite joint stiffness matrix $K_{art,i}$ by their conservative congruence transformation is not symmetric in general (S.-F. Chen and Kao 2000c,b, 2002; S.-F. Chen, Y. Li, and Kao 2001; Y. Li, S.-F. Chen, and Kao 2002; S.-F. Chen 2003, 2005).

Although asymmetric stiffness matrices still remain a matter of mathematical discussion (Kövecses and Angeles 2007; Metzger, Faruk Senan, and O'Reilly 2010), the previous works concluded that in general, the cartesian $(6,6)$ stiffness matrix of a manipulator at end-effector level is asymmetric, with a skew-symmetric part equal to negative one-half of the externally applied load at end-effector, expressed as a cross-product matrix (Ciblak and Lipkin 1994; S.-F. Chen and Kao 2000b), that is to say $-\frac{1}{2}\widehat{W}_{obj\to dp_i}$ in our notations. The cartesian stiffness matrix becomes symmetric:

1. When the manipulator is unloaded (Ciblak and Lipkin 1994; S.-F. Chen and Kao 2000b; Žefran and Kumar 2002).
2. Or when the twists, and consequently the stiffness matrix, are expressed in a generalized, *coordinate* basis of the twist space, rather than in the usual *non-coordinate* basis consisting of three linear velocities and three angular velocities around the same axes (Howard, Žefran, and Kumar 1998; S.-F. Chen and Kao 2000b, 2002; S.-F. Chen, Y. Li, and Kao 2001; S.-F. Chen 2003, 2005).
3. Or when it is restricted to its $(3,3)$ linear part (the upper left quarter of the whole matrix), whatever the physical load and the basis of the twist space are (S.-F. Chen and Kao 2000b; S.-F. Chen, Y. Li, and Kao 2001).

In our modeling, we used the usual, non-coordinate basis of the twist space, and there is a load at the end-effectors of the fingers. As a result the matrices $K_{dp_i}$ are not expected to be symmetric, so we can expect the resulting $K_{obj}$ not to be symmetric either.

Besides, depending on the finger structure (number of degrees of freedom and how their axes are arranged) and on the current articular configuration (if some joints have reached their end stops), there may be cases where the distal phalanges cannot

4. “Asymmetric” means “not symmetric”, not “skew-symmetric”.

move in the six directions of the twist space. A straightforward example is a planar finger (all joint axes are parallel): its distal phalanx has three blocked directions, one in translation and two in rotation. Such blocked directions are directions of infinite stiffness, and the corresponding terms in the cartesian $K_{dp_i}$ would be $+\infty$. Likewise, a planar two-finger pinch grasp would have a resulting $K_{obj}$ with the same blocked directions.

As a result, neither $K_{obj}$ nor $K_{dp_i}$ would qualify as stiffness matrices in the canonical sense of a symmetric, positive (semi)-definite matrix. Yet it remains possible that adequate submatrices correctly describe the elastic behavior of the grasp.

We should however take note that the assumptions of free rolling and free twisting we made directly limit the occurence of pathological cases like the one we are speaking about. For such cases outside our model hypotheses, the expression of $K_{obj}$ remains to be found.

In any case, it appears that there is quite a lot of work ahead to investigate and understand completely the structure, properties and physical meaning of the object cartesian stiffness matrix.

## 7.3 Simulation-based validation

In this section, we report on the simulation of a simple experiment to validate the theoretical result (7.28). We designed this simulated experiment with Arboris (Micaelli and Barthélémy 2006–2010), the dynamical engine we used for the simulations reported in the previous chapters: see chapter 5, sections 5.1.1 and 5.4, and chapter 6, section 6.4, for the description of this physical simulator and of how we use it. In a nutshell, it is a dynamical engine for the simulation of articulated rigid body mechanics, written in Matlab programming language at CEA/LIST [5] and UPMC/ISIR [6]. It is meant to be used in the Matlab programming environment.

The simulated experiment we propose is very basic and constitutes a first test of (7.28) only, nevertheless it makes it possible to verify the consistency of this relationship in a simple test case. This test involves a spherical object of radius $r_{obj} = 2\,\mathrm{cm}$, grasped in a tetrahedron grip by four "cartesian" fingers, namely spheres of radius $r_{dp} = 5\,\mathrm{mm}$, standing in for distal phalanges. Each of these spheres is connected to a fixed position/orientation in space by a six-dimensional elastic link of stiffness matrix $K_{dp_i}$ defined as follows, for various values of $k_{dp,tr}$ and $k_{dp,rot}$:

$$K_{dp_i} = \begin{pmatrix} k_{dp,tr}\, I_3 & 0_{3,3} \\ 0_{3,3} & k_{dp,rot}\, I_3 \end{pmatrix}$$

Also, the four spheres are controlled to apply constant contact forces $W_{dp_i \to obj}$ on the object, such that the object is in static equilibrium at the start of the experiment. Actually, we used optimal tightening forces as defined by the study on grasp robustness presented in chapter 6. The robustness objective is to resist disturbances of 1 N in the six linear directions, i.e. $\pm x$, $\pm y$, $\pm z$. The whole situation is schematically illustrated in figure 7.9.

5. *Commissariat à l'Énergie Atomique, Laboratoire d'Intégration des Systèmes et des Technologies*: French Atomic Energy Commission, Systems and Technologies Integration Laboratory (Fontenay-aux-Roses, south of Paris, France).

6. *Université Pierre et Marie Curie, Institut des Systèmes Intelligents et de Robotique*: Pierre and Marie Curie University, Institute for Intelligent Systems and Robotics (Paris, France).

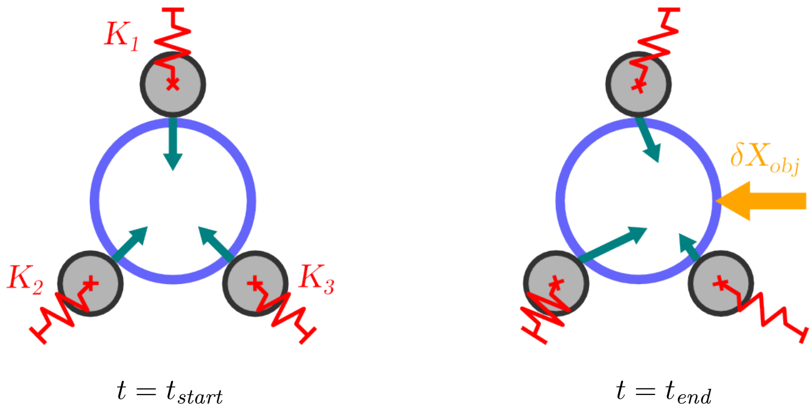



Figure 7.9 – Principle of the simulated experiment (which is actually in three dimensions, with a fourth distal phalanx not illustrated here). All the variations are highly exaggerated for clarity.

The object is subject to small displacements $\delta X_{obj}$ in the six directions of space, that is to say three translations and three rotations. The amplitude of these displacements is 1 mm for the translations and 10° for the rotations. We compare the small force variation $dW_{dp\to obj}$ occuring in the simulation with the small force variation $dW_{dp\to obj}$ predicted by the model (7.27). Let's note $dW^{exp}_{dp\to obj}$ the first one and $dW^{th}_{dp\to obj}$ the second one:

$dW^{exp}_{dp\to obj}$ is simply computed as the difference in the total contact wrench $W_{dp\to obj}$ between the start and the end of the small displacement $\delta X_{obj}$:

$$dW^{exp}_{dp\to obj} = W_{dp\to obj}(t_{end}) - W_{dp\to obj}(t_{start})$$

Actually, $W_{dp\to obj}(t_{start}) = 0_{6,1}$ since the object is in static equilibrium at the start of the displacement and the contact forces are the only forces it is subject to. At the end of the displacement, $W_{dp\to obj}(t_{end}) \neq 0_{6,1}$ even though the object is also in static equilibrium, because the contact forces are not the only forces applied on the object, they oppose the force maintaining the displacement.

$dW^{th}_{dp\to obj}$ is calculated from the theoretical expression of the object stiffness, equations (7.27) and (7.28):

$$dW^{th}_{dp\to obj} = K^{th}_{obj}\,\delta X_{obj}$$

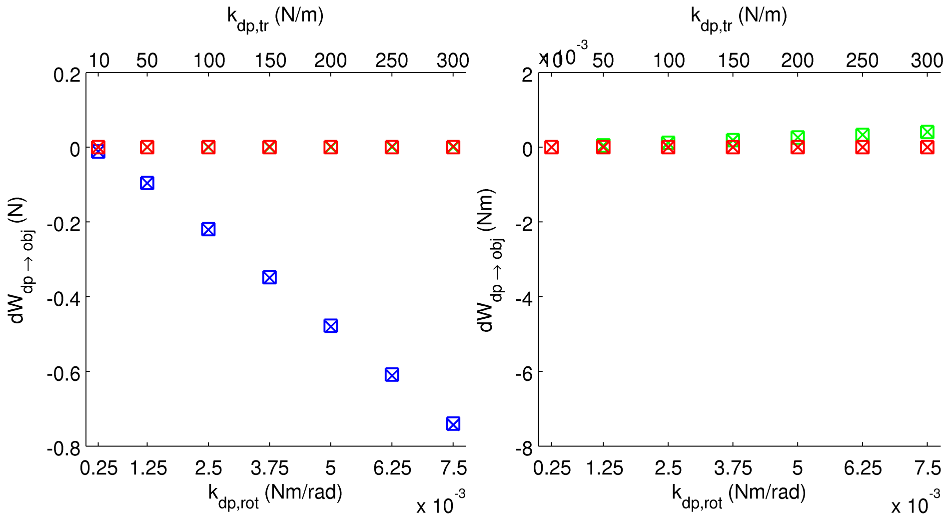
So by comparing the force variations $dW^{th}_{dp\to obj}$ and $dW^{exp}_{dp\to obj}$, we compare the cartesian stiffness matrix as we have modeled it with the cartesian stiffness matrix as it is produced by the finger stiffnesses in the simulated reality.

The results of this comparison are summarized in figure 7.10, 7.11, and 7.12. It appears that for each $\delta X_{obj}$ tested, the theoretical $dW^{th}_{dp\to obj}$ correctly matches the experimental $dW^{exp}_{dp\to obj}$, which indicates that the theoretical $K_{obj}$ of equation (7.28) models correctly the actual cartesian stiffness of the object.

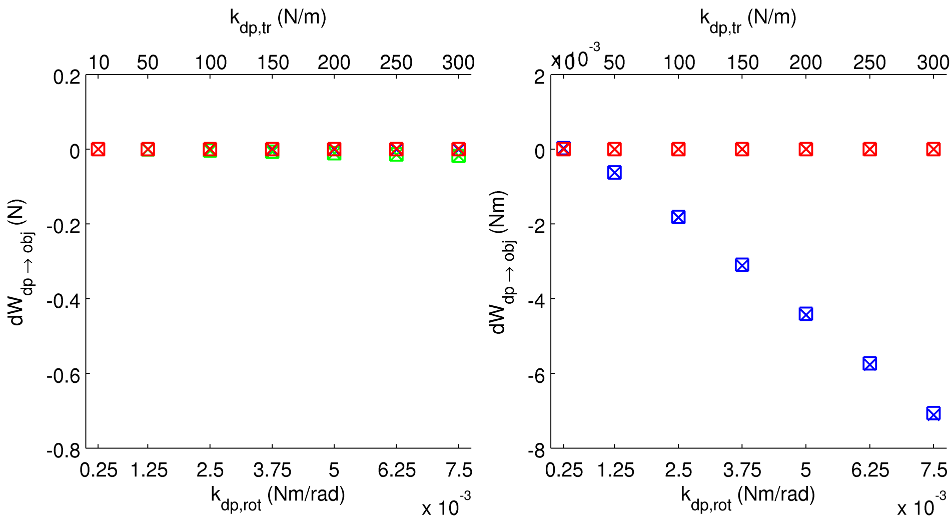
## 7.4 Conclusion

### 7.4.1 Summary

In this chapter, we proved an expression of the cartesian stiffness matrix that models the elastic behavior of an object grasped by a multifingered robot hand whose fingers

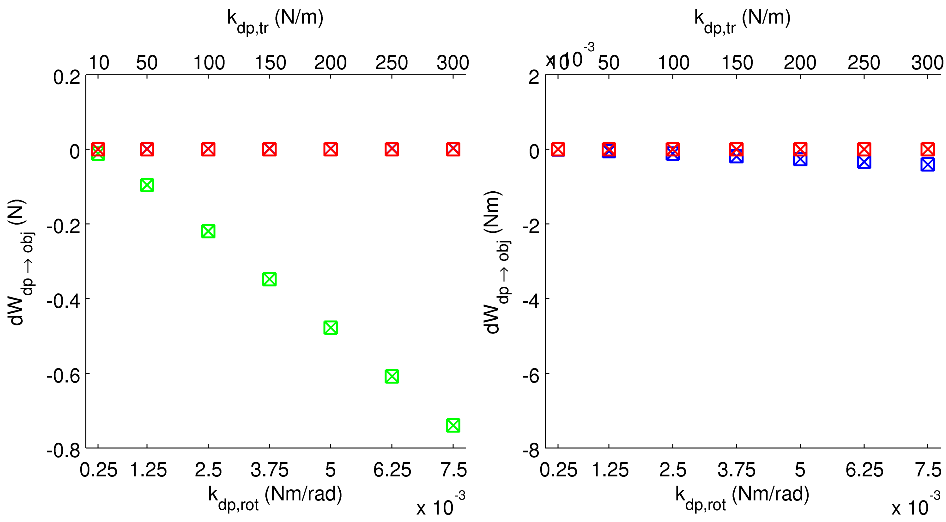



(a) $\delta X_{obj} = 1\,\mathrm{mm}$ along $x$

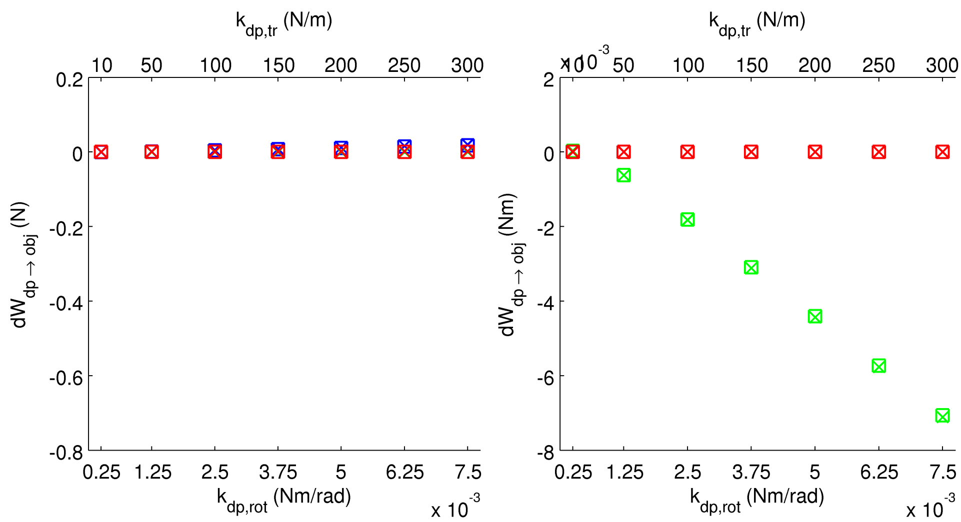



(b) $\delta X_{obj} = 10°$ around $x$

Figure 7.10 – $dW_{dp\to obj}$ as predicted by (7.27) (boxes) and returned by the simulation (ticks), for various values of $k_{dp,tr}$ (top horizontal axis) and $k_{dp,rot}$ (bottom horizontal axis). We tried six different cases of $\delta X_{obj}$; this figure presents the motions relative to the axis $x$ of the object frame. In each case, the left subplot shows the three coordinates of the force part of $dW_{dp\to obj}$ and the right subplot shows the three coordinates of its moment part. Blue, green, and red correspond respectively to the $x$, $y$, and $z$ coordinates of the forces and moments, in the object frame (blue boxes and ticks are sometimes hidden by the green or red ones at the zero horizontal line).

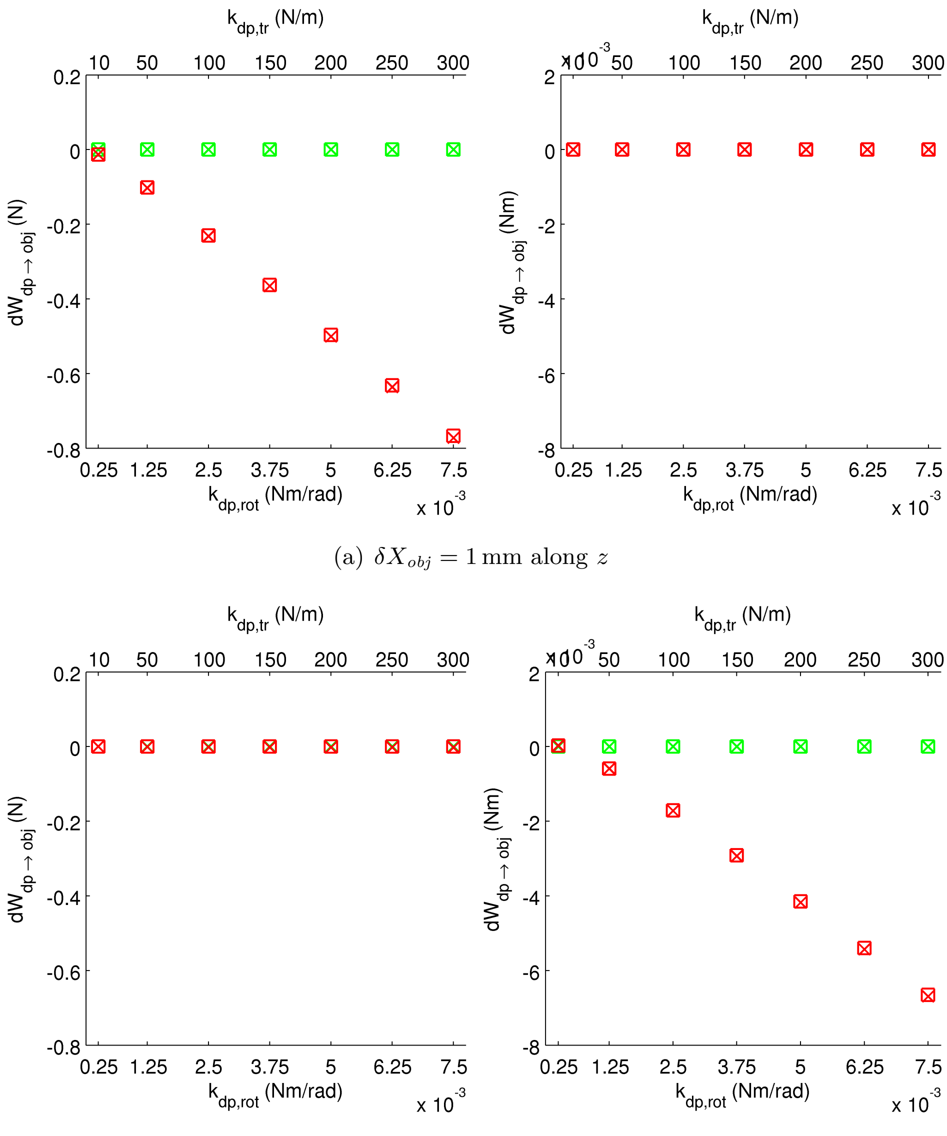



(a) $\delta X_{obj} = 1\,\mathrm{mm}$ along $y$




(b) $\delta X_{obj} = 10°$ around $y$

Figure 7.11 – Same as figure 7.10, but for the motions $\delta X_{obj}$ relative to the axis $y$ of the object frame.




(a) $\delta X_{obj} = 1\,\mathrm{mm}$ along $z$

(b) $\delta X_{obj} = 10°$ around $z$

Figure 7.12 – Same as figures 7.10 and 7.11, but for the motions $\delta X_{obj}$ relative to the axis $z$ of the object frame.

have an elastic behavior too, be it because of mechanical factors (passive stiffness) or control reasons (active stiffness). We proved that this expression is a non-linear function of the finger cartesian stiffness matrices, and depends also on the grasp configuration, the contact forces, and the local geometries of the contacting surfaces (their curvatures at the contact point).

The result we propose is valid under the assumptions that the phalanges and the object are rigid bodies, that the contacts are non-sliding, non-breaking point contacts with free rolling and free twisting, and that a certain matrix encountered during the modeling is invertible. This is mainly the possibility of rolling motion at the contact which made the modeling difficult.

### 7.4.2 Future work

We already underlined in section 7.2.3 the work ahead in the understanding of the structure, properties and physical meaning of the object cartesian stiffness matrix. Certain issues related to symmetry and positive-definiteness need to be investigated, such as the decomposition into symmetric and skew-symmetric parts and the physical interpretation in terms of potential energy and stability. Other issues will require a differential geometry approach, such as the expression of the cartesian stiffness matrix into coordinate bases of the twist space.

Also, we should investigate what happens when model hypotheses are removed or at least restricted. For instance, how is stiffness modeling affected if the rolling motion at the contacts is not possible in all the directions of the tangent plane? Is there still a stiffness relationship at object level if sliding is possible too? The motivation for such questions is that we all know of fingers whose distal phalanges have indeed limited, if not blocked, directions of motion, and whose grasps are still very able to produce an object-level stiffness without any blocked direction: our very own fingers.

Speaking about hypotheses, the invertibility of $\Xi_{dp_i}$ is also an issue to study. The singularities of this matrix should be identified and physically interpreted, which may not be easy, considering the expression of said matrix.

More numerical simulations, if not actual experiments, should be done to test our modeling, and validate or invalidate it. Besides, it would probably be interesting to try and quantify the importance of the various contributions to the stiffness of the object, at least in some numerical simulations. Are the finger stiffnesses the main contributors to the object stiffness? How well do the contact forces compete with the finger stiffnesses, in terms of contribution to the object stiffness? How important is the relative curvature of the surfaces? And if the contacts were fixtures, how different would be the object stiffness?

Last but not least, stiffness control of a multifingered grasp, with rolling contacts and based on the expression we propose for $K_{obj}$, should be tried out. It is, after all, the final purpose of all this stiffness analysis. To this aim, we will probably need to express the object cartesian stiffness matrix $K_{obj}$ as a function of the finger joint stiffness matrices $K_{art,i}$ instead of the finger cartesian stiffness matrices $K_{dp_i}$, as explained in section 7.1.1. That means that we will have to extend our stiffness modeling to the joint level instead of stopping at the distal phalanx level.

As it appears, the stiffness analysis presented in this chapter has opened much more questions than it has answered.

## 7.A Appendix: a relationship from rigid body mechanics

In this appendix, we prove the following property, used twice in this document: let $S_1$, $S_2$, $S_a$ and $S_b$ denote four rigid bodies and $a$ and $b$ denote two frames rigidly linked to $S_a$ and $S_b$ respectively, then:

$$\frac{d}{dt}({}^a\!Ad_b^{-T})\, W^b_{S_2\to S_1} = \widehat{W}^a_{S_2\to S_1}\, V^a_{S_a/S_b} \tag{7.29}$$

This property is not a new result and people fluent in differential geometry will know about it, albeit under a different form and with different notations. For the sake of completeness of the demonstrations of this chapter, we still propose a proof of this result here, in our notations, rather than refer to a specialized reference.

The proof we propose is not conceptually demanding (in terms of the mathematical notions involved), however it is a bit tricky in places and quite long, relying on three preliminary lemmas in the next three sections. Like the property, these lemmas are not new results. We recall them with propositions of demonstrations.

### 7.A.1 Change of frame of a twist-relative cross-product matrix

First of all, we recall the change of basis formula for a $(3,3)$ cross-product matrix (see chapter 4, section 4.A):

$$\hat{r}^a = {}^aR_b\hat{r}^{b\,b}R_a$$

There is a similar result about the change of frame formula for a twist-relative cross-product matrix:

$$\widehat{V}^a_{S_2/S_1} = {}^a\!Ad_b\widehat{V}^b_{S_2/S_1}\,{}^b\!Ad_a \tag{7.30}$$

The proof is elementary, though not straightforward. We start by calculating the right-hand side of (7.30), which is:

$${}^a\!Ad_b\widehat{V}^b_{S_2/S_1}\,{}^b\!Ad_a = \begin{pmatrix} {}^aR_b & \hat{r}^a_{a,b}\,{}^aR_b \\ 0_{3,3} & {}^aR_b \end{pmatrix} \begin{pmatrix} \hat{\omega}^b_{S_2/S_1} & \hat{v}^b_{B\in S_2/S_1} \\ 0_{3,3} & \hat{\omega}^b_{S_2/S_1} \end{pmatrix} \begin{pmatrix} {}^bR_a & \hat{r}^b_{b,a}\,{}^bR_a \\ 0_{3,3} & {}^bR_a \end{pmatrix}$$

After a number of changes of bases for the various $(3,3)$ cross-product matrices:

$${}^a\!Ad_b\widehat{V}^b_{S_2/S_1}\,{}^b\!Ad_a = \begin{pmatrix} \hat{\omega}^a_{S_2/S_1} & \hat{v}^a_{B\in S_2/S_1} + \hat{r}^a_{a,b}\hat{\omega}^a_{S_2/S_1} - \hat{\omega}^a_{S_2/S_1}\hat{r}^a_{a,b} \\ 0_{3,3} & \hat{\omega}^a_{S_2/S_1} \end{pmatrix}$$

From Jacobi identity it is possible to prove $\hat{r}^a_{a,b}\hat{\omega}^a_{S_2/S_1} - \hat{\omega}^a_{S_2/S_1}\hat{r}^a_{a,b} = (r^a_{a,b}\times\omega^a_{S_2/S_1})^\wedge$. Indeed, right-multiplying this relationship by some vector $u$ yields $r^a_{a,b}\times(\omega^a_{S_2/S_1}\times u^a) + \omega^a_{S_2/S_1}\times(u^a\times r^a_{a,b}) = (r^a_{a,b}\times\omega^a_{S_2/S_1})\times u^a$ in a few rewritings. As a matter of fact, this relationship is a general relationship which is nothing more than a rewriting of Jacobi identity. Namely, for any vectors $x$ and $y$:

$$\hat{x}\hat{y} - \hat{y}\hat{x} = (x\times y)^\wedge \tag{J}$$

all the vectors and matrices being written in the same basis of course. Proof from Jacobi identity:

$$\begin{aligned} & x \times (y \times z) + z \times (x \times y) + y \times (z \times x) = 0_{3,1} \\ \Leftrightarrow \quad & \hat{x}\hat{y}z - (x \times y) \times z - \hat{y}\hat{x}z = 0_{3,1} \\ \Leftrightarrow \quad & (\hat{x}\hat{y} - \hat{y}\hat{x})z = (x \times y) \times z \end{aligned}$$

This last relationship being true for all $z \in \mathbb{R}^3$, we have the result (J).

Consequently, the top-right term in the previous matrix may be rewritten: $\hat{v}^a_{B\in S_2/S_1} + (r^a_{a,b} \times \omega^a_{S_2/S_1})\hat{}$. Then we use the linearity of the map $[\hat{}: r \mapsto \hat{r}]$ to re-write this term again: $(v^a_{B\in S_2/S_1} + r^a_{a,b} \times \omega^a_{S_2/S_1})\hat{}$. At last we use a basic change of point for the velocity in the twist $V_{S_2/S_1}$; that is to say, it is just like using an adjoint matrix for a change of frame in which the rotational part is the identity matrix; see also Varignon's relationship in chapter 4, section 4.2. We get: $\hat{v}^a_{A\in S_2/S_1}$.

Thus we have:

$$^aAd_b \widehat{V}^b_{S_2/S_1} {}^bAd_a = \begin{pmatrix} \hat{\omega}^a_{S_2/S_1} & \hat{v}^a_{A\in S_2/S_1} \\ 0_{3,3} & \hat{\omega}^a_{S_2/S_1} \end{pmatrix} = \widehat{V}^a_{S_2/S_1}$$

There is of course a similar result for wrench-relative cross-product matrices. Just for the sake of completeness:

$$\widehat{W}^a_{S_1\to S_2} = {}^aAd_b^{-T} \widehat{W}^b_{S_1\to S_2} {}^aAd_b^{-1}$$

This change of frame formula is slightly different from the corresponding one for twists: the involved matrices are not inverses one another, but transposes. The proof is totally similar though.

### 7.A.2 A remarkable identity

We have the following remarkable identity:

$$(\widehat{V}^a_{S_2/S_1})^T W^a_{S_3\to S_4} + (\widehat{W}^a_{S_3\to S_4})^T V^a_{S_2/S_1} = 0_{6,1} \tag{7.31}$$

The proof consists in trivial matrix calculus and using the skew-symmetry of $\widehat{W}_{S_3\to S_4}$:

$$\begin{aligned} (\widehat{V}^a_{S_2/S_1})^T W^a_{S_3\to S_4} &= \begin{pmatrix} (\hat{\omega}^a_{S_2/S_1})^T & 0_{3,3} \\ (\hat{v}^a_{A\in S_2/S_1})^T & (\hat{\omega}^a_{S_2/S_1})^T \end{pmatrix} \begin{pmatrix} f^a_{S_3\to S_4} \\ m^a_{A,S_3\to S_4} \end{pmatrix} \\ &= \begin{pmatrix} -\hat{\omega}^a_{S_2/S_1} f^a_{S_3\to S_4} \\ -\hat{v}^a_{A\in S_2/S_1} f^a_{S_3\to S_4} - \hat{\omega}^a_{S_2/S_1} m^a_{A,S_3\to S_4} \end{pmatrix} \\ &= \begin{pmatrix} \hat{f}^a_{S_3\to S_4} \omega^a_{S_2/S_1} \\ \hat{f}^a_{S_3\to S_4} v^a_{A\in S_2/S_1} + \hat{m}^a_{A,S_3\to S_4} \omega^a_{S_2/S_1} \end{pmatrix} \\ &= \begin{pmatrix} 0_{3,3} & \hat{f}^a_{S_3\to S_4} \\ \hat{f}^a_{S_3\to S_4} & \hat{m}^a_{A,S_3\to S_4} \end{pmatrix} \begin{pmatrix} v^a_{A\in S_2/S_1} \\ \omega^a_{S_2/S_1} \end{pmatrix} \\ &= \widehat{W}^a_{S_3\to S_4} V^a_{S_2/S_1} \\ (\widehat{V}^a_{S_2/S_1})^T W^a_{S_3\to S_4} &= -(\widehat{W}^a_{S_3\to S_4})^T V^a_{S_2/S_1} \end{aligned}$$

### 7.A.3 Time derivative of an adjoint or co-adjoint matrix

In this section, contrary to the two previous ones, the rigid bodies $S_1$ and $S_2$ are specific: they are rigidly linked to the frames $a$ and $b$ respectively, so we denote them $S_a$ and $S_b$.

The time derivative of the adjoint matrix ${}^aAd_b$ has the following expression:

$$\frac{d}{dt}{}^aAd_b = {}^aAd_b \widehat{V}^b_{S_b/S_a}$$

To proove this, we start with the following expression of the twist of the motion of $S_b$ relatively to $S_a$, written in the frame $b$:

$$V^b_{S_b/S_a} = \begin{pmatrix} v^b_{B\in S_b/S_a} \\ \omega^b_{S_b/S_a} \end{pmatrix} \text{ with } \begin{cases} \hat{\omega}^b_{S_b/S_a} = {}^aR_b^T {}^a\dot{R}_b \\ v^b_{B\in S_b/S_a} = {}^aR_b^T \dot{r}^a_{a,b} = {}^bR_a v^a_{B\in S_b/S_a} \end{cases}$$

This expression is common knowledge; see, for instance, Murray, Z. Li, and Sastry (1994, chapter 2, section 4.2, equation 2.55). It is function of the time derivatives of the translational and rotational components of the homogeneous matrix between $a$ and $b$.

Then we can differentiate ${}^aAd_b = \begin{pmatrix} {}^aR_b & \hat{r}^a_{a,b}{}^aR_b \\ 0_{3,3} & {}^aR_b \end{pmatrix}$:

$$\begin{aligned}
{}^a\dot{A}d_b &= \begin{pmatrix} {}^a\dot{R}_b & \hat{\dot{r}}^a_{a,b}{}^aR_b + \hat{r}^a_{a,b}{}^a\dot{R}_b \\ 0_{3,3} & {}^a\dot{R}_b \end{pmatrix} \\
&\qquad \text{as of course } \dot{\hat{r}} = \hat{\dot{r}} \text{ (element-by-element derivation)} \\
&= \begin{pmatrix} {}^a\dot{R}_b & {}^aR_b\hat{v}^b_{B\in S_b/S_a} + \hat{r}^a_{a,b}{}^a\dot{R}_b \\ 0_{3,3} & {}^a\dot{R}_b \end{pmatrix} \\
&\qquad \text{because } \hat{\dot{r}}^a_{a,b} = \hat{v}^a_{B\in S_b/S_a} = {}^aR_b\hat{v}^b_{B\in S_b/S_a}{}^bR_a \text{ (see expression of} \\
&\qquad V^b_{S_b/S_a} \text{ above, plus change of basis of a cross-product matrix)} \\
&= \begin{pmatrix} {}^aR_b\hat{\omega}^b_{S_b/S_a} & {}^aR_b\hat{v}^b_{B\in S_b/S_a} + \hat{r}^a_{a,b}{}^aR_b\hat{\omega}^b_{S_b/S_a} \\ 0_{3,3} & {}^aR_b\hat{\omega}^b_{S_b/S_a} \end{pmatrix} \\
&\qquad \text{because } {}^a\dot{R}_b = {}^aR_b\hat{\omega}^b_{S_b/S_a} \text{ (see expression of } V^b_{S_b/S_a} \text{ above)} \\
&= \begin{pmatrix} {}^aR_b & \hat{r}^a_{a,b}{}^aR_b \\ 0_{3,3} & {}^aR_b \end{pmatrix} \begin{pmatrix} \hat{\omega}^b_{S_b/S_a} & \hat{v}^b_{B\in S_b/S_a} \\ 0_{3,3} & \hat{\omega}^b_{S_b/S_a} \end{pmatrix} \\
&\qquad \text{the matrix on the left is } {}^aAd_b\text{, the matrix on the right is } \widehat{V}^b_{S_b/S_a}
\end{aligned}$$

It is possible to prove very similarly the following expression of the time derivative of the inverse adjoint matrix ${}^aAd_b^{-1}$:

$$\frac{d}{dt}({}^aAd_b^{-1}) = -\widehat{V}^b_{S_b/S_a}{}^aAd_b^{-1} \tag{7.32}$$

Proof as above, but starting from the time derivation of ${}^aAd_b^{-1} = \begin{pmatrix} {}^aR_b^T & -{}^aR_b^T\hat{r}^a_{a,b} \\ 0_{3,3} & {}^aR_b^T \end{pmatrix}$.

### 7.A.4 Conclusion: proof of the relationship

Now we are ready to prove (7.29). Let $S_1$, $S_2$, $S_a$ and $S_b$ denote four rigid bodies and $a$ and $b$ denote two frames rigidly linked to $S_a$ and $S_b$ respectively. First we transpose (7.32) and get:

$$\frac{d}{dt}({}^a\!Ad_b^{-T}) = -{}^a\!Ad_b^{-T}(\widehat{V}^b_{S_b/S_a})^T$$

Then we use the change of frame formula (7.30) to rewrite this equation as:

$$\begin{aligned}
d({}^a\!Ad_b^{-T}) &= -{}^a\!Ad_b^{-T}({}^b\!Ad_a\widehat{V}^a_{S_b/S_a}{}^a\!Ad_b)^T dt \\
&= -{}^a\!Ad_b^{-T}{}^a\!Ad_b^T(\widehat{V}^a_{S_b/S_a})^T{}^b\!Ad_a^T dt \\
&= -(\widehat{V}^a_{S_b/S_a})^T{}^a\!Ad_b^{-T} dt
\end{aligned}$$

From this relationship and the lemma (7.31), we deduce:

$$\begin{aligned}
d({}^a\!Ad_b^{-T})W^b_{S_2\to S_1} &= -(\widehat{V}^a_{S_b/S_a})^T{}^a\!Ad_b^{-T}W^b_{S_2\to S_1} dt \\
&= -(\widehat{V}^a_{S_b/S_a})^T W^a_{S_2\to S_1} dt \\
&= (\widehat{W}^a_{S_2\to S_1})^T V^a_{S_b/S_a} dt
\end{aligned}$$

And as $\widehat{W}_{S_2\to S_1}$ is skew-symmetric:

$$\begin{aligned}
d({}^a\!Ad_b^{-T})W^b_{S_2\to S_1} &= -\widehat{W}^a_{S_2\to S_1}V^a_{S_b/S_a} dt \\
&= \widehat{W}^a_{S_2\to S_1}V^a_{S_a/S_b} dt
\end{aligned}$$

This last relationship is (7.29).

# 8 Conclusion

## Contents



In this thesis, we have been investigating three problems of multifingered dextrous manipulation control: the control of the motion of the grasped object, the determination of appropriate contact forces, and the elastic behavior given to the object by the compliant nature of the fingers. In this last chapter, we sum up these problems very briefly and recall the main research perspectives that could be developed in the future, as a continuation of the ideas of this work.

## 8.1 Summary

We started this report with information about the human hand and humanoid robot hands, in chapters 1, 2, 3, so as to set the thesis in context. We presented the anatomy and the abilities of our hands, as well as the history and the state of the art of artificial hands in prosthetics and robotics. We explained the reasons why humanoid hands should be preferred to more generic and traditional end effectors, in the case of robots working in human environments, and we also mentioned where in actuation, sensing, and control they lag behind their human counterparts.

Then after a short summary of rigid body mechanics in chapter 4, we dealt with the above-mentioned control problems, in chapters 5, 6, 7.

In chapter 5, we proposed a new control method for multifingered dextrous manipulation, based on mathematical optimization. We formulated the control problem as a constrained optimization problem, whose constraints and objective function come from the equations of the model and the objectives of the control. Solving this optimization problem yields control torques that realize the control objectives as closely as possible (there may be unattainable objectives, or objectives conflicting with each other), while satisfying the equations chosen as constraints (in particular physical and mechanical constraints that must be respected no matter what happens). The control scheme we propose is able to ensure the control of the motion of the object or the force it applies on the environment, both through impedance control actually, as well as the control of the contact forces applied on the object (tightening, in addition to motion), the enforcement of physical consistency of the contact forces and the robot dynamics, non-sliding at the contacts, the observance of torque limits and joint limits, the weak coupling between the distal and proximal interphalangeal joints, and the minimality of control torques on top of that.

In chapter 6, we complemented this optimization-based control scheme with a study of the robustness of the grasp to external disturbances. We proposed a method for calculating tightening contact forces for a multifingered grasp, according to a certain robustness objective against disturbances. This objective is described by a polytope in wrench space, representing expected disturbance wrenches; the vertices of this polytope are the largest of them. We want the tightening forces we look for to be optimal, in the sense that the force variations between them and the contact forces withstanding each disturbance at a vertex of the polytope are minimal. We ensure this optimality by two consecutive constrained optimization problems. The first one makes it possible to find the largest polytope whose disturbances the grasp can withstand, as well as corresponding optimal tightening forces for this limit case (maximal robustness). The second one makes it possible to find optimal tightening forces for a chosen, smaller polytope, representing a lesser robustness to disturbances, but also smaller contact forces. In the end, we obtain optimal contact forces that can be integrated into control schemes of dextrous manipulation, as desired values for the contact forces.

In chapter 7, we investigated a second approach to ensure object restraining: increasing its stiffness by stiffening the fingers. More generally, this chapter was about the elastic behavior given to the object by the compliant nature of the fingers – the fingers being compliant because of mechanical factors (passive stiffness) and/or control reasons (active stiffness). We calculated an analytical expression of the cartesian stiffness matrix that models the elastic behavior of the object, in the case that the relative motion at the interface between the object and the fingers is free rolling without sliding. We proved that this expression is a non-linear function of the finger cartesian stiffness matrices, and that it depends also on the grasp configuration, the contact forces, and the local geometries of the contacting surfaces (their curvatures at the contact point). The modeling of this relation was made difficult by the possibility of rolling motion: in the case that there is no relative motion, the stiffness analysis is trivial, and already known.

## 8.2 Future work

There are numerous research perspectives for the future, in relation to the ideas developed in this thesis. A lot of them can be gathered under the theme of "getting closer to the reality", that is to say dealing with less idealized models and situations.

Indeed, as a whole, our modeling of multifingered dextrous manipulation is very simplified. It is especially visible in the chosen contact model, of course: human hands don't manipulate objects through five rigid point contacts with dry Coulomb friction; nor do robot hands either, their fingertips are at least covered in some kind of compliant plastic. On that matter, we should get closer to the reality, and adapt our control law, robustness study, and stiffness analysis to the case of several contacts per finger, and most importantly to the case of soft finger contacts, with possibly large contact areas.

The simplified character of our modeling is also visible in the fact that in our robustness analysis, the grasp is supposed to be infinitely rigid, with fixed contacts and fingers so stiff that we do not have to take them into account. However, during a disturbance, the fingers move and the contact points move too. This motion should perhaps be taken into account in the determination of the optimal tightening contact forces.

Also, our stiffness analysis requires that the distal phalanx be able to move freely in rotation relatively to the object (free rolling, free twisting). But this is definitely not the way real distal phalanges move, be it ours or robots' ones: their motion is much more constrained. We should investigate what happens when the possible relative motion between the object and the phalanges is determined by the kinematic structure of the fingers, as it is the case in human and robot hands.

The absence of palm motion is also restricting. Of course, in-hand manipulation is primarily due to finger motion, not wrist motion, so leaving out palm motion is not far-fetched. Nevertheless, it is not uncommon for in-hand manipulation to feature some amount of wrist motion too. This should be taken into account, here again to get closer to the reality.

Last but not least, regrasping should not be left out. It is an essential component of in-hand manipulation, whether it happens by controlled sliding and/or controlled rolling, or by finger gaiting (breaking certain contacts and making them again somewhere else). Flipping a pencil over to use its eraser end, then flipping it over again and walking the fingers down the shaft to go back to the lead end and start writing again, all of that in a human-like manner, is a typical example of dextrous manipulation that includes a lot of regrasping (and is out of reach of current humanoid robot hand control schemes). Without aiming straight at this particular manipulation, we should at least try to adapt our control law to manipulations with regrasping.

Before trying to get closer to the reality by “un-simplifying” our models and our assumptions, though, we should test the results proposed in this thesis more extensively. Indeed, numerical tests in dynamic simulation are precious tools to find omissions and loopholes in the theoretical developments, and we could use some more tests. In particular, stiffness control based on our stiffness analysis should be tried out, and it would also be nice to get to test in-hand manipulations of other objects than spheres and boxes: complex shapes, articulated objects, objects attached to the environment, and so on. The time required to code a complex motion objective for the manipulation and the cost of collision detection with complex shapes in Matlab have been somewhat dissuasive for now.

Another research perspective, more related to the theoretical developments, is the investigation of the structure, properties and physical meaning of the cartesian stiffness matrix of the object. We have indeed noticed that its symmetry and positive-definiteness were not evident, similarly to the cartesian stiffness matrix of a finger or a manipulator. All of this needs physical interpretation. Also, the various contributions to the overall stiffness of the object ought to be compared if possible, in order to gain some insight into how important the sources of the object stiffness are: finger stiffness, contact forces, and surface curvatures.

Eventually, it would be interesting to investigate how our control law, robustness study, and stiffness analysis are affected when there is uncertainty in the model of the hand, in the dynamics of the object, and in the position of the contact points. It is indeed a convenience of dynamic simulation that everything can be known about anything in the simulated scene, with tremendous precision. In real life, the knowledge a robot has about itself and the world is dependent on the quantity and quality of its sensors. In other words, our work cannot be applied directly to real robot hands right now: some adaptation is likely to be required.

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**Modélisation et contrôle de la manipulation dextre multidigitale
pour les mains robotisées humanoïdes**

En robotique, lorsque les exigences de dextérité et de polyvalence sont élevées, les effecteurs terminaux traditionnels montrent vite leurs limites et les mains robotisées humanoïdes semblent une alternative séduisante. Malheureusement, si l'on sait aujourd'hui fabriquer de telles mains satisfaisantes sur le plan mécanique, leur utilisation pose toujours problème car leur contrôle est difficile.

Dans cette thèse, on s'est intéressé à trois problèmes relatifs au contrôle des mains robotisées humanoïdes : le contrôle du mouvement de l'objet saisi et des efforts qui lui sont appliqués, le maintien de l'objet en cas de perturbations extérieures, et la raideur de la prise, c'est-à-dire son comportement élastique.

**Mots-clés** Mains robotisées humanoïdes, manipulation dextre, contrôle de la manipulation, forces de serrage, raideur de saisie.

**Laboratoire d'accueil** Cette thèse a été réalisée au Laboratoire de Simulation Interactive du Commissariat à l'Énergie Atomique, à Fontenay-aux-Roses.

**Modeling and control of multifingered dextrous manipulation
for humanoid robot hands**

In robotics, when the demands for dexterity and versatility are high, traditional end effectors quickly show their limits and humanoid robot hands look like an appealing alternative. Unfortunately, although such hands can be built nowadays that are mechanically satisfactory, using them still remains problematic because their control is difficult.

In this thesis, we have investigated three problems related to the control of humanoid robot hands: controlling the motion of the grasped object and the forces it is subject to, keeping hold of the object in case of external disturbances, and calculating the stiffness of the grasp, that is to say its elastic behavior.

**Keywords** Humanoid robot hands, multifingered dextrous manipulation, manipulation control, tightening forces, grasp stiffness.

**Research laboratory** This thesis was prepared at the Interactive Simulation Laboratory, Atomic Energy Commission, Fontenay-aux-Roses, France.