Multimedia Contents

19. Robot Hands

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Multifingered robot hands have a potential capability for achieving dexterous manipulation of objects by using rolling and sliding motions. This chapter addresses design, actuation, sensing and control of multifingered robot hands. From the design viewpoint, they have a strong constraint in actuator implementation due to the space limitation in each joint. After briefly introducing the overview of anthropomorphic end-effector and its dexterity in Sect. 19.1, various approaches for actuation are provided with their advantages and disadvantages in Sect. 19.2. The key classification is (1) remote actuation or build-in actuation and (2) the relationship between the number of joints and the number of actuator. In Sect. 19.3, actuators and sensors used for multifingered hands are described. In Sect. 19.4, modeling and control are introduced by considering both dynamic effects and friction. Applications and trends are given in Sect. 19.5. Finally, this chapter is closed with conclusions and further reading.

Human hands have great potentialities not only for grasping objects of various shapes and dimensions, but also for manipulating them in a dexterous manner. It is common experience that, by training, one can perform acrobatic manipulation of stick-shaped objects, manipulate a pencil by using rolling or sliding motions, perform precise operations requiring fine control of small tools or objects. It is obvious that this kind of dexterity cannot be achieved by a simple gripper capable of open/close motion only. A multifingered robot hand can therefore provide a great opportunity for achieving such a dexterous manipulation in a robotic system. Moreover, we have also to consider that human beings do not use hands only for grasping or manipulating objects. Exploration, touch, perception of physical properties (roughness, temperature, weight, just to mention a few) are other fundamental tasks that we usually are able to perform thanks to our hands. We expect this type of capabilities also from robotic end-effectors and therefore, by adding quite advanced sensing equipments and proper control strategies, we may improve the interaction capabilities with the environment, achieving for example active exploration, detection of sensing surface properties (local friction, impedance, and so on), tasks that are usually very hard or impossible for simple grippers. For these and other reasons the study of multifingered robot hands has strongly interested the research community since the early days of Robotics.

It was in late 1970s that Okada developed a multifingered robot hand with a tendon driving system and demonstrated a nut opening motion [19.1]. In early 1980s, two major projects on multifingered robot hands have been launched: the Stanford/Jet Propulsion Laboratory (JPL; VIDEO 751) hand and the Utah/Massachusetts Institute of Technology (MIT) hand [19.2, 3]. These two robot hands still represent a milestone and a term of comparison for the design of new devices. Since then, several multifingered hands have been designed and developed in a number research institutes all over the world. Among the most known, one can mention the Deutsches Zentrum für Luft- und Raumfahrt (DLR) hand(s) (VIDEO 754, VIDEO 768, and VIDEO 769), Mechanical Engineering Laboratory (MEL) hand, Electro-Technical Laboratory (ETL) hand, Darmstadt hand, Karlsruhe hand, University of Bologna (UB) hand (VIDEO 756, VIDEO 767), Barrett hand (VIDEO 752), Yasukawa hand, Gifu hand, U-Tokyo hand, Hiroshima hand, Soft Pisa/IIT hand (VIDEO 749, VIDEO 750), and many others [19.4–10].

When designing a multifingered hand, on the basis of its utilization, one should first define the following key issues: number and kinematic configuration of the fingers, anthropomorphic or nonanthropomorphic aspect, built-in or remote actuation, transmission system (in case of remote actuation), sensor assignment, integration with a carrying device (robot arm), control. All these aspects are considered in this chapter.

19.1 Basic Concepts

Before illustrating the main issues involved in the design and use of a robotic hand, it is necessary to discuss some basic concepts and definitions often encountered when dealing with these devices. In particular, terms like *dexterity* and *anthropomorphism* must be defined, and their implications on robotic hand design specified.

19.1.1 Anthropomorphic End-Effectors

The term *anthropomorphism* denotes the capability of a robotic end-effector to mimic the human hand, partly or totally, as far as shape, size, consistency, and general aspect (including color, temperature, and so on) are considered. As the word itself suggests, anthropomorphism is related to the external perceivable properties, and is not, itself, a measure of what the hand can do. On the contrary, *dexterity* is related to actual functionality and not to shape or aesthetic factors. In this sense anthropomorphism and dexterity are *orthogonal* concepts, whose reciprocal dependance (at least in the robotic field) has been not proved yet.

As a matter of fact, we can find in the literature anthropomorphic end-effectors with very poor dexterity level, even though they are called *hands*, as the tasks they can perform are limited to very rough grasping procedures [19.11]. Similarly, we can find smart end-effectors, capable of sophisticated manipulation procedures, without any level of anthropomorphism, e.g., the DxGrip-II [19.12]. Anthropomorphism itself is neither necessary nor sufficient to achieve dexterity, although it is quite evident that the human hand achieves a very high level of dexterity and represents a preferential paradigm for dexterous robotic manipulation.

Anthropomorphism is a desirable goal in the design of robotic end-effectors mainly for the following reasons:

- The end-effector can operate in a human-oriented environment (e.g., servicing robots), where tasks may be executed by robots or men as well.
- The end-effector can be tele-operated by a human operator, by means of special-purpose interfaces (e.g., a data-glove), directly reproducing the operator's hand behavior.
- For purposes of entertainment, assistance, and so on, a human-like aspect and behavior may be specifically required, like for humanoid robots.
- For prosthetic devices anthropomorphism is a quite evident design goal. The development of end-effectors for prosthetic purposes [19.13–15] has recently produced so advanced devices that they can be fully considered robotic systems.

While it is difficult to quantify the effective degree of dexterity of a robotic system, its anthropomorphism can be defined in a precise and objective way. In particular, the aspects that mainly contribute to determine the anthropomorphism level of a robotic hand are:

- *Kinematics*: concerning the presence of the main morphological elements (principal upper fingers, secondary upper fingers, opposable thumb, palm).
- *Contact surfaces*: extension and smoothness of the contact surfaces, aspect that reflects on the capability to locate contacts with objects all over the surface of the available links and on the presence of external compliant pads [19.16].

- *Size*: i. e., the size of the robotic hand both referring to the average size of a human hand and the *correct* size ratio between the links.

19.1.2 Dexterity of a Robotic Hand

Besides the *geometrical* reproduction of the human hand, the main research target remains the emulation of those functionalities which make it such a versatile end-effector.

Two are the main capabilities of a human hand:

- *Prehension*, i. e., the hand's ability to grasp and hold objects of different size and shape
- *Apprehension*, or the hand's ability to understand through active touch.

In this sense, the human hand is both an *output* and *input* device [19.17]. As output device, it can apply forces in order to obtain stable grasps or perform manipulation procedures. As input device, it is capable to explore an unknown environment providing information about the state of the interaction with it. The same features are desirable in robot hands. As a matter of fact, the application of robotic systems in unknown environments requires dexterous manipulation abilities to execute complex operations in a flexible way.

A widely accepted definition states that the dexterity of a robotic end-effector is a measure of its capability of changing the configuration of the manipulated object from an initial configuration to a final one, arbitrarily chosen within the device workspace. Generally speaking, with the term *dexterity* we intend the capability of the end-effector, operated by a suitable robotic system, to autonomously perform tasks with a certain level of complexity. An exhaustive review of scientific work developed so far about dexterity of robotic hands, with a quite complete and updated list of references, can be found in [19.18].

Even though the word dexterity itself has a very positive meaning, it may be useful to consider different levels of dexterity, associated with growing complexity and criticality of performable tasks. The dexterity domain for robotic hands can be roughly divided in two main areas, i. e., *grasping* and *internal manipulation*.

Grasping is intended as the capability of constraining objects with a constraint configuration that is substantially invariant with time (the object is fixed with respect to the hand).

Internal manipulation is a controlled motion of the grasped object in the hand workspace, with the constraint configuration changing with time.

Further subdivisions of these two domains have been widely discussed in the literature (different grasp topologies [19.19], different internal manipulation modes based on internal mobility and/or contact sliding or rolling [19.18]).

Although the notion of dexterity is well settled, the way to achieve it remains debated. Factors affecting the actual capabilities of a robotic end-effector are so many that often the analysis and above all the synthesis of dexterous hands do not take into proper consideration some of these elements, namely: morphological features; sensory equipment; control algorithms; task planning strategies; and so on.

19.2 Design of Robot Hands

The mechanical design of an articulated robotic hand can be performed according to many possible design concepts and options, even if a kinematical architecture has already been defined and size and shape specifications imposed. One of the main issues is the design of a proper actuation and transmission system. This aspect is crucial because space and dimensions are usually limited, being in general an anthropomorphic aspect and dimension a design goal to be pursued. Another aspect that is relevant for the design is the adoption of compliant structures (Fig. 19.1), in place of conventional mechanical joints, e.g., rolling pairs [19.20, 21].

Note that, since many solutions and operating concepts can be adopted, what is presented here aims only at illustrating the most significant solutions, and does not pretend to be a complete discussion of all the possible choices.

19.2.1 Actuators Placement and Motion Transmission

In order to actuate the joints of a robot hand, two basic approaches for the placement of the actuators are possible, i. e.:

- Placing the motors as close as possible to each joint, directly in the fingers and sometimes integrating them within the joint itself.
- Placing the motors into the palm or in the forearm; in this case motion is transmitted to each joint by means of (complex) kinematic chains.

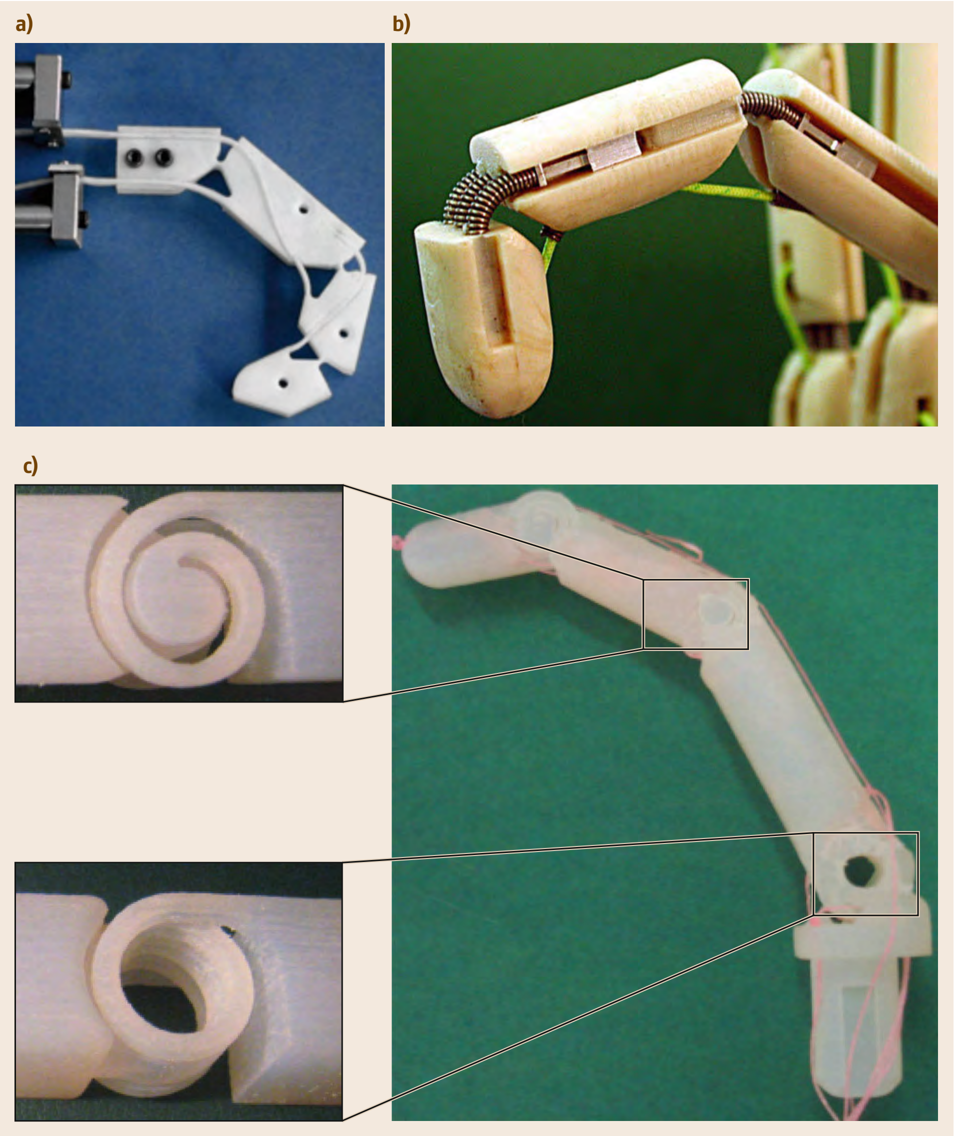


Fig.19.1a–c Three robotic fingers based on compliant joints. **(a)** The finger is obtained in a single teflon piece; **(b)** joint compliance is achieved with metallic springs; **(c)** fast prototyping allows for different compliant mechanisms as joints

In-site actuation can be defined as the case in which the actuator is hosted inside one of the two links connected by the actuated joint or is placed directly inside the joint:

- *Direct-drive actuation*: the actuator is placed directly on the joint, without transmission elements.
- *Link-hosted actuation*: the actuator is placed inside one of the two links constituting the actuated kinematic chain.

In-site actuation simplifies the mechanical configuration of the joint, reducing the transmission chain complexity. In particular, it has the great advantage that the motion of the joint is kinematically independent with respect to other joints. Usually, 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 of the human hand. Furthermore, the motors occupy a large room inside the finger structure, and it is a serious problem to host other elements, like sensors or compliant skin layers. A further negative aspect is that, since the mass of the actuators is concentrated inside the finger, the dynamic behavior of the system and its response bandwidth are reduced.

Nevertheless, the recent advancement of actuator technology enables us to directly implement a quite powerful actuator with reasonable size in each joint.

This built-in actuation has been adopted, e.g., for DLR hand [19.4, 22], ETL hand, Karlsruhe hand, Yasukawa hand, Barrett hand, Gifu hand, U-Tokyo hand, and Hiroshima hand. Since this actuation does not include compliant element like tendons, we can keep a stiff transmission system, which leads to a stable control system even under a high gain (Sect. 19.4). An issue is the routing of wires for both power and signal cables. This issue is more serious in distal joints than for the base joint, since the cables in distal joints produce a relatively large torque disturbance on the first joint, and therefore it is difficult to achieve a precise torque control for this joint.

Remote Actuation

Remote actuation is an alternative solution to in-site actuation. In remote actuation, the joint is driven by actuators placed outside the links connected by the joint itself. Remote actuation requires a motion transmission system, that must pass through the joints between the motor and the actuated joint. In some way, remote actuation must consider the problem of kinematic coupling between the actuated joint and the previous ones. Remote actuation is prevalent in biological structures (e.g., in human hand), where the finger joints are moved by muscles placed on the palm or in the forearm. This human-like approach has been adopted in projects of robotic hands like the UB hand or the National Aeronautics and Space Agency (NASA) Robonaut hand [19.23, 24].

Remote actuation systems can be classified according to the type of adopted transmission elements, i. e., flexible- or rigid-link transmission.

Flexible Link Transmission. Flexible link transmission is based on deformable connections, either flexible or rotational, that can adapt to variations of configuration by changing the transmission path. Linear flexible transmissions are based on flexible elements with translating motion, subject to tension (more frequently) or tension and compression. Two further subcategories can be identified: pulley-routed flexible elements (tendons, chains, belts) or sheath-routed flexible elements (mainly tendon-like elements). Rotational flexible transmissions are based on flexible rotary shafts, that can transmit rotational motion inside the finger structure to the joint, where a final transforming mechanism (a bevel gear or a worm gear) can be used to actuate the joint.

Rigid Link Transmission. Rigid link transmission is mainly based on articulated linkages or on rolling conjugated profiles (mainly gear trains). A further subdivision can be made between parallel and nonparallel axes gear trains, like bevel gears, worm gears, and so on.

19.2.2 Actuation Architectures

Both in-site and remote actuation can be applied according to different types of organization, i. e., by using one ore more actuators for each joint and by making these actuators work in different ways.

In general, we can consider an overall number N of joints for the robotic hand (the wrist joints are not considered) and a number M of actuators that are used to drive, directly or indirectly, the joints. According to different concepts of actuation and transmission, three main categories of actuation schemes can be identified:

- $M < N$: some joints are passive, coupled, or underactuated.
- $M = N$: each joint has its own actuator and there are no passive, coupled or underactuated joints.
- $M > N$: more than one actuator is operating on a single joint.

These architectures strongly depends on the type of motors. In particular, it is possible to recognize two main actuation modalities:

- *Single-acting actuators* – each motor can generate a controlled motion in one direction only: return motion in opposite direction must be obtained by an external action, that can be a passive (e.g., a spring) or an active system (e.g., an antagonistic actuator); this is the case of tendon-based transmission systems.
- *Double-acting actuators* – each motor can generate a controlled motion in both directions and can be used alone to drive the joint or to cooperate with other actuators; in this case the functional redundancy can allow sophisticated drive techniques, like push-pull cooperation.

Each category can be further subdivided. In the following, a brief description of the most frequently adopted schemes is presented.

Single-Acting Actuators with Passive Return Elements

Passive elements, like springs, can store energy during the actuation phase, restituting it during the return stroke (Fig. 19.2a). This mechanism leads to a simplification of actuation scheme, but requires mechanically backdrivable actuators. Other possible drawbacks are related to the loss of available power for the grasp and the limited response bandwidth in case of low spring stiffness.

Agonistic–Antagonistic Single-Acting Actuators

Two actuators drives the same joint, acting in opposition in different directions (agonistic-antagonistic couple) (Fig. 19.2b). This solution leads to an *N joints-2N actuators* scheme and is quite complex since a large number of actuators must be placed in the hand. On the other hand, it may allow sophisticated control procedures, as both actuators can pull at the same time, with different intensity, generating a driving torque on the joint and a preloading of the joint itself (cocontraction, typical of tendon-driven joints):

- *Pros*: cocontraction strategies, possibility to change the joint stiffness according to the grasping phase and therefore to limit the influence of friction during fast approaching motions; independent position/tension control on each actuator can allow compensation of different path length in case of remote transmission; it is the most flexible solution for driving a joint.
- *Cons*: back-drivability of actuators is required; high difficulty in hosting two actuators for each joint, both in in-site and in remote location; higher control complexity; higher cost.

Single-Acting Actuators Organized According to the Concept of Actuation Net

This is a very interesting case, mimicking biological systems, but has not been implemented yet in robotic hands, except for some preliminary studies. N joints are driven by M actuators, being $N < M < 2N$. Each actuator cooperates in moving more than one joint, thanks to proper net-shaped transmissions:

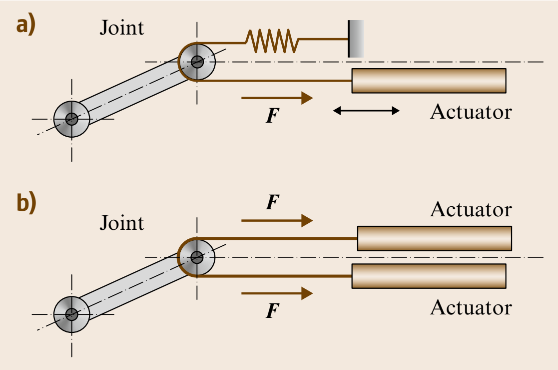


Fig.19.2a,b Single-acting actuator with an antagonist passive element **(a)** and in an agonist-antagonist configuration **(b)**

- *Pros*: cocontraction strategies, possibility to change the joint stiffness according to the grasping phase and therefore to limit the influence of friction during fast approaching motions; reduced number of actuators with respect to the $2N$ actuators scheme.
- *Cons*: back-drivability of actuators is required; high complexity of the kinematic scheme and therefore high complexity in control.

The simplest case of actuation net is represented by the so called $N+1$ *actuation* (being N in this case the number of joints of a finger), frequently adopted in practice (Fig. 19.3). In this case, all actuators are coupled, and therefore a damage of any of them will result in a general failure.

Double Acting Actuators with $M < N$

In this case, the number of actuators is less than the number of joints. With reference to a single motor and several joints, two main subcases can be defined:

1. The joints are kinematically coupled, in a fixed or variable way, so that the number of degrees of freedom of this subsystems is reduced to one.
2. The joints are selectively actuated by the motor, according to an active or passive selection subsystem.

The former case can be further subdivided:

- *Joints kinematically coupled in a fixed way*: In this kind of kinematical configuration, each motor can move more joints connected by rigid mechanisms with fixed transmission ratios. A typical application is obtained with the use of a gear train: the first link is directly actuated by a motor, while a gear transmission between a wheel fixed to the frame and a final wheel connected to the joint generates the relative motion of the second link (Fig. 19.4a). Should the motion of two parallel fingers be required, their connection could be easily obtained mounting two gear wheels on the same shaft. Another very common way to obtain this kind of kinematical linkage is to use tendon driven devices

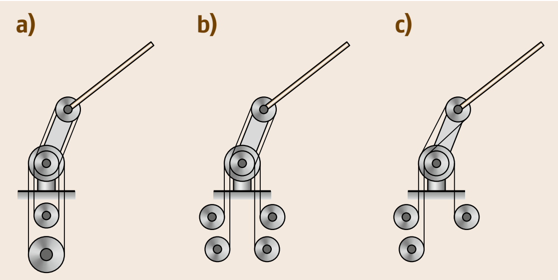


Fig.19.3a–c Remote actuation. **(a)** N-type, **(b)** $2N$-type, **(c)** $N+1$-type

as shown in Fig. 19.4b. In artificial hand design, the main advantage when using joints driven by fixed-ratio mechanisms is the possibility to know and control the position of the second link. A disadvantage is that this kind of mechanisms does not adapt to the shapes of the grasped objects, and this may cause grasp instability.

- *Joints coupled in a non-fixed way*: This is the case of underactuated mechanisms and deformable passive-driven joints. A mechanism is said to be *underactuated* when the number of actuators is smaller than the number of degrees of freedom. When applied to mechanical fingers, this concept may lead to shape adaptation, i. e., underactuated fingers can envelope the objects to be grasped and adapt to their shape even with a reduced number of actuators. In order to obtain a statically determined system, elastic elements and mechanical limits must be introduced in underactuated systems (simple linear spring are often used). In the case of a finger closing on an object, for instance, the configuration of the finger is determined by the external constraints associated with the object. An example of an underactuated two-degrees of freedom finger is shown in Fig. 19.5 [19.25]. The finger is actuated through the lower link, and a spring is used to maintain the finger fully extended. A mechanical limit is used to keep the phalanges aligned under the action of this spring when no external forces are applied on the phalanges. Since the joints cannot be controlled independently, the behavior of the finger is determined by the design parameters (i. e., the geometric and the stiffness properties). Hence, the choice of these design parameters is a crucial issue.
  Another approach consists in coupling the motion of two adjacent joints by means of deformable linkages. This feature introduces in the kinematical chain the needed compliance to fit to the shapes of the grasped objects. A very simple mechanism of this category is reported in Fig. 19.6. Structurally it is similar to the mechanisms based on a fixed coupling, the only important difference is the addition of a spring to give extensibility to the tendon. This spring allows to decouple the motion between the first and second link when an external force is applied to the distal one. This solution is widely used: a well known example is the DLR hand. The benefits of this solution are mainly due to the possibility to fit to the shapes of objects. A design problem is the choice of the stiffness of the deformable element in order to achieve at the same time a strong grasp and a good shape adaptability.
- *Joints selectively driven by only one motor*: With this solution, the motion generated by only one (large) motor is transmitted and distributed to several joints. Actuation and control of each joint is obtained by means of insertion-disinsertion devices like self-acting or commanded clutches.

Double-Acting Actuation, with $M = N$

This is a very common case: each joint is driven in both directions by the same actuator. The achievable performances are therefore similar (equal) in both directions, but particular attention must be paid to backlash, and it is usually necessary to preload the transmission system. In particular, preload is mandatory in case of transmission by means of flexible elements like tendons (Fig. 19.3a). Furthermore, the adoption of a closed-

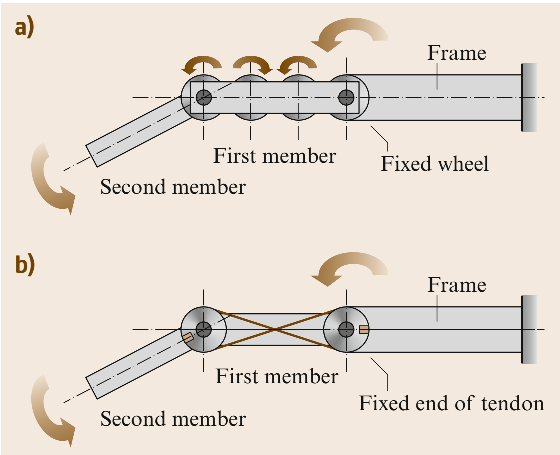


Fig. 19.4 Double-acting actuator with $N = M$ based on gears **(a)** and tendons **(b)**

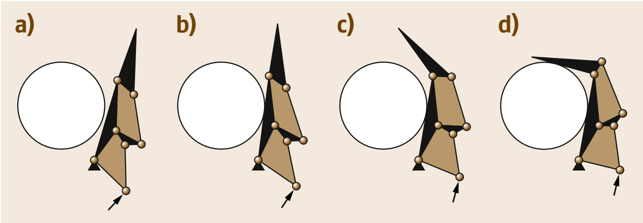


Fig.19.5a–d Grasping sequence performed by a finger based on underactuated mechanism

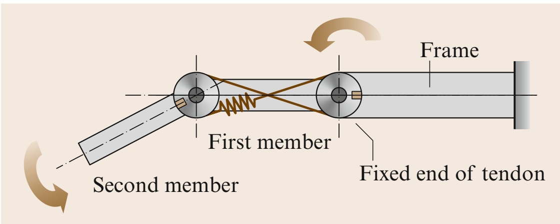


Fig. 19.6 Joints coupled in non fixed way

loop tendon transmission requires that the overall length of the tendon route must be kept constant, according to the concept that winded and unwinded parts of the tendon on the motor pulley have the same length; this involves the need of length-compensating mechanisms (e.g., pulley-trains, cams) every time that changes in the geometry of the finger cause a differential displacement of the tendons. In spite of this required complexity, this actuation scheme has been widely used, with simple pulley routing (UB hand, Okada hand, ...), or sheath-routing (Salisbury hand, Dipartmento di Informatica Sistemica e Telematica (DIST) hand), that has a simpler mechanical structure but must face the problem of sheath-tendon friction (application of high preload is not convenient in this case).

19.3 Technologies for Actuation and Sensing

In this Section, a brief description of the main issues related to technological aspects of actuation and sensing for robot hands is reported. A more general presentation and detailed description of these aspects is given in Part A (Chaps. 4 and 5) and Part C (Chap. 28).

19.3.1 Actuation

Electrical actuators are without doubt the most common choice for actuating robot hands. As a matter of fact, electric motors have very good performance in terms of position/velocity control, have a reasonable mass/power ratio, and are a very common technology, that does not require external devices (as for hydraulic or pneumatic actuators). However, there are several other possibilities. For example: ultrasonic motors (Keio hand [19.26]), chemical actuators, pneumatic actuators (McKibben in the Shadow hand [19.27]; VIDEO 753), spring based actuators (as for the 100G Capturing Robot [19.28] VIDEO 755), twisted string actuators (Fig. 19.7) [19.29] (Dexmart hand [19.30]; VIDEO 767), and others.

In particular, for pursuing quick responses, either pneumatic or spring-based actuators may be good solutions, although it should be noted that a braking system with quick response is essential for achieving good position controllability for this type of actuators.

19.3.2 Sensors

In robot hands, as in other robotic devices, sensors can be classified in two main categories: *proprioceptive* and *exteroceptive* sensors. The first type of sensors measures physical information related to the state of the device itself (e.g., position, velocity, and so on), while the second one is devoted to the measurement of data related to the interaction with objects/environment (e.g., applied forces/torques, friction, shape, and so on).

Joint Position/Velocity Sensors

For control purposes, there is the obvious necessity of measuring position/velocity of the actuated joints. A major problem consists in the limitation of the available space, both for the sensors and for the wires. Different technological solutions can be adopted, but a rather common choice is based on Hall-effect sensors, that are sufficiently small, precise and reliable for this type of application. In case of remote actuation, there is the possibility of having two position/velocity sensors for each joint: one located in the actuator (e.g.,

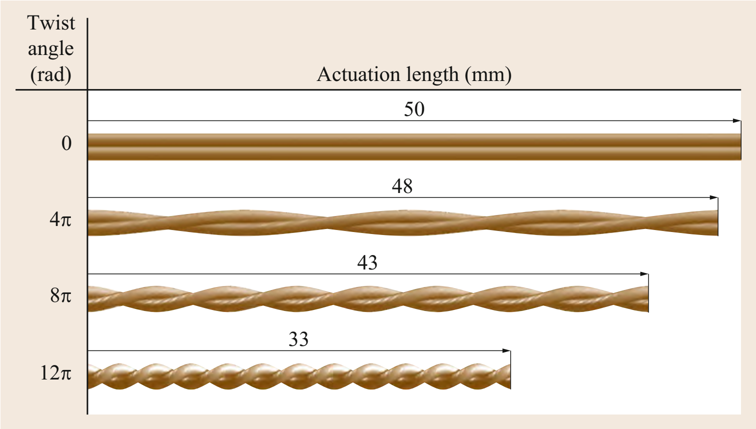


Fig. 19.7 The twisted string concept: by twisting the string, its twisted string concept length is reduced transforming a rotational motion into a linear one

an encoder) and one placed in the joint itself, often necessary because of the non linearities introduced by the transmission system (elasticity, friction, and so on). Quite often, this latter sensor is specifically designed and implemented for the given hand, being commercially available sensors too large and not suitable for installation in the joints.

Tendon Tension Sensor and Joint Torque Sensor

It is well known that humans can control finger tip compliance as well as finger tip force by controlling voluntary muscles. In remote actuation, it is essential to measure the tendon tension for two main reasons: for compensating the friction existing in the transmission system, and for measuring the external contact force. Figure 19.8 shows a way for measuring the tendon tension where the tendon is pressed by an elastic plate with a strain gauge. When a tension is applied to the tendon, the sensor measures a force composed of axial and bending force components. The displacement of the elastic plate due to the axial force component is negligibly small compared with that due to the bending force component. As a result, the bending force component generates a bending deformation for the elastic plate. This deformation is transformed in an electric signal by means of proper transducers, such as strain gauges attached on the surface of the plate or optoelectronic components [19.31, 32]. Now, suppose N-type actuation with two tension sensors, as shown in Fig. 19.9, where joint torque τ is given. Note that $\tau = r(T_1 - T_2)$ where r, T_1, and T_2 are the pulley radius and tendon tensions, respectively. Since we can measure e_1 and e_2 corresponding to T_1 and T_2, τ can be obtained by feeding both e_1 and e_2 into the differential circuit. This approach, however, includes a couple of issues. The main problem is the plastic deformation of the sensor plate under an extreme large pretension. Once such a plastic deformation has happened, the sensor will never work appropriately anymore. Another minor issue is are that two sensors are always necessary for measuring a joint torque. To cope with these issues, the tension-differential-type torque sensor [19.28] can be used as shown in Fig. 19.10. The sensor is designed with just a single body and it partially includes an elastic part where at least one strain gauge is attached. The working principle of the sensor, shown in Fig. 19.10a, supposes that a torque is applied to the joint. This means that T_1 and T_2 have different values. This difference causes a bending force around the strain gauge. The key is that the bending force is kept to zero even under an extremely large tension as far as no joint torque is given. Therefore, we are completely released from the plastic deformation of the elastic plate due to pretension. Furthermore, the sensor is constructed with just a single body. There are couple of variations in this type of torque sensor. As decreasing the pulley distance in Fig. 19.10a, the sensor eventually results in the single-pulley-version with zero distance, as shown in Fig. 19.10b. The single-pulley-version has been implemented into Darmstadt

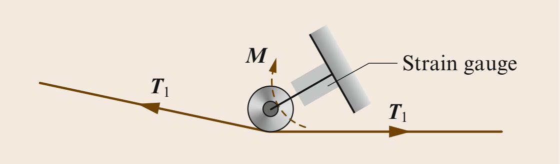


Fig. 19.8 Tendon tension sensing

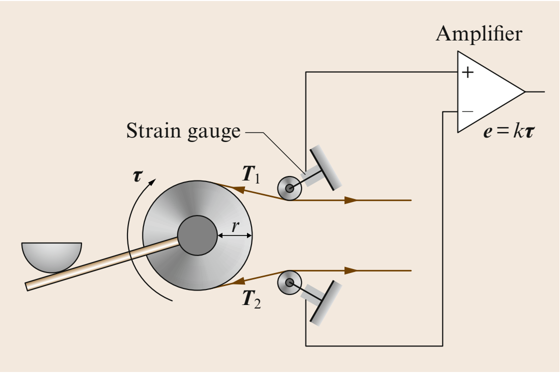


Fig. 19.9 Tension sensor based torque sensing

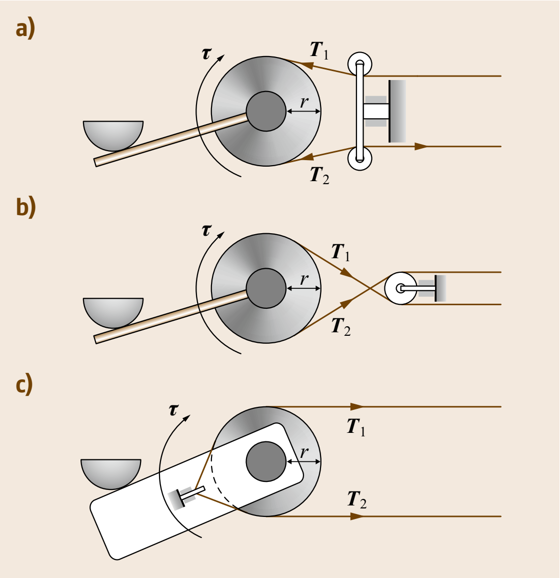


Fig.19.10a–c Tension-differential type (TDT) sensor. **(a)** Double pulley version, **(b)** single pulley version, **(c)** pulley-less version (after [19.28])

hand [19.33] and MEL hand [19.34]. Furthermore, if the sensor is built in the finger link connected by the concerned tendon, there is no relative motion between the sensor and the tendon. As a result, we can remove the pulley, as shown in Fig. 19.10c. This is called as the pulley-less version and has been implemented into Hiroshima hand. The tension-differential-type torque sensor will be a powerful tool for measuring a tendon drive joint.

Finger Tip Tactile (or Force) Sensors

Most robot manipulation and assembly tasks would benefits of the utilization of tactile sensory information. When lifting an object, tactile sensing could detect the onset of slip in time for corrective action to be taken. In addition to the contact point between the finger tip and the object, several objects properties, such as friction coefficient of the object surfaces, surface texture, and weight can be determined by utilizing a finger tip tactile (or force) sensor. A six-axis force sensor allows us to detect contact point as well as contact force between finger and environment, if a single contact is assumed. For the finger model as shown in Fig. 19.11, the following relationship between the sensor output and contact force may be defined

$$\boldsymbol{F}_\mathrm{s} = \boldsymbol{f}\,, \tag{19.1}$$

$$\boldsymbol{M}_\mathrm{s} = \boldsymbol{x}_\mathrm{c} \times \boldsymbol{f}\,, \tag{19.2}$$

where $\boldsymbol{f} \in \mathbb{R}^3$, $\boldsymbol{F}_\mathrm{s} \in \mathbb{R}^3$, $\boldsymbol{M}_\mathrm{s} \in \mathbb{R}^3$, and $\boldsymbol{x}_\mathrm{c} \in \mathbb{R}^3$ are the external force vector, the force vector measured by the six-axis force sensor, the moment vector measured by the six-axis force sensor, and the position vector indicating the contact position, respectively. From the first equation, we can directly obtain the contact force. Putting $\boldsymbol{F}_\mathrm{s}$ into the second equation leads to $\boldsymbol{M}_\mathrm{s} = \boldsymbol{x}_\mathrm{c} \times \boldsymbol{F}_\mathrm{s}$. $\boldsymbol{x}_\mathrm{c}$ is determined in such a way that $\boldsymbol{M}_\mathrm{s} = \boldsymbol{x}_\mathrm{c} \times \boldsymbol{F}_\mathrm{s}$ may be satisfied. For a finger with convex object, we have always two mathematical solutions as shown in Fig. 19.12a where the meaningful solution is the one satisfying $\boldsymbol{f}^\mathrm{t}\boldsymbol{n} < 0$, n being the outward normal direction to the finger's surface (a finger can only push the object). However, for a finger with concave shape, we have at least four mathematical solutions, as shown in Fig. 19.12b where two of those are physically possible. A finger with the six-axis force sensor located in the fingertip, Fig.19.12.c, can avoid multiple solutions. On the other hand, only forces applied to the fingertip can be detected, and if more links are in contact with the object it would be necessary to have a force/torque sensor placed in each of them.

This type of solution, i. e., a multiaxis sensor for measuring not only forces and torques but also the position of the contact point, is known in the literature as the *intrinsic tactile* (IT) principle [19.35]. In general, with respect to the use of traditional tactile sensors, see later, it leads to a simplification in the design since it requires less wires and connections for the sensor.

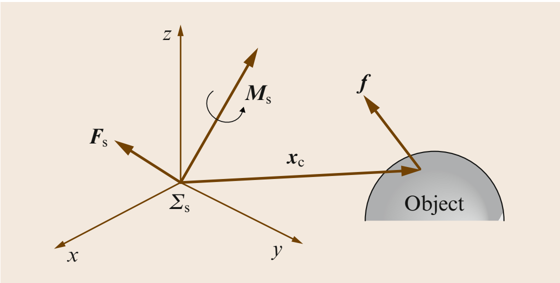


Fig. 19.11 Sensor coordinate system $\sum_S$

Tactile Sensors

Another important class of sensing devices consists of tactile sensors, which are used for several purposes, such as shape recognition, contact point determination, pressure/force measurement. A number of tactile sensors have been proposed in the literature, with several different solutions concerning the implementation features: optical, piezoresistive, piezoelectric, and so on. References [19.36, 37] give an overview on technologies and applications.

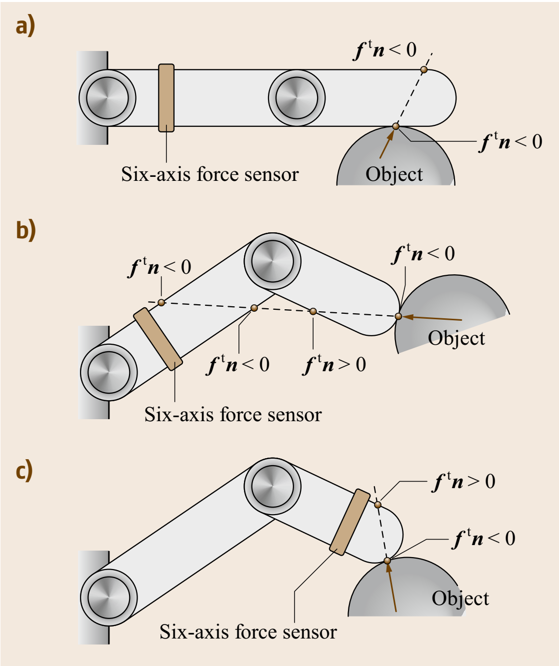


Fig. 19.12 Interpretation of solutions. **(a)** Convex shape, **(b)** finger with a concave shape, **(c)** sensor located in the fingertip

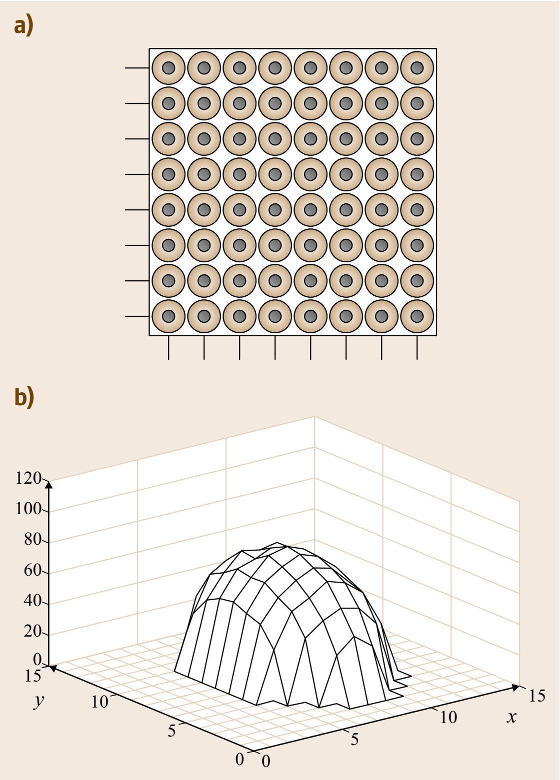


Fig.19.13a,b A Tactile sensor. **(a)** Scheme of a tactile sensor, **(b)** example of data from a tactile sensor

Tactile sensors have been introduced in robotics since the late 1970s. Nowadays, as the force sensors, also tactile sensors are commercially available devices. Probably, they represent the most commonly adopted sensorial class for industrial grippers, even though they are often used as advanced *on/off* devices to check whether a grasp or contact condition occurs.

Usually, they consist in a matrix (array) of sensing elements. Each sensing element is usually referred to as a *taxel* (from *tactile element*), and the whole set of information is called a *tactile image*, Fig. 19.13. Main goal of this class of sensors is to measure the map of pressures over the sensing area.

In general, the types of information that may be obtained from a tactile sensor are:

- *Contact*: This is the most simple information given by the sensor, concerning the presence or absence of a contact.
- *Force*: Each sensing element provides an information related to the amount of locally applied force, which can be used in several manners for successive elaborations.
- *Simple geometrical information*, i. e., position of the contact area, geometrical shape of the contact itself (planar, circular, and so on).
- *Main geometrical features of the object*: By proper elaborations of the data of the taxels, it is possible to deduce the type of object in contact with the sensor, for example a sphere, a cylinder and so on (data relative to the 3-D (three-dimensional) shape).
- *Mechanical properties*, such as friction coefficient, roughness, and so on. Also thermal properties of the object may be measured by a tactile sensor.
- *Slip condition*, i. e., the relative movement between the object and the sensor.

Several technologies have been adopted for the design of tactile sensors, ranging from piezoresistive to magnetic, to optical effects, and so on. Among the most common, one can mention:

- Resistive and conductive effect
- Electromagnetic effect
- Capacitive effect
- Piezoelectric effect
- Optical effect
- Mechanical methods.

Each of these technologies has positive and negative aspects. Common drawbacks, however, are the size of these sensors, usually quite large in comparison with the available space, and the necessity of a high number of electrical connections.

19.4 Modeling and Control of a Robot Hand

The dynamic model of a robot hand with in-site actuation is very similar to the model of a traditional (industrial) robot, and the hand can be considered as a collection of robot manipulators. On the other hand, remote actuation introduces some peculiar features that have to be carefully considered. In particular, the problems tied to nonlinear phenomena (e.g., friction and backlash), compliance of the transmission system, and noncolocation of sensors and actuators are very critical for the design of the control. Moreover, the use of single-acting actuators, such as tendon based actuation systems, requires the adoption of proper control techniques, which allow the imposition of the desired torque at each joint of the hand, despite the coupling among them.

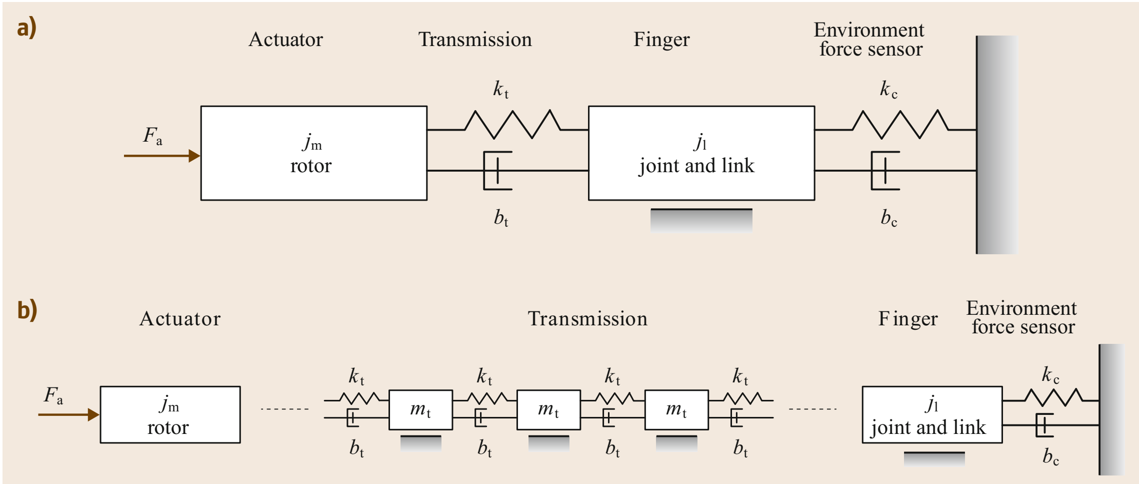


Fig.19.14a,b Model of a robot joint **(a)** with transmission flexibility, and **(b)** with tendon based transmission

19.4.1 Dynamic Effects of Flexible Transmission Systems

The transmission system of robot hands with remote actuation is usually characterized by an high level of friction and non negligible dynamic effects which complicate the control problem. A simple representation considers a single axis motion with two inertial elements linked by an elastic transmission. This is the typical representation of elastic joints in which the former element represents the motor inertia, while the latter is related to the inertial properties of the actuated joint/link (Fig. 19.14a). More complex models assume a dynamic model for the transmission system, i. e., the classical representation of tendons based on the serial repetition of masses linked by springs/dampers, reported in Fig. 19.14b. These simple models are particularly useful to understand some drawbacks and limitations due to the fact that actuation system and actuated element are located in two different places and the motion is transmitted by a nonideal (that is not purely static) element. If we consider the capability of the fingers' joint of applying a force on the environment, the effect of the transmission system on the open loop response of the system modeled as in Fig. 19.14a, are a noticeable reduction of the bandwidth, and an important phase delay between the input F_a (the force applied by the motor) and the output F_c (the force exchanged at the contact). As shown in Fig. 19.15, the open-loop transfer function

$$\frac{F_a}{F_c} = \frac{(b_c s + k_c)(b_t s + k_t)}{\left[j_l s^2 + (b_t + b_c)s + k_t + k_c\right](j_m s^2 + b_t s + k_t) - (b_t s + k_t)^2} \tag{19.3}$$

is characterized by four poles that, for growing values of the transmission stiffness k_s, move from their initial locations (that depend on the values of physical parameters j_l, j_m, etc., although for $k_s = 0$ at least one pole is in the origin of the Gauss plane) towards the poles of a system with an infinitely rigid transmission (for k_c tending to ∞, two poles go to infinity) (and a total inertia given by the contributions of both the motor and the link) whose transfer function is

$$\frac{F_a}{F_c} = \frac{(b_c s + k_c)}{(j_l + j_m)s^2 + b_c s + k_c} \tag{19.4}$$

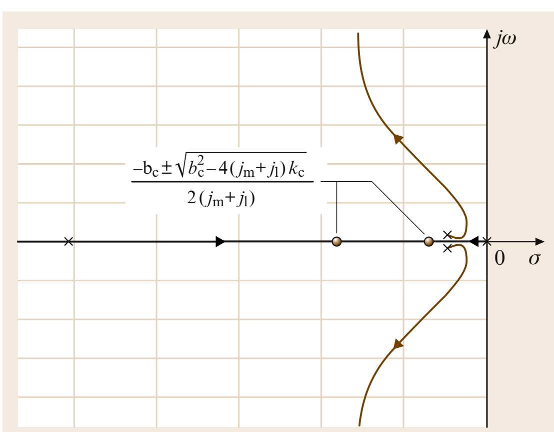
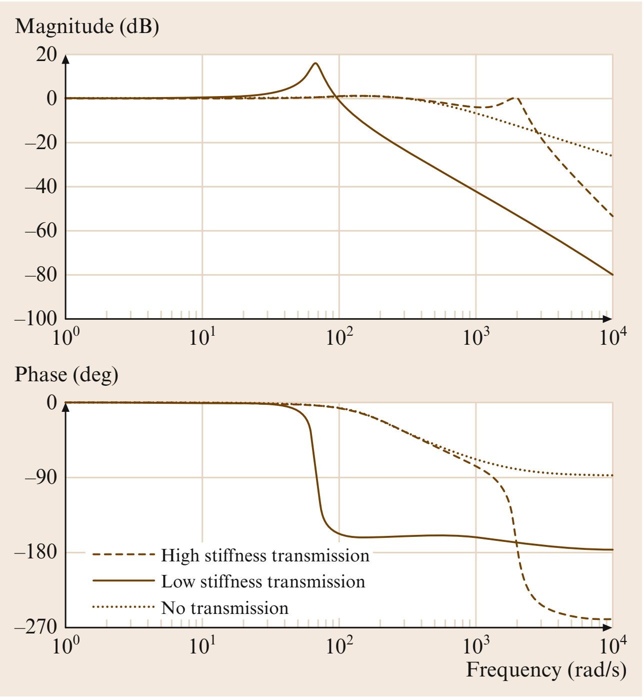


Fig. 19.15 Root contour of the transfer function (19.3) with variable k_t

As a consequence, the bandwidth of the system with flexible transmission, that for high values of k_s approx-

Fig. 19.16 Bode plots of the open loop transfer function (19.3) for low stiffness values (*continuous line*) high stiffness value (*dashed line*) and with no transmission (*dotted line*) ►



imates those of (19.4), decreases when the compliance of the transmission is not negligible, see the Bode plots reported in Fig. 19.16. The bandwidth of the system with flexible transmission is strongly affected by the location of the speed reducer: when the reducer is placed at the joint the bandwidth is K_r times (K_r is the reduction ratio) higher than the one achievable with the reduction applied directly on the motor [19.38] (Fig. 19.17). Moreover, it is worth to notice that for low level of the stiffness k_t a sharp phase drop occurs at the frequency of the flexible mode. Therefore, there are some frequencies (relatively low) at which the force applied by the motor and the one measured with a sensor in the finger's joint are completely out of phase. These effects, which may cause the instability of the overall system under force control (or impedance control) are referred to as *noncolocation*. In general, when actuators and sensors are physically located at different points of a flexible structure (or a structure with flexible transmission), there will be unstable modes in the closed-loop system [19.39].

From the control viewpoint, the problem of mechanical transmission flexibility is further exasperated by the non linear frictional phenomena that inevitably affect remote actuation and motion transmission. As a matter of fact, the linear viscous friction, represented in Fig. 19.14 by the damping coefficient b_t, is accompanied by stiction and Coulomb friction, both of which are discontinuous at zero velocity (Fig. 19.18). These nonlinearities may cause limit cycles and input-dependent stability, and must be accurately taken into account in the design of the robot hand structure as well as of its control architecture [19.40]. For instance, in the design of the Utah/MIT dexterous hand, depicted in Fig. 19.19, in order to reduce static friction, the idea of using tendon sheaths was abandoned in favor of pulleys [19.3]. In order to find an optimal trade-off between complexity and reliability of the mechanical arrangement and achieved friction level, a number of solutions, which combine sheaths and pulleys for routing the tendon from actuators to fingers' joints has been adopted in the design of robot hands, e.g., the Stanford/JPL hand (VIDEO 751) and the UB hand 3 reported in Fig. 19.20. This device is characterized by an extremely simple structure, with the tendons completely routed within sheaths, but on the other hand the friction cannot be absolutely neglected and a precise modeling of the interaction between the tendons and the tube is necessary for control purposes [19.41].

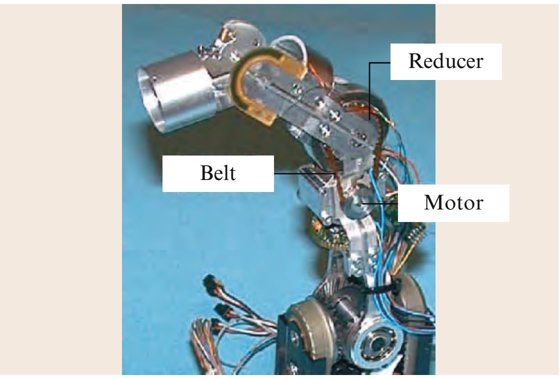


Fig. 19.17 Reducer location on the medial joint of the DLR hand II

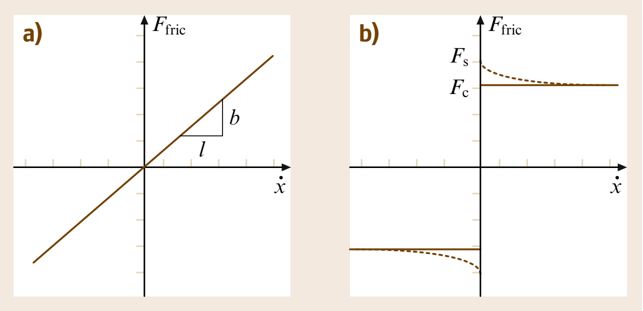


Fig.19.18a,b Frictional phenomena: viscous friction **(a)** and stiction and Coulomb friction **(b)**

19.4.2 Transmission Model of Tendon-Outer-Tube System

This system can be modeled as shown in Fig. 19.21 where T_{in}, T_{out}, T_0, ξ_{in}, ξ_{out}, R_{i}, x, and L are the tension at the input side, the tension at the output side, the initial pretension, the displacement at the input side, the displacement at the output side, the local radius of routing, the coordinate system along the wire, and the length of the tendon, respectively. The relationship between the tension at output and the input displacement is given by [19.42],

$$T_{\text{out}} - T_0 = K_{\text{t}}(\xi_{\text{in}}\phi_{\text{B}}) , \tag{19.5}$$

Fig. 19.19 The Utah/MIT robotic hand

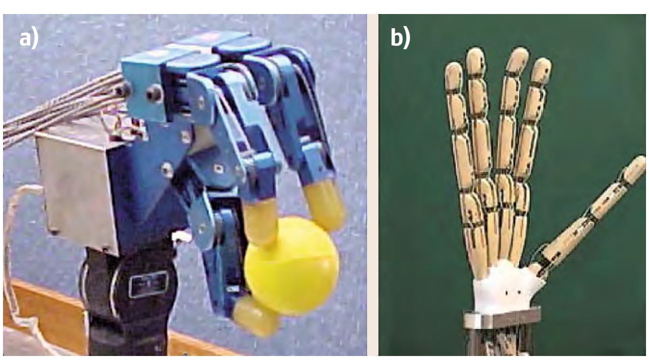


Fig.19.20a,b Tendon based robot hands: Stanford/JPL hand **(a)** and UB hand 3 **(b)**

where K_{t} and ϕ_{B} are the total stiffness and the equivalent backlash, respectively, and those are given by,

$$\frac{1}{K_{\text{t}}} = \frac{1}{K_{\text{e}}} + \frac{1}{K_{\text{s}}} + \frac{1}{K_{\text{ap}}} \tag{19.6}$$

$$K_{\text{ap}} = K_{\text{w}} \frac{\lambda}{\exp(\lambda) - 1} \tag{19.7}$$

$$\phi_{\text{B}} = \frac{T_0 L}{EA} \cdot \frac{\exp(\lambda) - \lambda - 1}{\lambda} \tag{19.8}$$

$$\lambda = \sum |\beta_{\text{i}}| \mu \operatorname{sgn} \xi_{\text{in}} \tag{19.9}$$

where K_{e}, K_{s}, K_{w}, K_{ap}, μ, E, A and β_{i} are the stiffness of environment, the stiffness of force sensor, the apparent stiffness of the tendon, the friction coefficient, Young's modulus, the cross sectional area, and the bending angle of each segment of tendon, respectively. For example,

$$\sum |\beta_{\text{i}}| = 2\pi$$

for the case given in Fig. 19.21. As can be seen from this example, the friction related parameter λ increases dramatically when the tube is heavily bent. While we have a big advantage of choosing a free route for the power transmission, it brings a large nonlinearity for the transmission system. We would note that while both the apparent stiffness of the tendon and the equivalent backlash vary depending upon λ which is the function of the curvature of the route as well as the friction coefficient, ϕ_{B} and K_{ap} result in $\phi_{\text{B}} = 0$ and $K_{\text{ap}} = K_{\text{w}}$ under $\mu = 0$. From the view point of control, such hysteresis is, of course, not desirable. To cope with these issues, each tendon should be designed as short as possible, so that we may keep high stiffness and small backlash in the transmission system.

19.4.3 The Control Through Single-Acting Actuators

The use of single-acting actuators (i. e., standard motors with tendinous transmission), which are commonly

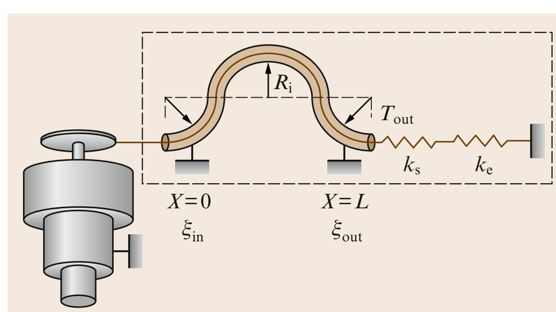


Fig. 19.21 Model of tendon-outer-tube transmission

assumed in the design of robot hands with remote actuation, requires the adoption of specific control techniques in order to guarantee the desired torques at the joints and to maintain at each time a positive tension on the tendons. To this purpose, the tendons are treated like inelastic frictionless elements and the problem is coped in a way completely decoupled from the issue of the device stability, discussed in previous sections.

A tendon, routed in the finger structure through sheaths or/and pulleys, can be modeled by means an *extension function* $l_{\mathrm{i}}(\theta)$ [19.43] relating the joints' configuration with the tendon elongation. In the case of the tendon network represented in Fig. 19.3, the extension functions of the three tendons have the form

$$l_{\mathrm{i}}(\boldsymbol{\theta}) = l_{0\mathrm{i}} \pm R\boldsymbol{\theta}_1 \pm R\boldsymbol{\theta}_2 \,,$$

where R is the radius of the pulleys and

$$\boldsymbol{\theta} = [\boldsymbol{\theta}_1 \boldsymbol{\theta}_2]^{\mathrm{T}}$$

is the vector of the joint variables. Once the extension function has been determined, it is straightforward to derive the relationship between tendons forces and resulting joints torques. As a matter of fact, the relation between the joint speeds $\dot{\boldsymbol{\theta}}$ and tendon speeds $\dot{\boldsymbol{l}}$ can be deduced by simply differentiating the expression of extension functions

$$\dot{\boldsymbol{l}} = \frac{\partial \boldsymbol{l}}{\partial \boldsymbol{\theta}}(\boldsymbol{\theta})\dot{\boldsymbol{\theta}} = \mathbf{P}(\boldsymbol{\theta})\dot{\boldsymbol{\theta}} \,. \tag{19.10}$$

Because of the conservation of the power, from (19.10), one can achieve

$$\boldsymbol{\tau} = \mathbf{P}^{\mathrm{T}}(\boldsymbol{\theta})\boldsymbol{f} \,, \tag{19.11}$$

where $\boldsymbol{\tau}$ are the torques exerted on the joints, and $\boldsymbol{f}$ are the force applied by tendons. From (19.11) it results that the force transmitted by a tendon may affect (and, in general, will affect) more than one joint.

In order to guarantee the possibility of exerting joint torques in every direction under the constraint of pure tensile forces, for any $\boldsymbol{\tau} \in \mathbb{R}^n$ it must exist a set of forces $\boldsymbol{f}_{\mathrm{i}} \in \mathbb{R}^m$ (n and m are respectively the number of joints and the number of tendons) such that

$$\boldsymbol{\tau} = \mathbf{P}^{\mathrm{T}}(\boldsymbol{\theta})\boldsymbol{f} \quad \text{and} \quad \boldsymbol{f}_i > 0, i = 1, \ldots, m \,. \tag{19.12}$$

In this case the tendon network is said *force closure*. If the condition expressed by (19.12) is verified, given a desired torque vector $\boldsymbol{\tau}$ it is possible to compute the force that the actuators must provide to the tendons according to

$$\boldsymbol{f} = \mathbf{P}^{\dagger}(\boldsymbol{\theta})\boldsymbol{\tau} + \boldsymbol{f}_{\mathrm{N}} \,, \tag{19.13}$$

where

$$\mathbf{P}^{\dagger} = \mathbf{P}(\mathbf{P}^{\mathrm{T}}\mathbf{P})^{-1}$$

is the pseudo-inverse of the coupling matrix $\mathbf{P}^{\mathrm{T}}$ and

$$\boldsymbol{f}_{\mathrm{N}} \in \mathcal{N}(\mathbf{P}^{\mathrm{T}})$$

is a vector of *internal forces* that insures that all tendon tensions are positive. In general, internal forces will be chosen as small as possible, so that the tendons are always taut but are not subject to excessive strains.

19.4.4 Control of a Robot Hand

The modeling and control aspects described in the previous Sections, although very important and fundamental, can be considered as a sort of *low level* problems in the control of a robot hand, in the sense that they are related to the specific physical properties of the device.

There are also other problems that must be faced and solved in order to operate in a profitable manner with a multifingered hand. These problems are solved by a proper design of a *high level* control for the hand, that must take into account the interaction of the hand with the objects and more in general with the environment. In this context, general aspects that must be considered are: the control of forces/torques applied at the contact points, the necessity to model contact compliance/friction effects, the type of mobility both for the fingers and at the contact (rolling, sliding, ...), a suitable planning algorithm for grasping and/or manipulating the objects, and so on.

These problems are illustrated in detail in Part C, Chaps. 37–39.

19.5 Applications and Trends

In the industrial environment, simplicity and cost are the main guidelines for the design of end-effectors, and therefore simple devices, as open-close grippers, are very common and widely used. This situation has led during the years to the development of a number of special-purpose devices, optimized for single specialized operations but not suitable for other tasks. At the moment, dexterous multifingered hands have not really been applied to any major application, mainly because of problems of reliability, complexity, cost.

On the other hand, more and more operations are currently envisaged for robots working in environments designed for, and utilized by, human operators. Entertainment, maintenance, space/underwater applications, help to disable persons are just a few examples of use of robotic systems in which interaction with tools and objects designed for human beings (or directly with them) is implied. In all these circumstances, the robot must be able to grasp and manipulate objects (different in dimension, shape, weight, ...) similarly to humans, and therefore a robot hand, with a proper number of fingers and joints and also with an anthropomorphic appearance, seems to be the most adequate solution.

There are several projects aiming at developing anthropomorphic robots. Among others, one can mention the NASA/JPL Robonaut [19.24], Fig. 19.22, the devices developed at the DLR, the several projects on humanoid robots currently under development.

Fig. 19.22 The NASA/JPL Robonaut

19.6 Conclusions and Further Reading

The design of multifingered robot hands has attracted the interest of the research community since the early days of robotics, not only as a challenging technical problem itself but, probably, also because of anthropomorphic motivations and the intrinsic interest for a better knowledge of the human beings. In the last decades, has previously discussed, several important projects have been launched, and important examples of robot hands developed. Nevertheless, the current situation is that reliable, flexible, dexterous hands are still not available for real applications. For these motivations, it is easy to foresee also for the future a consistent research activity in this fascinating field, with developments at the technological (sensor, actuator, material, ...) and methodological (control, planning, ...) level. Important connections with other scientific fields are also expected, as for example with cognitive science.

Being this research area so wide, it is not simple to suggest to interest readers further readings, except for quite classical books such as [19.43–45]. As a matter of fact, depending on the specific research area, many publications are available, although often not organized as reference books, but mainly as technical papers published in journals or presented at international conferences. Moreover, since hundreds of new papers are published every year covering the different aspects of this robotic field, it is really quite difficult, and also not fair, to give at the moment specific suggestions for further readings. We can only refer to the citations already provided in the references.

Video-References

VIDEO 749 The PISA-IIT SoftHand
available from http://handbookofrobotics.org/view-chapter/19/videodetails/749

VIDEO 750 The PISA-IIT SoftHand
available from http://handbookofrobotics.org/view-chapter/19/videodetails/750

VIDEO 751 The Salisbury Hand
available from http://handbookofrobotics.org/view-chapter/19/videodetails/751

VIDEO 752 The Barrett Hand
available from http://handbookofrobotics.org/view-chapter/19/videodetails/752

VIDEO 753 The Shadow Hand
available from http://handbookofrobotics.org/view-chapter/19/videodetails/753

VIDEO 754 The DLR Hand
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VIDEO 755 A high-speed Hand
available from http://handbookofrobotics.org/view-chapter/19/videodetails/755
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VIDEO 767 The Dexmart Hand
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VIDEO 768 DLR Hand
available from http://handbookofrobotics.org/view-chapter/19/videodetails/768
VIDEO 769 The DLR Hand performing several task
available from http://handbookofrobotics.org/view-chapter/19/videodetails/769

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