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15. 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. 15.1, various approaches for actuation are provided with their advantages and disadvantages in Sect. 15.2. 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. 15.3, actuator and sensors used for multifingered hands are described. In Sect. 15.4, modeling and control are introduced by considering both dynamic effects and friction. Applications and trends are given in Sect. 15.5. Finally, this chapter is closed with conclusions and further reading.

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Human hands have great potentiality 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, and 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, and perception of physical properties (roughness, temperature, weight, to mention just a few) are other fundamental tasks that we are usually 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 greatly 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 [15.1]. In the early 1980s, two major projects on multifingered robot hands have been launched: the Stanford/Jet Propulsion Laboratory (JPL) hand and the Massachusetts Institute of Technology (MIT)/Utah hand [15.2, 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, the Mechanical Engineering Laboratory (MEL) hand, the Electro-Technical Laboratory (ETL) hand, the Darmstadt hand, the Karlsruhe hand, the Bologna hand, the Barrett hand, the Yasukawa hand, the Gifu hand, the U-Tokyo-hand, the Hiroshima hand, and many others [15.4–8].

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), and control. All these aspects are considered in this chapter.

15.1 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.

15.1.1 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 dependence (at least in the robotic field) has been not proved yet.

In 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 [15.9]. Similarly, we can find smart end-effectors, capable of sophisticated manipulation procedures, without any level of anthropomorphism, e.g., the DxGrip-II [15.10]. 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 either by robots or men;
- the end-effector can be teleoperated by a human operator, by means of special-purpose interfaces (e.g., a data glove), directly reproducing the operator's hand behavior;
- for the 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 [15.11, 12] has recently produced such 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 main aspects that contribute to determining the anthropomorphism level of a robotic hand are:

- *Kinematics*: the presence of the main morphological elements (principal upper fingers, secondary upper fingers, opposable thumb, and palm);
- *Contact surfaces*: the extension and smoothness of the contact surfaces, an 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;
- *Size*: both referring to the average size of a human hand and the *correct* size ratio between the links.

15.1.2 Dexterity of a Robotic Hand

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

Two are the main capabilities of a human hand:

- *prehension*: the ability to grasp and hold objects of different size and shape;
- *apprehension*: the ability to understand through active touch.

In this sense, the human hand is both an *output* and *input* device (see [15.13]). As an output device, it can apply forces in order to obtain stable grasps or perform manipulation procedures. As an input device, it is capable of exploring an unknown environment providing information about the state of the interaction with it. The same features are desirable in robot hands. In 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 perform autonomously tasks with a certain level of complexity. An exhaustive review of scientific work developed so far about the dexterity of robotic hands, with a quite complete and up-to-date list of references, can be found in [15.14].

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

Grasping means the capability to constrain objects in a configuration that is substantially invariant with time (the object is fixed with respect to the hand).

Internal manipulation is 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 [15.15] and different internal manipulation modes based on internal mobility and/or contact sliding or rolling [15.14]).

Although the notion of dexterity is 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.

15.2 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.

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

15.2.1 Actuator 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:

- 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.

In-Site Actuation

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 complexity of the transmission chain. 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 space inside the finger structure, making it difficult 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 the DLR hand [15.4,16], the ETL hand, the Karlsruhe hand, the Yasukawa hand, the Barrett hand, the Gifu hand, the U-Tokyo hand, and the Hiroshima hand. Since this actuation does not include compliant elements such as tendons, we can keep a stiff transmission system, which leads to a stable control system even under a high gain, see Sect. 15.4. 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 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, which 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 the 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 University of Bologna (UB) hand or the National Aeronautics and Space Agency (NASA) Robonaut hand [15.17,18].

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.

15.2.2 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 depend 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 the opposite direction must be obtained by an external action, which 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, see Fig. 15.1a. This mechanism leads to a simplification of the 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 drive the same joint, acting in opposition in different directions (agonistic–antagonistic couple), see Fig. 15.2b. This solution leads to an N-joint $2N$-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 pre-loading of the joint itself (co-contraction, typical of tendon-driven joints).

- *Pros:* co-contraction 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:* backdrivability of actuators is required; difficulty in hosting two actuators for each joint, both in-site and at a remote location; higher control complexity; greater cost.

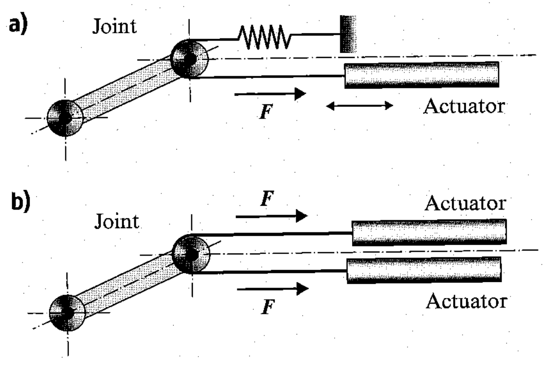


Fig. 15.1 **(a)** Single-acting actuator with an antagonist passive element and **(b)** in an agonist–antagonist configuration

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

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

- *Pros:* co-contraction 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 $2N$-actuator scheme.
- *Cons:* backdrivability of actuators is required; high complexity of the kinematic scheme and therefore high complexity in control.

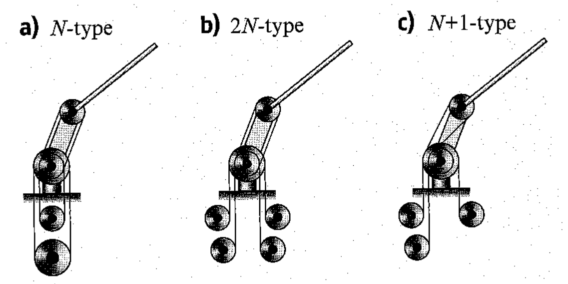


Fig. 15.2a–c Remote actuation **(a)** N-type **(b)** $2N$-type **(c)** N+1-type

jor 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 Hall-effect sensors, which are sufficiently small, precise, and reliable for this type of application. In the case of remote actuation, there is the possibility of having two position/velocity sensors for each joint: one located in the actuator (e.g., an encoder) and one placed in the joint itself, often necessary because of the nonlinearities introduced by the transmission system (elasticity, friction, and so on). Quite often, this latter sensor is specifically designed and implemented for the given hand, as commercially available sensors are 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 fingertip compliance as well as fingertip force by controlling voluntary muscles. In remote actuation, it is essential to measure the tendon tension for two main reasons: to compensate for the friction existing in the transmission system, and to measure the external contact force. Figure 15.6 shows a way of measuring the tendon tension in which the tendon is pressed by an elastic plate with a strain gauge. When 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 into an electric signals by the strain gauges attached on the surface of the plate. Now, suppose N-type actuation with two tension sensors, as shown in Fig. 15.7, 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 pre-tension. Once such a plastic deformation has happened, the sensor will never work appropriately anymore. Another minor issue is that two sensors are always necessary for measuring a joint torque. To cope with these issues, the tension-differential-type torque sensor [15.22] can be used, as shown in Fig. 15.8. The sensor is designed with just a single body and partially includes an elastic part where at least one strain gauge is attached. The working principle of the sensor, shown in Fig. 15.8a, 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 long as no joint torque is applied. Therefore,

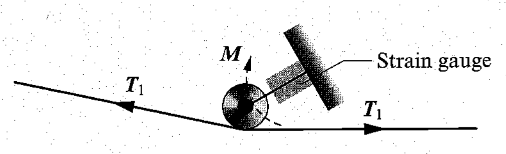


Fig. 15.6 Tendon tension sensing

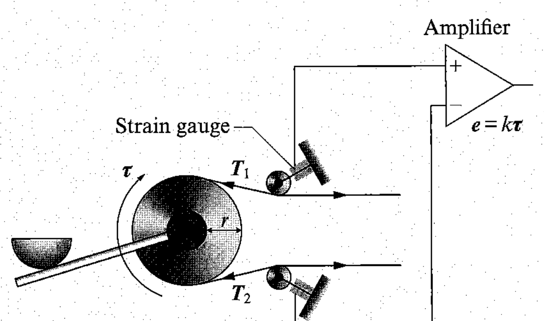


Fig. 15.7 Tension-sensor-based torque sensing

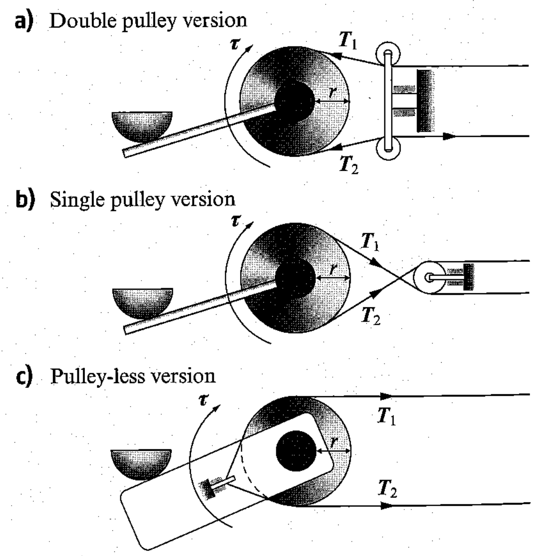


Fig. 15.8 A tension differential type (TDT) sensor [15.22]

we are completely released from the plastic deformation of the elastic plate due to pre-tension. Furthermore, the sensor is constructed with just a single body. There are a couple of variations of this type of torque sensor. When decreasing the pulley distance in Fig. 15.8a, the sensor eventually results in the single-pulley version with zero distance, as shown in Fig. 15.8b. The single-pulley version has been implemented into the Darmstadt hand [15.23] and the MEL hand [15.24]. Furthermore, if the sensor is built into 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. 15.8c. This is called the pulley-less version and has been implemented in the Hiroshima hand. The tension-differential-type torque sensor will be a powerful tool for measuring a tendon drive joint.

Fingertip Tactile (or Force) Sensors

Most robot manipulation and assembly tasks would benefit from 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 fingertip and the object, several object properties, such as the friction coefficient of the object surfaces, surface texture, and weight can be determined by utilizing a fingertip tactile (or force) sensor. A six-axis force sensor allows us to detect contact point as well as the contact force between the finger and the environment if a single contact is assumed. For the finger model shown in Fig. 15.9 we have the following relationship between the sensor output and contact force

$$\boldsymbol{F}_s = \boldsymbol{f}\,, \tag{15.1}$$

$$\boldsymbol{M}_s = \boldsymbol{x}_c \times \boldsymbol{f}\,, \tag{15.2}$$

where $\boldsymbol{f} \in \mathbb{R}^3$, $\boldsymbol{F}_s \in \mathbb{R}^3$, $\boldsymbol{M}_s \in \mathbb{R}^3$, and $\boldsymbol{x}_c \in \mathbb{R}^3$ 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 $\boldsymbol{F}_s$ into the second equation leads to $\boldsymbol{M}_s = \boldsymbol{x}_c \times \boldsymbol{F}_s$. $\boldsymbol{x}_c$ is determined in such a way that $\boldsymbol{M}_s = \boldsymbol{x}_c \times \boldsymbol{F}_s$ may be satisfied. For a finger with a convex object, we always have two mathematical solutions, as shown in Fig. 15.10a, where the meaningful solution is the one satisfying $\boldsymbol{f}^t\boldsymbol{n} > 0$ (a finger can only push the object). However, for a finger with a concave object, we have at least four mathematical solutions, as shown in Fig. 15.10b, where two of those are physically possible. A finger with a six-axis force sensor located in the fingertip, Fig. 15.10c, 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 [15.25]. In general, compared with the use of traditional tactile sensors (see below) this leads to a simplification in the design since it requires fewer wires and connections for the sensor.

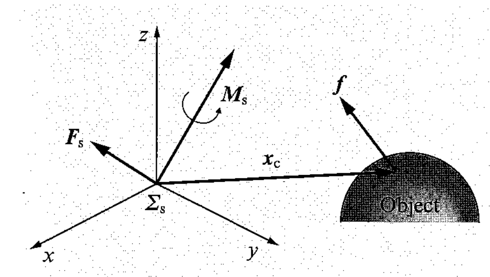


Fig. 15.9 Sensor coordinate system $\sum_S$

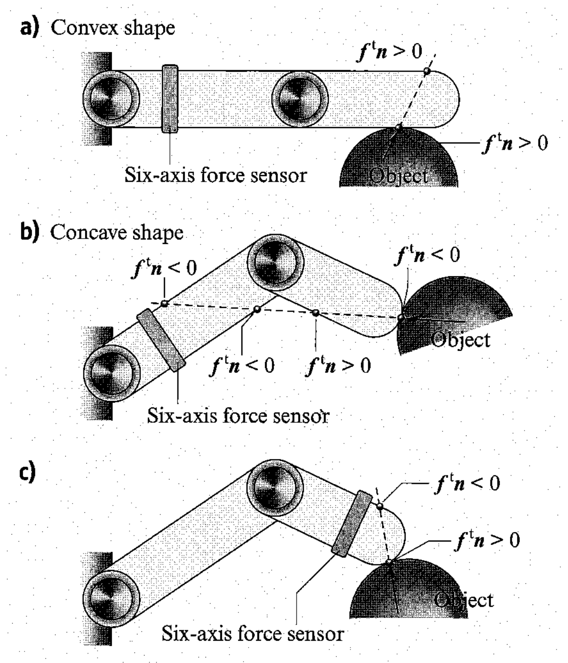


Fig. 15.10a–c Interpretation of solutions: **(a)** convex shape, **(b)** concave shape, and **(c)** six-axis force sensor

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, and pressure/force measurement. A number of tactile sensors have been proposed in the literature, with several different solutions concerning the realizable features: optical, piezoresistive, piezoelectric, and so on; see, e.g., [15.26, 27] for an overview on technologies and applications.

Tactile sensors have been introduced in robotics since the late 1970s. Nowadays, as with force sensors, tactile sensors are also 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 of 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. 15.11). The main goal of this class of sensors is to measure the pressure map 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 information related to the amount of locally applied force, which can be used in several ways for successive elaborations;
- *simple geometrical information*, i. e., the position of the contact area, the geometrical shape of the contact itself (planar, circular, and so on);
- *the main geometrical features of the object*: by proper elaborations of the data from the taxels, it is possible to deduce the type of object in contact with the sensor, for example, a sphere or a cylinder (data relative to the three-dimensional shape);
- *mechanical properties*, such as friction coefficient or roughness. 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.

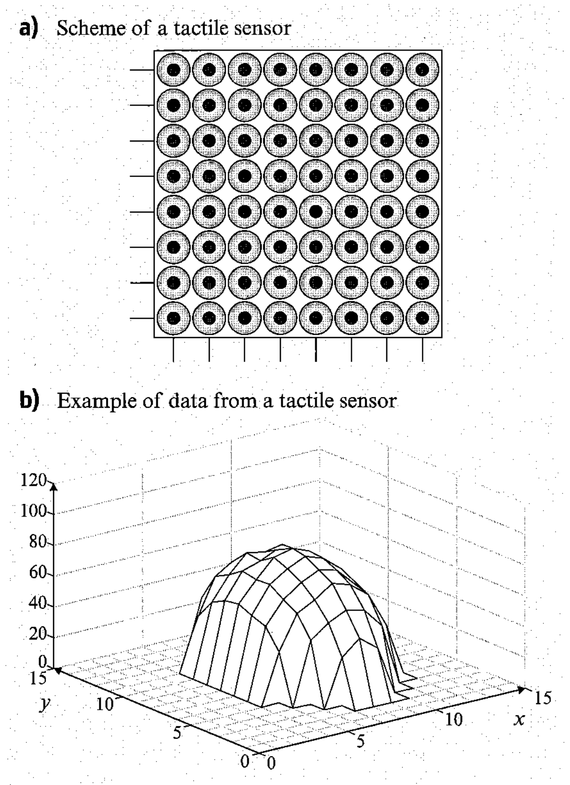


Fig. 15.11a,b A tactile sensor: **(a)** scheme and **(b)** example data

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, which are usually quite large in comparison with the available space, and the necessity of a large number of electrical connections.

15.4 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 linked to nonlinear phenomena (e.g., friction and backlash), the compliance of the transmission system, and the non-collocation of sensors and actuators are 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 that allow the imposition of the desired torque at each joint of the hand despite the coupling among them.

15.4.1 Dynamic Effects of Flexible Transmission Systems

The transmission system of robot hands with remote actuation is usually characterized by a high level of friction and nonnegligible 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, see Fig. 15.12a. 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. 15.12b. 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 to apply a force on environment, the effects of the transmission system on the open-loop response of the system modeled as in Fig. 15.12a 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. 15.13, the open-loop transfer function

$$\frac{F_a}{F_c} = \frac{(b_c s + k_c)(b_t s + k_t)}{\left[j_l s^2 + (b_t + b_c)s + k_t + k_c\right](j_m s^2 + b_t s + k_t) - (b_t s + k_t)^2} \tag{15.3}$$

is characterized by four poles that, for increasing values of the transmission stiffness k_s, move from their initial locations (which 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

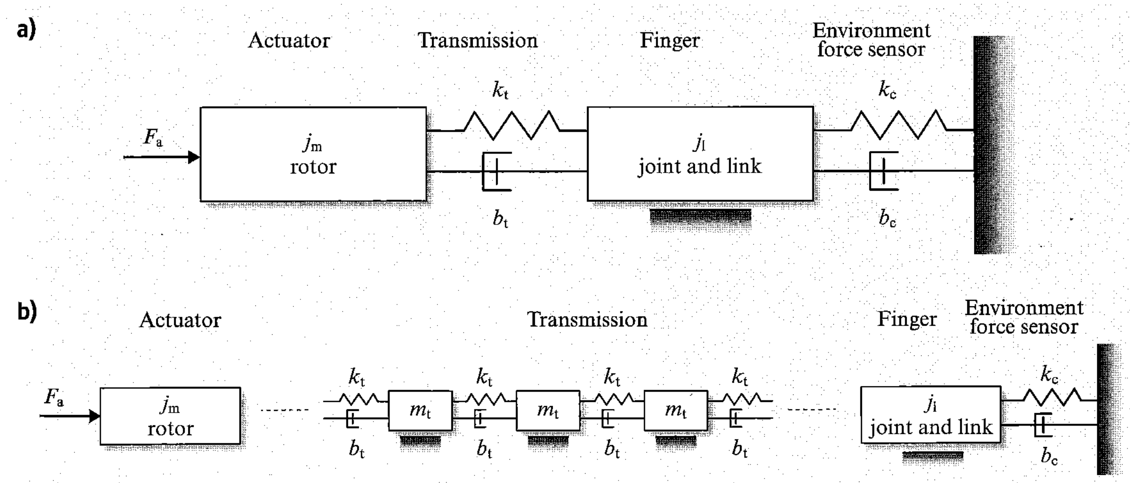


Fig. 15.12 **(a)** Model of a robot joint with transmission flexibility and **(b)** with tendon-based transmission

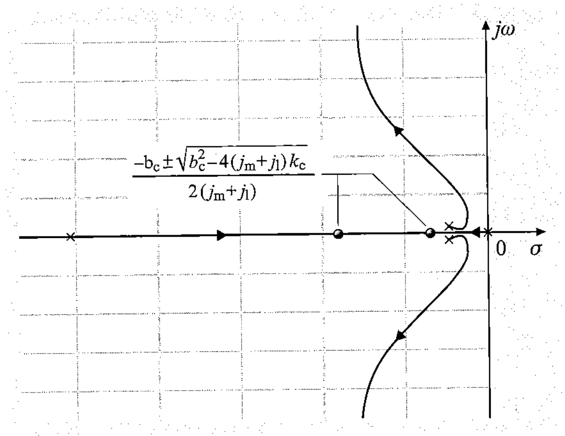
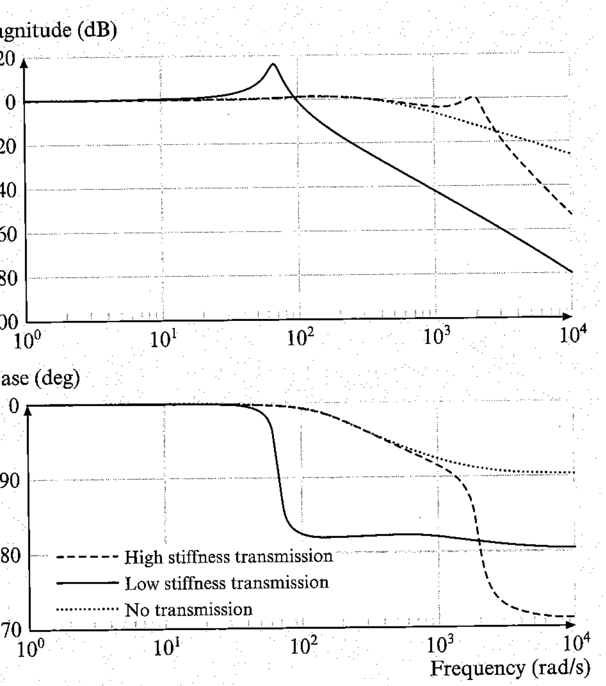


Fig. 15.13 Root contour of the transfer function (15.3) with variable k_t

motor and the link. In this case the transfer function is:

$$\frac{F_a}{F_c} = \frac{(b_c s + k_c)}{(j_l + j_m)s^2 + b_c s + k_c} \tag{15.4}$$



15.14 Bode plots of the open-loop transfer function (15.3) for stiffness values (*continuous line*) high stiffness value (*dashed*) and with no transmission (*dotted line*)

As a consequence, the bandwidth of the system with flexible transmission, which for high values of k_s approximates those of (15.4), decreases when the compliance of the transmission is not negligible; see the Bode plots reported in Fig. 15.14. The bandwidth of a 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 higher than the one achievable with the reduction applied directly on the motor [15.28] (see Fig. 15.15; K_r is the reduction ratio). Moreover, it is worth noticing that for low values of the stiffness k_t a sharp phase drop occurs at the frequency of the flexible mode. Therefore, there are some (relatively low) frequencies 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 *non-collocation*. 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 [15.29].

From the control viewpoint, the problem of mechanical transmission flexibility is further exasperated by the nonlinear frictional phenomena that inevitably affect remote actuation and motion transmission. In fact, the linear viscous friction, represented in Fig. 15.12 by the damping coefficient b_t, is accompanied by stiction and Coulomb friction, both of which are discontinuous at zero velocity (see Fig. 15.16). 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

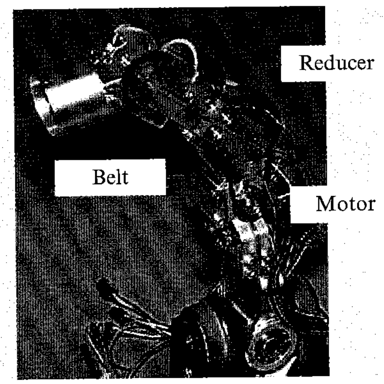


Fig. 15.15 Reducer location on the medial joint of the DLR hand II

architecture [15.30], for instance, in the design of the Utah/MIT dexterous hand (Fig. 15.17) in order to reduce static friction, the idea of using tendon sheaths was abandoned in favor of pulleys [15.3]. In order to find an optimal tradeoff between complexity and reliability of the mechanical arrangement and achieved friction level, a number of solutions that combine sheaths and pulleys for routing the tendon from actuators to fingers' joints have been adopted in the design of robot hands, e.g., the Stanford hand and the UB hand 3 reported in Fig. 15.18. The UB hand 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 precise modeling of the interaction between the tendons and the tube is necessary for control purposes.

15.4.2 Transmission Model of Tendon-Outer-Tube System

This system can be modeled as shown in Fig. 15.19, 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 [15.31]

$$T_{out} - T_0 = K_t(\xi_{in}\phi_B)\,, \tag{15.5}$$

where K_t and ϕ_B are the total stiffness and the equivalent backlash, respectively, given by

$$\frac{1}{K_t} = \frac{1}{K_e} + \frac{1}{K_s} + \frac{1}{K_{ap}}\,, \tag{15.6}$$

$$K_{ap} = K_w \frac{\lambda}{e^{\lambda} - 1}\,, \tag{15.7}$$

$$\phi_B = \frac{T_0 L}{EA} \cdot \frac{e^{\lambda} - \lambda - 1}{\lambda}\,, \tag{15.8}$$

$$\lambda = \sum |\beta_i| \mu \operatorname{sgn} \xi_{in}\,, \tag{15.9}$$

where K_e, K_s, K_w, K_{ap}, μ, E, A, and β_i are the stiffness of the environment, the stiffness of the force sensor, the apparent stiffness of the tendon, the friction coefficient, the Young's modulus, the cross-sectional area, and the bending angle of each segment of tendon, respectively. For example, $\sum |\beta_i| = 2\pi$ for the case given in Fig. 15.19. As can be seen from this example, the friction-related parameter λ increases dramatically when the tube is heavily bent. While we have the great advantage of choosing a free route for the power transmission, it results in a large nonlinearity for the transmission system. We should note that, while both the apparent stiffness of the tendon and the equivalent backlash vary with λ which is a function of the curvature of the route as well as the friction coefficient, ϕ_B and K_{ap} result in $\phi_B = 0$ and $K_{ap} = K_w$ under $\mu = 0$. From the control

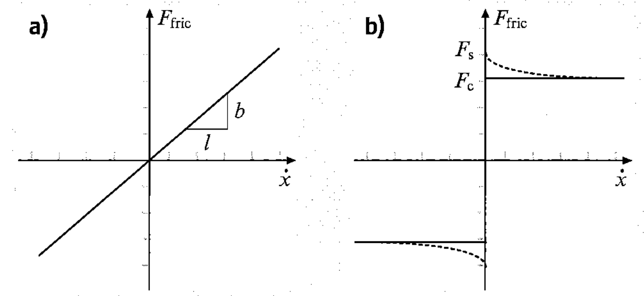


Fig. 15.16a,b Frictional phenomena: **(a)** viscous friction and **(b)** stiction and Coulomb friction

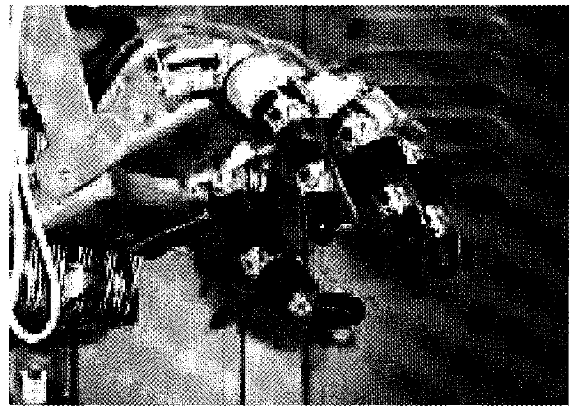


Fig. 15.17 The Utah/MIT robotic hand

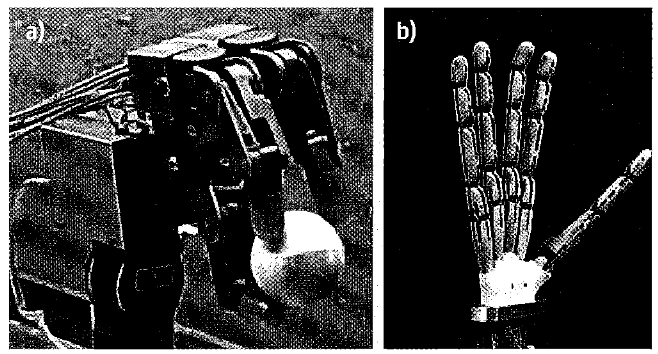


Fig. 15.18a,b Tendon-based robot hands: **(a)** Stanford/JPL hand and **(b)** UB hand 3

Part B | 15.4

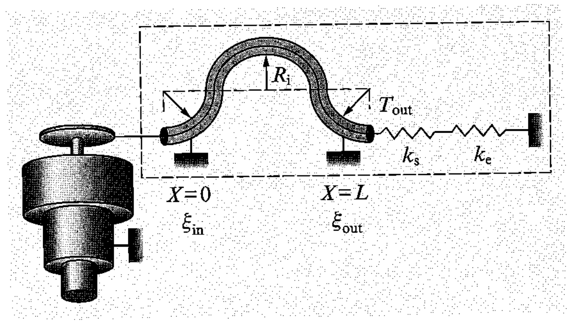


Fig. 15.19 Model of tendon-outer-tube transmission

viewpoint, such hysteresis is, of course, undesirable. To cope with these issues, each tendon should be designed to be as short as possible, so that we may keep high stiffness and small backlash in the transmission system.

15.4.3 Control Through Single-Acting Actuators

The use of single-acting actuators (i. e., standard motors with tendinous transmission), which are commonly 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 addressed in a way completely decoupled from the issue of device stability, discussed in previous sections.

A tendon, routed in the finger structure through sheaths or/and pulleys, can be modeled by means of an *extension function* $l_i(\boldsymbol{\theta})$ [15.32] that relates the joints' configuration with the tendon elongation. In the case of the tendon network represented in Fig. 15.2, the extension functions of the three tendons have the form:

$$l_i(\boldsymbol{\theta}) = l_{0i} \pm R\theta_1 \pm R\theta_2 \,,$$

where R is the radius of the pulleys and $\boldsymbol{\theta} = [\theta_1 \ \theta_2]^{\mathrm{T}}$ is the vector of the joint variables. Once the extension function has been determined, it is straightforward to derive the relationship between the tendons forces and the resulting joints torques. In fact, the relation between the joint speeds $\dot{\boldsymbol{\theta}}$ and the tendon speeds $\dot{\boldsymbol{l}}$ can be deduced by simply differentiating the expression of extension functions

$$\dot{\boldsymbol{l}} = \frac{\partial \boldsymbol{l}}{\partial \boldsymbol{\theta}}(\boldsymbol{\theta})\dot{\boldsymbol{\theta}} = \boldsymbol{P}(\boldsymbol{\theta})\dot{\boldsymbol{\theta}} \,. \tag{15.10}$$

Because of the conservation of the power, from (15.10), one can deduce

$$\boldsymbol{\tau} = \boldsymbol{P}^{\top}(\boldsymbol{\theta})\boldsymbol{f} \,, \tag{15.11}$$

where the $\boldsymbol{\tau}$ are the torques exerted on the joints, and the $\boldsymbol{f}$ are the force applied by tendons. From (15.11) 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 $\boldsymbol{\tau} \in \mathbb{R}^n$ there must exist a set of forces $\boldsymbol{f}_i \in \mathbb{R}^m$ such that

$$\boldsymbol{\tau} = \boldsymbol{P}^{\top}(\boldsymbol{\theta})\boldsymbol{f} \quad \text{and} \quad f_i > 0, i = 1, \dots, m \,, \tag{15.12}$$

where n and m are, respectively, the number of joints and the number of tendons. In this case the tendon network is said *force closure*. If the condition expressed by (15.12) 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

$$\boldsymbol{f} = \boldsymbol{P}^{\dagger}(\boldsymbol{\theta})\boldsymbol{\tau} + \boldsymbol{f}_{\mathrm{N}} \,, \tag{15.13}$$

where $\boldsymbol{P}^{\dagger} = \boldsymbol{P}(\boldsymbol{P}^{\top}\boldsymbol{P})^{-1}$ is the pseudo-inverse of the coupling matrix $\boldsymbol{P}^{\top}$ and $\boldsymbol{f}_{\mathrm{N}} \in \mathcal{N}(\boldsymbol{P}^{\top})$ is a vector of *internal forces* that ensures 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.

15.4.4 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* problem 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 the *high-level* control for the hand, which must take into account the interaction of the hand with the objects and more generally 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, etc.), a suitable planning algorithm for grasping and/or manipulating the objects, and so on.

These problems are illustrated in details in Chap. 26, Chap. 27, and Chap. 28.

15.5 Applications and Trends

In the industrial environment, simplicity and cost are the main guidelines for the design of end-effectors, and therefore simple devices, such as open/close grippers, are very common and widely used. This situation has led over 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 exploration, help to disable persons are just a few examples the 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, etc.) 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.

Fig. 15.20 The NASA/JPL Robonaut

At the moment, there are several projects aimed at the development of anthropomorphic robots. Among the most well known, one can mention the NASA/JPL Robonaut [15.18] (Fig. 15.20), the devices developed at the DLR, and the several projects on humanoid robots currently under development.

15.6 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 in better knowledge of the human body. In the last decades, as previously discussed, several important projects have been launched, and important examples of robot hands have been developed. Nevertheless, the current situation is that reliable, flexible, dexterous hands are still not available for real applications. For these motivations, it is also easy to foresee in the future a consistent research activity in this fascinating field, with developments at the technological (sensor, actuator, material, etc.) and methodological (control, planning, etc.) levels. Important connections with other scientific fields, such as cognitive science, are also expected.

As this research is so wide, it is not simple to suggest to interested readers further readings, except for classic books such as [15.32–34]. In fact, depending on the specific research area, many publications are available, although often not organized as reference books, 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 specific suggestions for further readings at this time. We can therefore only refer to the citations already provided in the chapter.

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16. Legged Robots

Shuuji Kajita, Bernard Espiau

In this chapter, we introduce legged robots. After introducing the history of legged robot research in Sect. 16.1, we start to discuss hopping robots and analyze a simple passive walker as a typical cycling walking robot in Sect. 16.2; the Poincaré map is one of the most important tools to analyze its dynamics and stability. In Sect. 16.3, the dynamics and control of general biped robots are discussed. The key is the forward dynamics subject to the unilateral constraint between the feet and the ground. Its formal treatment leads to walking trajectory generation and various control methods. As a practical scheme to control biped robots, we discuss the zero-moment point (ZMP) in Sect. 16.4, including its definition, physical meaning, measurement, calculation, and usage. In Sect. 16.5, we move to multilegged robots. In this field, the most important subject is the relationship between gaits and stability. We also introduce the landmark robots in this field. In Sect. 16.6, we overview the divergence of the legged robots. We see leg-wheel hybrid robots, leg-arm hybrid robots, tethered walking robots, and wall-climbing robots. To compare these legged robots with different configurations, we use some useful performance indices such as the Froude number and the specific resistance, which are introduced in Sect. 16.7. We conclude the chapter and address future trends in Sect. 16.8.

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The idea of designing and realizing artificial entities is almost as old as humanity. After some wonderful formal studies by Leonardo Da Vinci, the first notable artificial machines, called *automatons* were built, among others by Jacquard, Jacquet-Droz, Vaucanson (including his famous duck) mainly in France around the 18th century. This was followed by a florilegium of realizations from 1850 to World War I. The area then experienced a long