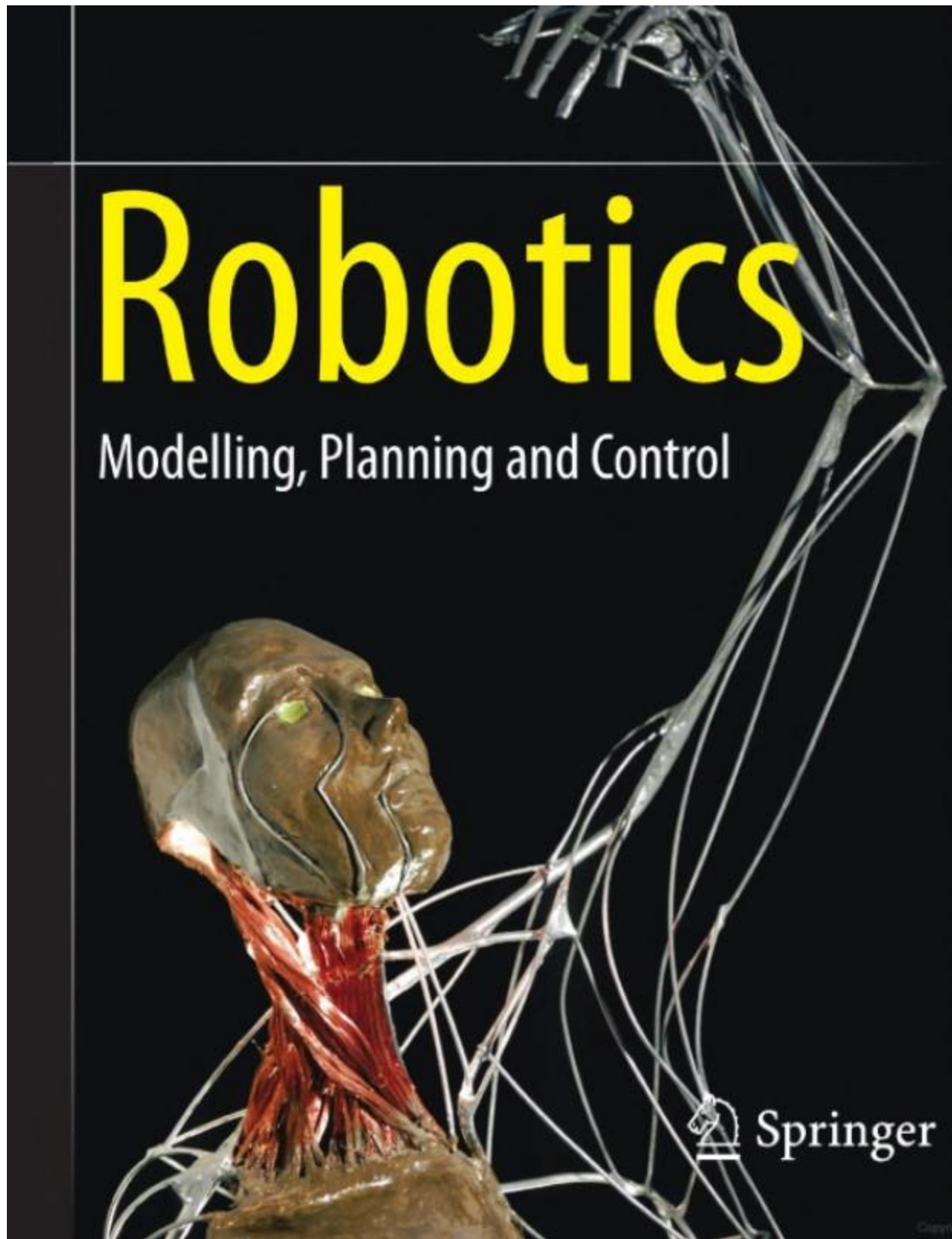


Robotics

Modelling, Planning and Control



Springer

Introduction

Robotics is concerned with the study of those machines that can replace human beings in the execution of a task, as regards both physical activity and decision making. The goal of the introductory chapter is to point out the problems related to the use of *robots* in *industrial* applications, as well as the perspectives offered by *advanced robotics*. A classification of the most common mechanical structures of *robot manipulators* and *mobile robots* is presented. Topics of *modelling*, *planning* and *control* are introduced which will be examined in the following chapters. The chapter ends with a list of references dealing with subjects both of specific interest and of related interest to those covered by this textbook.

1.1 Robotics

Robotics has profound cultural roots. Over the course of centuries, human beings have constantly attempted to seek substitutes that would be able to mimic their behaviour in the various instances of interaction with the surrounding environment. Several motivations have inspired this continuous search referring to philosophical, economic, social and scientific principles.

One of human beings' greatest ambitions has been to give life to their artifacts. The legend of the Titan Prometheus, who molded humankind from clay, as well as that of the giant Talus, the bronze slave forged by Hephaestus, testify how Greek mythology was influenced by that ambition, which has been revisited in the tale of Frankenstein in modern times.

Just as the giant Talus was entrusted with the task of protecting the island of Crete from invaders, in the Industrial Age a mechanical creature (*automaton*) has been entrusted with the task of substituting a human being in subordinate labor duties. This concept was introduced by the Czech playwright Karel Čapek who wrote the play *Rossum's Universal Robots (R.U.R.)* in 1920. On that occasion he coined the term *robot* — derived from the term

robota that means executive labour in Slav languages — to denote the automaton built by Rossum who ends up by rising up against humankind in the science fiction tale.

In the subsequent years, in view of the development of science fiction, the behaviour conceived for the robot has often been conditioned by feelings. This has contributed to rendering the robot more and more similar to its creator.

It is worth noticing how Rossum's robots were represented as creatures made with organic material. The image of the robot as a mechanical artifact starts in the 1940s when the Russian Isaac Asimov, the well-known science fiction writer, conceived the robot as an automaton of human appearance but devoid of feelings. Its behaviour was dictated by a "positronic" brain programmed by a human being in such a way as to satisfy certain rules of ethical conduct. The term *robotics* was then introduced by Asimov as the science devoted to the study of robots which was based on the *three fundamental laws*:

1. A robot may not injure a human being or, through inaction, allow a human being to come to harm.
2. A robot must obey the orders given by human beings, except when such orders would conflict with the first law.
3. A robot must protect its own existence, as long as such protection does not conflict with the first or second law.

These laws established rules of behaviour to consider as specifications for the design of a robot, which since then has attained the connotation of an industrial product designed by engineers or specialized technicians.

Science fiction has influenced the man and the woman in the street that continue to imagine the robot as a humanoid who can speak, walk, see, and hear, with an appearance very much like that presented by the robots of the movie *Metropolis*, a precursor of modern cinematography on robots, with *Star Wars* and more recently with *I, Robot* inspired by Asimov's novels.

According to a scientific interpretation of the science-fiction scenario, the robot is seen as a machine that, independently of its exterior, is able to modify the environment in which it operates. This is accomplished by carrying out actions that are conditioned by certain rules of behaviour intrinsic in the machine as well as by some data the robot acquires on its status and on the environment. In fact, *robotics* is commonly defined as the science studying the *intelligent connection between perception and action*.

With reference to this definition, a *robotic system* is in reality a complex system, functionally represented by multiple subsystems (Fig. 1.1).

The essential component of a robot is the *mechanical system* endowed, in general, with a locomotion apparatus (wheels, crawlers, mechanical legs) and a manipulation apparatus (mechanical arms, end-effectors, artificial hands). As an example, the mechanical system in Fig. 1.1 consists of two mechanical arms (manipulation apparatus), each of which is carried by a mobile vehicle

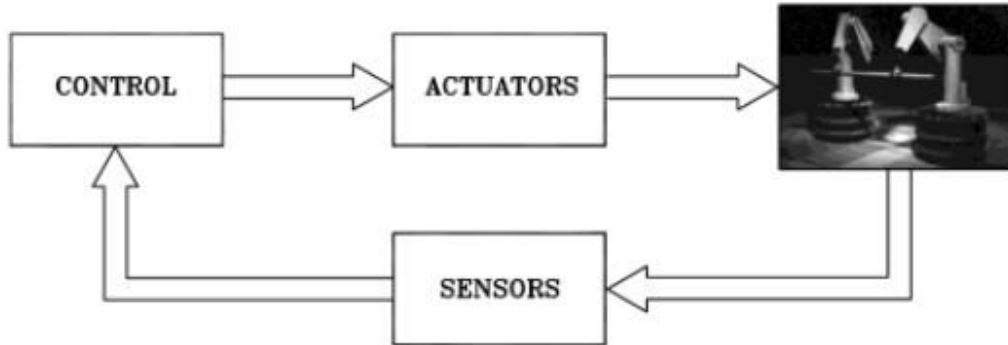


Fig. 1.1. Components of a robotic system

(locomotion apparatus). The realization of such a system refers to the context of design of articulated mechanical systems and choice of materials.

The capability to exert an action, both locomotion and manipulation, is provided by an *actuation system* which animates the mechanical components of the robot. The concept of such a system refers to the context of *motion control*, dealing with *servomotors*, *drives* and *transmissions*.

The capability for perception is entrusted to a *sensory system* which can acquire data on the internal status of the mechanical system (*proprioceptive sensors*, such as position transducers) as well as on the external status of the environment (*exteroceptive sensors*, such as force sensors and cameras). The realization of such a system refers to the context of materials properties, signal conditioning, data processing, and information retrieval.

The capability for connecting action to perception in an intelligent fashion is provided by a *control system* which can command the execution of the action in respect to the goals set by a task *planning* technique, as well as of the constraints imposed by the robot and the environment. The realization of such a system follows the same feedback principle devoted to *control* of human body functions, possibly exploiting the description of the robotic system's components (*modelling*). The context is that of cybernetics, dealing with control and supervision of robot motions, artificial intelligence and expert systems, the computational architecture and programming environment.

Therefore, it can be recognized that robotics is an interdisciplinary subject concerning the cultural areas of *mechanics*, *control*, *computers*, and *electronics*.

1.2.1 Robot Manipulators

The mechanical structure of a *robot manipulator* consists of a sequence of rigid bodies (*links*) interconnected by means of articulations (*joints*); a manipulator is characterized by an *arm* that ensures mobility, a *wrist* that confers dexterity, and an *end-effector* that performs the task required of the robot.

The fundamental structure of a manipulator is the serial or *open kinematic chain*. From a topological viewpoint, a kinematic chain is termed open when there is only one sequence of links connecting the two ends of the chain. Alternatively, a manipulator contains a *closed kinematic chain* when a sequence of links forms a loop.

A manipulator's mobility is ensured by the presence of joints. The articulation between two consecutive links can be realized by means of either a *prismatic* or a *revolute* joint. In an open kinematic chain, each prismatic or revolute joint provides the structure with a single degree of freedom (DOF). A prismatic joint creates a relative translational motion between the two links, whereas a revolute joint creates a relative rotational motion between the two links. Revolute joints are usually preferred to prismatic joints in view of their compactness and reliability. On the other hand, in a closed kinematic chain, the number of DOFs is less than the number of joints in view of the constraints imposed by the loop.

The *degrees of freedom* should be properly distributed along the mechanical structure in order to have a sufficient number to execute a given task. In the most general case of a task consisting of arbitrarily positioning and orienting an object in three-dimensional (3D) space, *six* DOFs are required, three for positioning a point on the object and three for orienting the object with respect to a reference coordinate frame. If more DOFs than task variables are available, the manipulator is said to be *redundant* from a kinematic viewpoint.

The *workspace* represents that portion of the environment the manipulator's end-effector can access. Its shape and volume depend on the manipulator structure as well as on the presence of mechanical joint limits.

The task required of the arm is to position the wrist which then is required to orient the end-effector. The type and sequence of the arm's DOFs, starting from the base joint, allows a classification of manipulators as *Cartesian*, *cylindrical*, *spherical*, *SCARA*, and *anthropomorphic*.

Cartesian geometry is realized by three prismatic joints whose axes typically are mutually orthogonal (Fig. 1.2). In view of the simple geometry, each DOF corresponds to a Cartesian space variable and thus it is natural to perform straight motions in space. The Cartesian structure offers very good mechanical stiffness. Wrist positioning accuracy is constant everywhere in the workspace. This is the volume enclosed by a rectangular parallel-piped

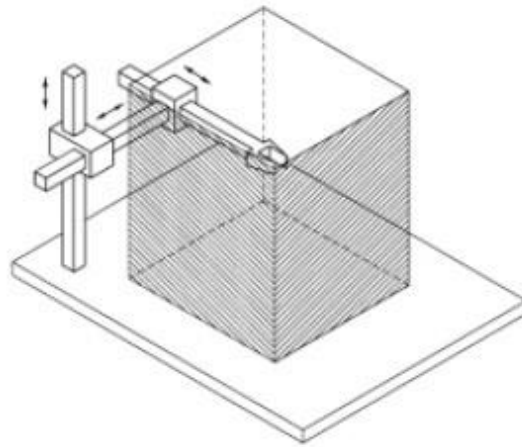


Fig. 1.2. Cartesian manipulator and its workspace

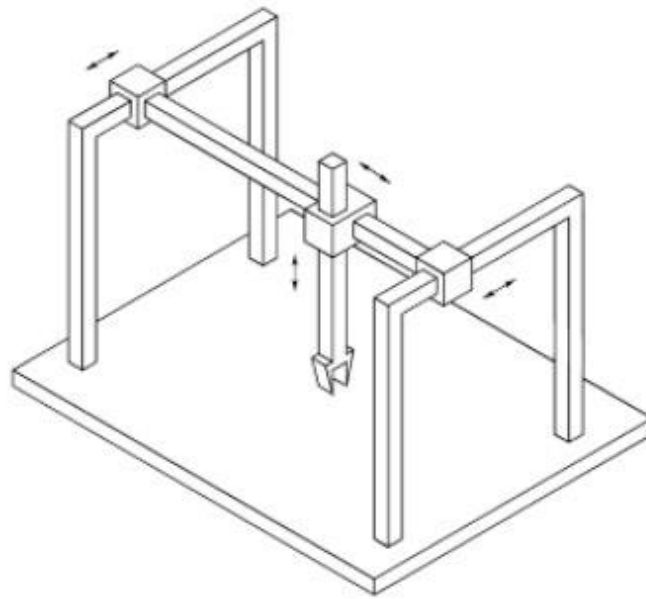


Fig. 1.3. Gantry manipulator

(Fig. 1.2). As opposed to high accuracy, the structure has low dexterity since all the joints are prismatic. The direction of approach in order to manipulate an object is from the side. On the other hand, if it is desired to approach an object from the top, the Cartesian manipulator can be realized by a *gantry* structure as illustrated in Fig. 1.3. Such a structure makes available a workspace with a large volume and enables the manipulation of objects of large dimensions and heavy weight. Cartesian manipulators are employed for material handling and assembly. The motors actuating the joints of a Cartesian manipulator are typically electric and occasionally pneumatic.

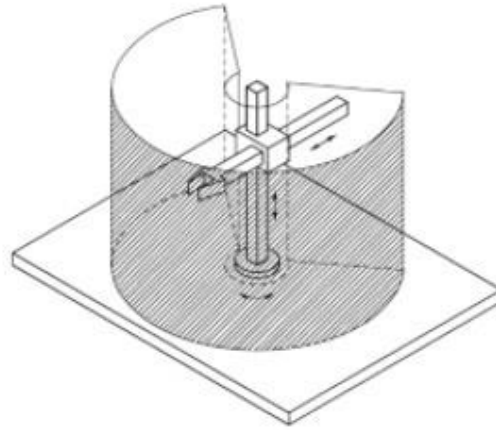


Fig. 1.4. Cylindrical manipulator and its workspace

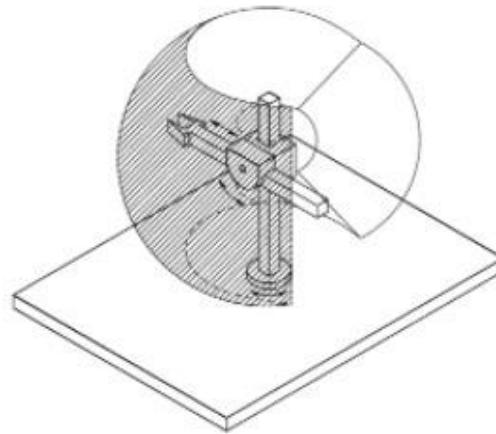


Fig. 1.5. Spherical manipulator and its workspace

cal coordinates, in this case each DOF also corresponds to a Cartesian space variable. The cylindrical structure offers good mechanical stiffness. Wrist positioning accuracy decreases as the horizontal stroke increases. The workspace is a portion of a hollow cylinder (Fig. 1.4). The horizontal prismatic joint makes the wrist of a cylindrical manipulator suitable to access horizontal cavities. Cylindrical manipulators are mainly employed for carrying objects even of large dimensions; in such a case the use of hydraulic motors is to be preferred to that of electric motors.

Spherical geometry differs from cylindrical in that the second prismatic joint is replaced with a revolute joint (Fig. 1.5). Each DOF corresponds to a Cartesian space variable provided that the task is described in spherical coordinates. Mechanical stiffness is lower than the above two geometries and mechanical construction is more complex. Wrist positioning accuracy decreases as the radial stroke increases. The workspace is a portion of a hollow sphere (Fig. 1.5); it can also include the supporting base of the manipulator and thus

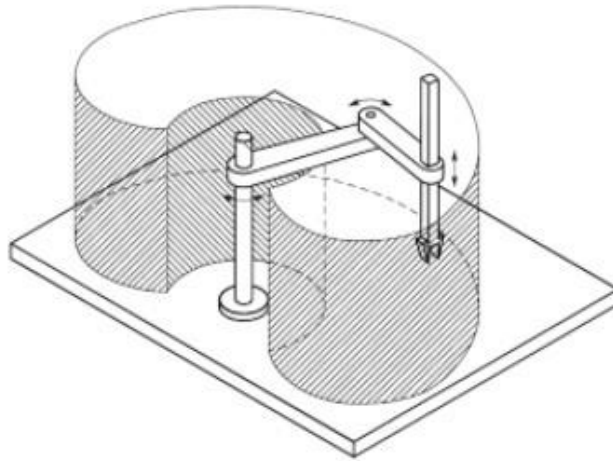


Fig. 1.6. SCARA manipulator and its workspace

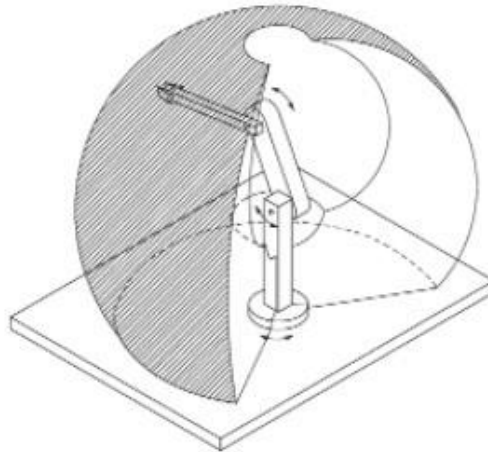


Fig. 1.7. Anthropomorphic manipulator and its workspace

it can allow manipulation of objects on the floor. Spherical manipulators are mainly employed for machining. Electric motors are typically used to actuate the joints.

A special geometry is *SCARA* geometry that can be realized by disposing two revolute joints and one prismatic joint in such a way that all the axes of motion are parallel (Fig. 1.6). The acronym SCARA stands for *Selective Compliance Assembly Robot Arm* and characterizes the mechanical features of a structure offering high stiffness to vertical loads and compliance to horizontal loads. As such, the SCARA structure is well-suited to vertical assembly tasks. The correspondence between the DOFs and Cartesian space variables is maintained only for the vertical component of a task described in Cartesian coordinates. Wrist positioning accuracy decreases as the distance of the wrist from the first joint axis increases. The typical workspace is illustrated

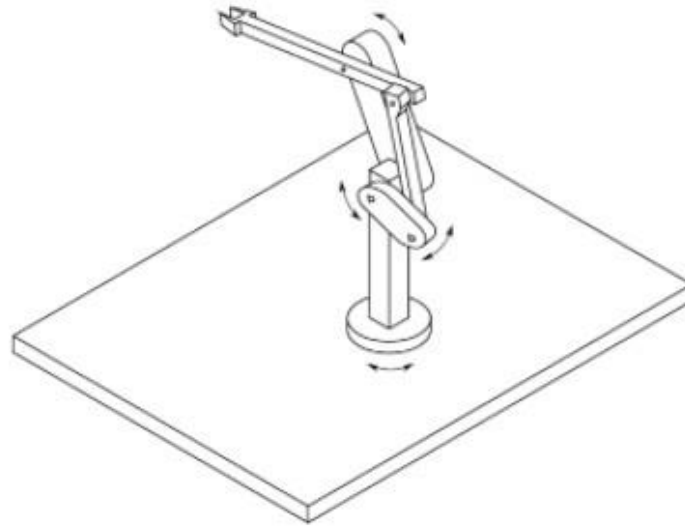


Fig. 1.8. Manipulator with parallelogram

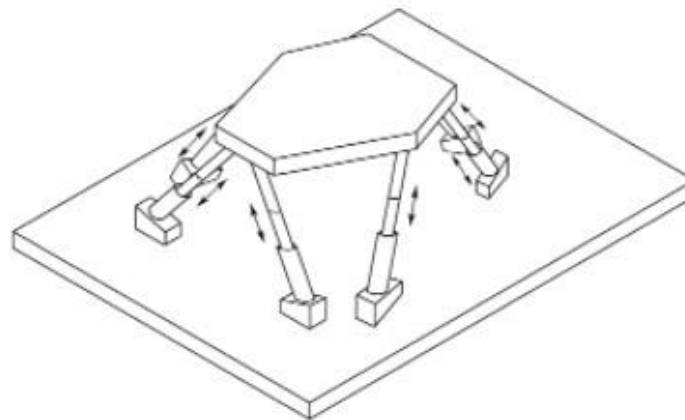


Fig. 1.9. Parallel manipulator

in Fig. 1.6. The SCARA manipulator is suitable for manipulation of small objects; joints are actuated by electric motors.

Anthropomorphic geometry is realized by three revolute joints; the revolute axis of the first joint is orthogonal to the axes of the other two which are parallel (Fig. 1.7). By virtue of its similarity with the human arm, the second joint is called the shoulder joint and the third joint the elbow joint since it connects the “arm” with the “forearm.” The anthropomorphic structure is the most dexterous one, since all the joints are revolute. On the other hand, the correspondence between the DOFs and the Cartesian space variables is lost, and wrist positioning accuracy varies inside the workspace. This is approximately a portion of a sphere (Fig. 1.7) and its volume is large compared to manipulator encumbrance. Joints are typically actuated by electric motors. The range of industrial applications of anthropomorphic manipulators is wide.

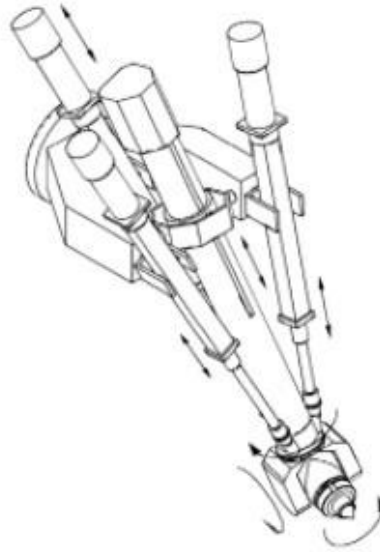


Fig. 1.10. Hybrid parallel-serial manipulator

According to the latest report by the *International Federation of Robotics* (IFR), up to 2005, 59% of installed robot manipulators worldwide has anthropomorphic geometry, 20% has Cartesian geometry, 12% has cylindrical geometry, and 8% has SCARA geometry.

All the previous manipulators have an open kinematic chain. Whenever larger payloads are required, the mechanical structure will have higher stiffness to guarantee comparable positioning accuracy. In such a case, resorting to a closed kinematic chain is advised. For instance, for an anthropomorphic structure, parallelogram geometry between the shoulder and elbow joints can be adopted, so as to create a closed kinematic chain (Fig. 1.8).

An interesting closed-chain geometry is *parallel* geometry (Fig. 1.9) which has multiple kinematic chains connecting the base to the end-effector. The fundamental advantage is seen in the high structural stiffness, with respect to open-chain manipulators, and thus the possibility to achieve high operational speeds; the drawback is that of having a reduced workspace.

The geometry illustrated in Fig. 1.10 is of hybrid type, since it consists of a parallel arm and a serial kinematic chain. This structure is suitable for the execution of manipulation tasks requiring large values of force along the vertical direction.

The manipulator structures presented above are required to position the wrist which is then required to orient the manipulator's end-effector. If arbitrary orientation in 3D space is desired, the wrist must possess at least three DOFs provided by revolute joints. Since the wrist constitutes the terminal part of the manipulator, it has to be compact; this often complicates its mechanical design. Without entering into construction details, the realization endowing the wrist with the highest dexterity is one where the three revolute