

# 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.

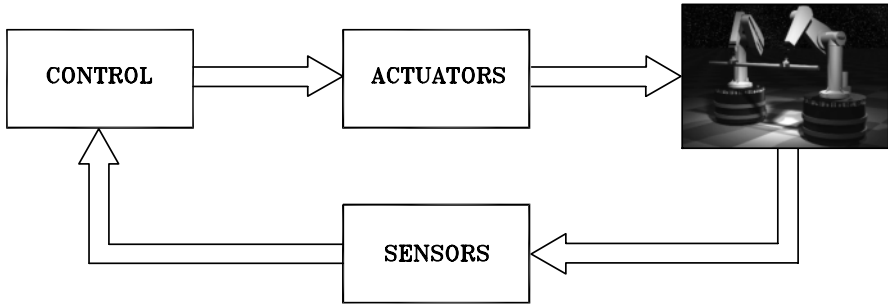
These laws established rules of behaviour to consider as specifications for the design of a robot, which since then has attained the connotation of an industrial product designed by engineers or specialized technicians.

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 Robot Mechanical Structure

The key feature of a robot is its mechanical structure. Robots can be classified as those with a fixed base, *robot manipulators*, and those with a mobile base,

*mobile robots*. In the following, the geometrical features of the two classes are presented.

### 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.

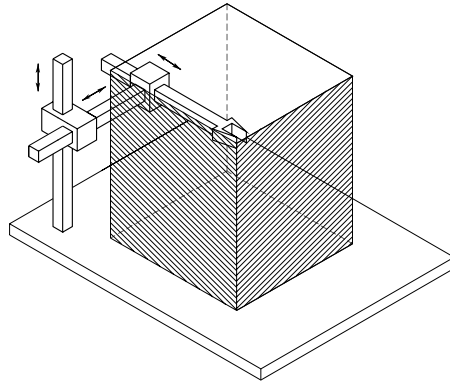
A manipulator's mobility is ensured by the presence of joints. The articulation between two consecutive links can be realized by means of either a *prismatic* or a *revolute* joint. In an open kinematic chain, each prismatic or revolute joint provides the structure with a single degree of freedom (DOF). 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.

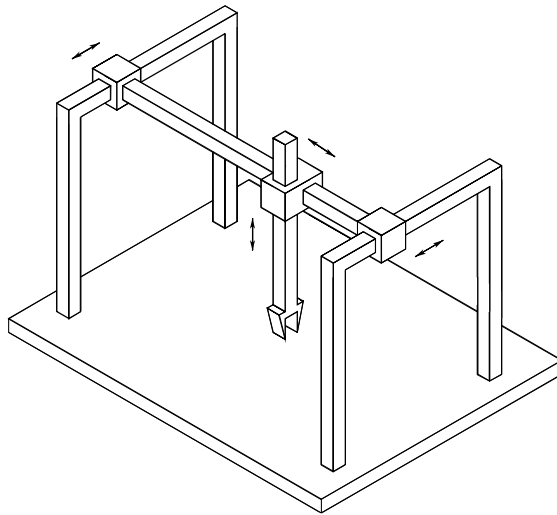
The *workspace* represents that portion of the environment the manipulator's end-effector can access. Its shape and volume depend on the manipulator structure as well as on the presence of mechanical joint limits.

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



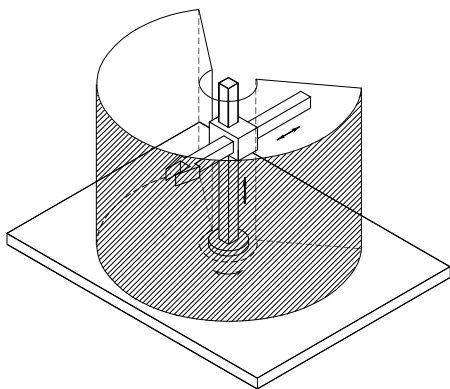
**Fig. 1.2.** Cartesian manipulator and its workspace



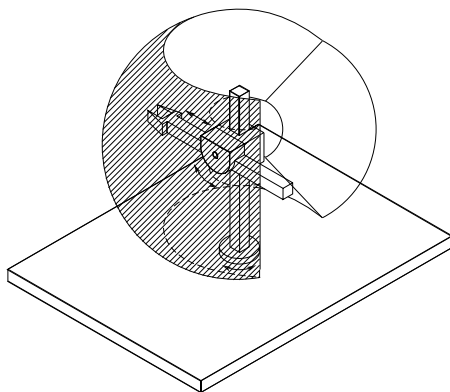
**Fig. 1.3.** Gantry manipulator

(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.

*Cylindrical* geometry differs from Cartesian in that the first prismatic joint is replaced with a revolute joint (Fig. 1.4). If the task is described in cylindri-



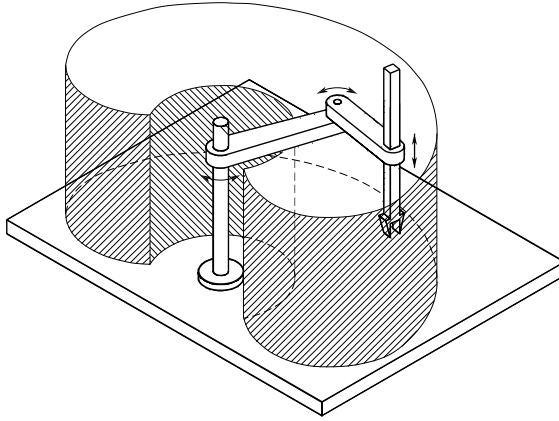
**Fig. 1.4.** Cylindrical manipulator and its workspace



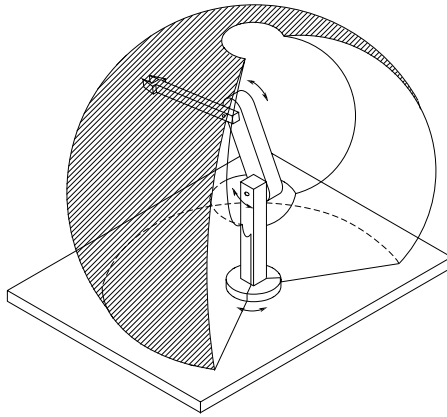
**Fig. 1.5.** Spherical manipulator and its workspace

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

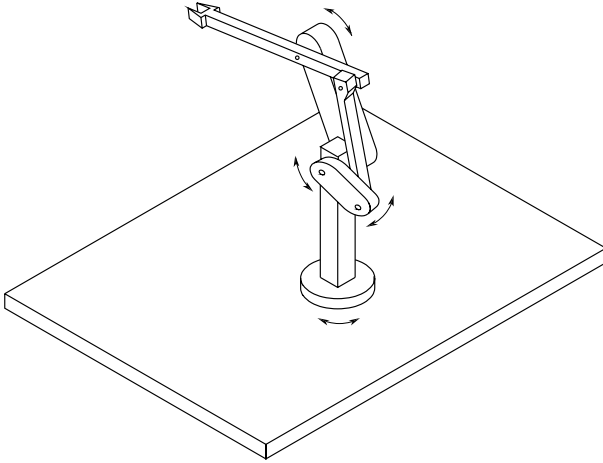


Fig. 1.8. Manipulator with parallelogram

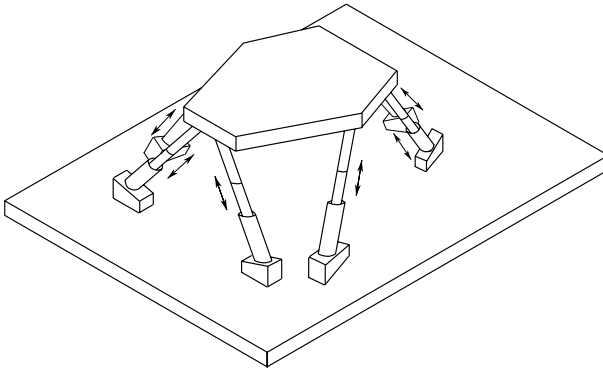
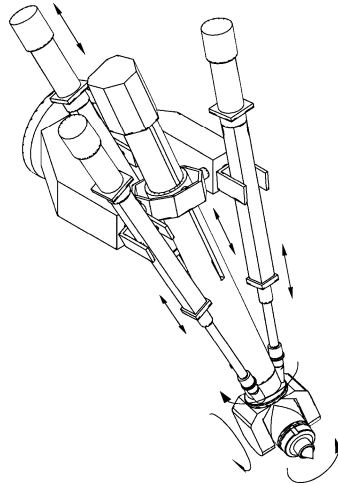


Fig. 1.9. Parallel manipulator

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

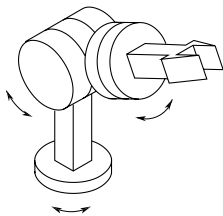
According to the latest report by the *International Federation of Robotics* (IFR), up to 2005, 59% of installed robot manipulators worldwide has anthropomorphic geometry, 20% has Cartesian geometry, 12% has cylindrical geometry, and 8% has SCARA geometry.

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



**Fig. 1.11.** Spherical wrist

axes intersect at a single point. In such a case, the wrist is called a *spherical wrist*, as represented in Fig. 1.11. The key feature of a spherical wrist is the decoupling between position and orientation of the end-effector; the arm is entrusted with the task of positioning the above point of intersection, whereas the wrist determines the end-effector orientation. Those realizations where the wrist is not spherical are simpler from a mechanical viewpoint, but position and orientation are coupled, and this complicates the coordination between the motion of the arm and that of the wrist to perform a given task.

The *end-effector* is specified according to the task the robot should execute. For material handling tasks, the end-effector consists of a gripper of proper shape and dimensions determined by the object to be grasped (Fig. 1.11). For machining and assembly tasks, the end-effector is a tool or a specialized device, e.g., a welding torch, a spray gun, a mill, a drill, or a screwdriver.

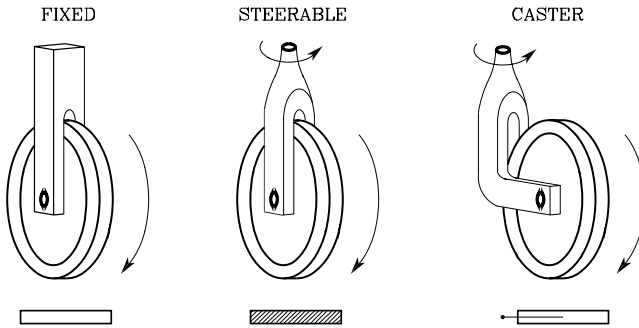
The versatility and flexibility of a robot manipulator should not induce the conviction that all mechanical structures are equivalent for the execution of a given task. The choice of a robot is indeed conditioned by the application which sets constraints on the workspace dimensions and shape, the maximum payload, positioning accuracy, and dynamic performance of the manipulator.

### 1.2.2 Mobile Robots

The main feature of *mobile robots* is the presence of a mobile base which allows the robot to move freely in the environment. Unlike manipulators, such robots are mostly used in service applications, where extensive, autonomous motion capabilities are required. From a mechanical viewpoint, a mobile robot consists of one or more rigid bodies equipped with a *locomotion* system. This description includes the following two main classes of mobile robots:<sup>1</sup>

- *Wheeled* mobile robots typically consist of a rigid body (*base* or *chassis*) and a system of wheels which provide motion with respect to the ground.

<sup>1</sup> Other types of mechanical locomotion systems are not considered here. Among these, it is worth mentioning *tracked locomotion*, very effective on uneven terrain, and *undulatory locomotion*, inspired by snake gaits, which can be achieved without specific devices. There also exist types of locomotion that are not constrained to the ground, such as flying and navigation.



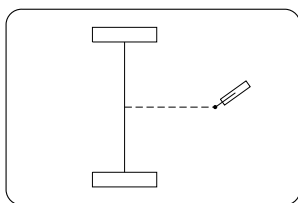
**Fig. 1.12.** The three types of conventional wheels with their respective icons

Other rigid bodies (*trailers*), also equipped with wheels, may be connected to the base by means of revolute joints.

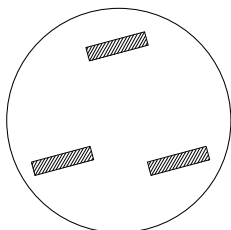
- *Legged* mobile robots are made of multiple rigid bodies, interconnected by prismatic joints or, more often, by revolute joints. Some of these bodies form lower limbs, whose extremities (*feet*) periodically come in contact with the ground to realize locomotion. There is a large variety of mechanical structures in this class, whose design is often inspired by the study of living organisms (*biomimetic robotics*): they range from biped humanoids to hexapod robots aimed at replicating the biomechanical efficiency of insects.

Only wheeled vehicles are considered in the following, as they represent the vast majority of mobile robots actually used in applications. The basic mechanical element of such robots is indeed the wheel. Three types of conventional wheels exist, which are shown in Fig. 1.12 together with the icons that will be used to represent them:

- The *fixed wheel* can rotate about an axis that goes through the center of the wheel and is orthogonal to the wheel plane. The wheel is rigidly attached to the chassis, whose orientation with respect to the wheel is therefore constant.
- The *steerable wheel* has two axes of rotation. The first is the same as a fixed wheel, while the second is vertical and goes through the center of the wheel. This allows the wheel to change its orientation with respect to the chassis.
- The *caster wheel* has two axes of rotation, but the vertical axis does not pass through the center of the wheel, from which it is displaced by a constant *offset*. Such an arrangement causes the wheel to swivel automatically, rapidly aligning with the direction of motion of the chassis. This type of wheel is therefore introduced to provide a supporting point for static balance without affecting the mobility of the base; for instance, caster wheels are commonly used in shopping carts as well as in chairs with wheels.



**Fig. 1.13.** A differential-drive mobile robot



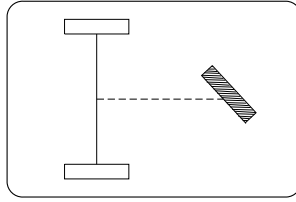
**Fig. 1.14.** A synchro-drive mobile robot

The variety of kinematic structures that can be obtained by combining the three conventional wheels is wide. In the following, the most relevant arrangements are briefly examined.

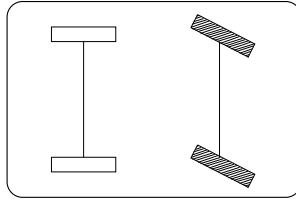
In a *differential-drive* vehicle there are two fixed wheels with a common axis of rotation, and one or more castor wheels, typically smaller, whose function is to keep the robot statically balanced (Fig. 1.13). The two fixed wheels are separately controlled, in that different values of angular velocity may be arbitrarily imposed, while the castor wheel is passive. Such a robot can rotate on the spot (i.e., without moving the midpoint between the wheels), provided that the angular velocities of the two wheels are equal and opposite.

A vehicle with similar mobility is obtained using a *synchro-drive* kinematic arrangement (Fig. 1.14). This robot has three aligned steerable wheels which are synchronously driven by only two motors through a mechanical coupling, e.g., a chain or a transmission belt. The first motor controls the rotation of the wheels around the horizontal axis, thus providing the driving force (traction) to the vehicle. The second motor controls the rotation of the wheels around the vertical axis, hence affecting their orientation. Note that the heading of the chassis does not change during the motion. Often, a third motor is used in this type of robot to rotate independently the upper part of the chassis (a turret) with respect to the lower part. This may be useful to orient arbitrarily a directional sensor (e.g., a camera) or in any case to recover an orientation error.

In a *tricycle* vehicle (Fig. 1.15) there are two fixed wheels mounted on a rear axle and a steerable wheel in front. The fixed wheels are driven by a single



**Fig. 1.15.** A tricycle mobile robot



**Fig. 1.16.** A car-like mobile robot

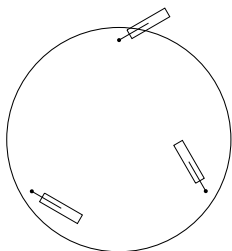
motor which controls their traction,<sup>2</sup> while the steerable wheel is driven by another motor which changes its orientation, acting then as a steering device. Alternatively, the two rear wheels may be passive and the front wheel may provide traction as well as steering.

A *car-like* vehicle has two fixed wheels mounted on a rear axle and two steerable wheels mounted on a front axle, as shown in Fig. 1.16. As in the previous case, one motor provides (front or rear) traction while the other changes the orientation of the front wheels with respect to the vehicle. It is worth pointing out that, to avoid slippage, the two front wheels must have a different orientation when the vehicle moves along a curve; in particular, the internal wheel is slightly more steered with respect to the external one. This is guaranteed by the use of a specific device called *Ackermann steering*.

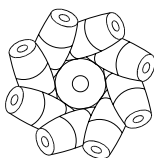
Finally, consider the robot in Fig. 1.17, which has three caster wheels usually arranged in a symmetric pattern. The traction velocities of the three wheels are independently driven. Unlike the previous cases, this vehicle is *omnidirectional*: in fact, it can move instantaneously in any Cartesian direction, as well as re-orient itself on the spot.

In addition to the above conventional wheels, there exist other special types of wheels, among which is notably the *Mecanum* (or *Swedish*) *wheel*, shown in Fig. 1.18. This is a fixed wheel with passive rollers placed along the external rim; the axis of rotation of each roller is typically inclined by  $45^\circ$  with respect to the plane of the wheel. A vehicle equipped with four such wheels mounted in pairs on two parallel axles is also omnidirectional.

<sup>2</sup> The distribution of the traction torque on the two wheels must take into account the fact that in general they move with different speeds. The mechanism which equally distributes traction is the *differential*.



**Fig. 1.17.** An omnidirectional mobile robot with three independently driven caster wheels

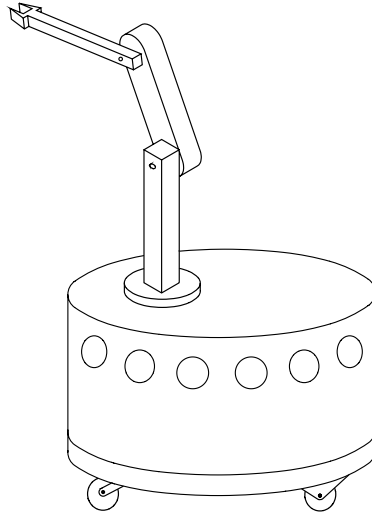


**Fig. 1.18.** A Mecanum (or Swedish) wheel

In the design of a wheeled robot, the mechanical balance of the structure does not represent a problem in general. In particular, a three-wheel robot is statically balanced as long as its center of mass falls inside the *support triangle*, which is defined by the contact points between the wheels and ground. Robots with more than three wheels have a support *polygon*, and thus it is typically easier to guarantee the above balance condition. It should be noted, however, that when the robot moves on uneven terrain a suspension system is needed to maintain the contact between each wheel and the ground.

Unlike the case of manipulators, the *workspace* of a mobile robot (defined as the portion of the surrounding environment that the robot can access) is potentially unlimited. Nevertheless, the local mobility of a non-omnidirectional mobile robot is always reduced; for instance, the tricycle robot in Fig. 1.15 cannot move instantaneously in a direction parallel to the rear wheel axle. Despite this fact, the tricycle can be manoeuvred so as to obtain, at the end of the motion, a net displacement in that direction. In other words, many mobile robots are subject to constraints on the admissible instantaneous motions, without actually preventing the possibility of attaining any position and orientation in the workspace. This also implies that the number of DOFs of the robot (meant as the number of admissible instantaneous motions) is lower than the number of its configuration variables.

It is obviously possible to merge the mechanical structure of a manipulator with that of a mobile vehicle by mounting the former on the latter. Such a robot is called a *mobile manipulator* and combines the dexterity of the articulated arm with the unlimited mobility of the base. An example of such a mechanical structure is shown in Fig. 1.19. However, the design of a mobile manipulator involves additional difficulties related, for instance, to the static



**Fig. 1.19.** A mobile manipulator obtained by mounting an anthropomorphic arm on a differential-drive vehicle

and dynamic mechanical balance of the robot, as well as to the actuation of the two systems.

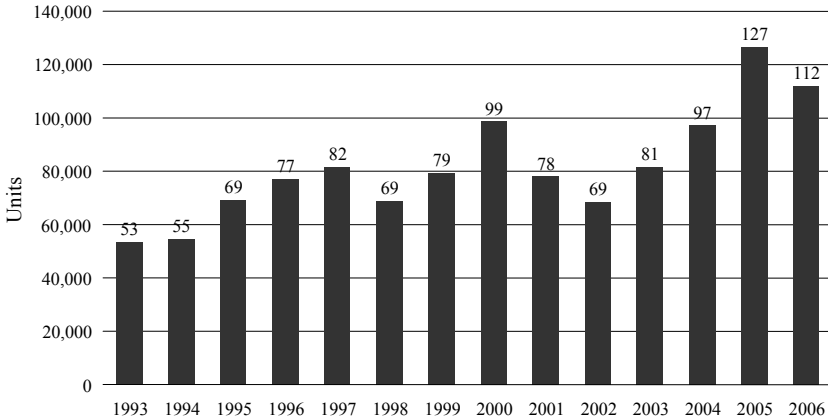
### 1.3 Industrial Robotics

*Industrial robotics* is the discipline concerning robot design, control and applications in industry, and its products have by now reached the level of a mature technology. The connotation of a robot for industrial applications is that of operating in a *structured environment* whose geometrical or physical characteristics are mostly known a priori. Hence, limited autonomy is required.

The early industrial robots were developed in the 1960s, at the confluence of two technologies: numerical control machines for precise manufacturing, and teleoperators for remote radioactive material handling. Compared to its precursors, the first robot manipulators were characterized by:

- versatility, in view of the employment of different end-effectors at the tip of the manipulator,
- adaptability to a priori unknown situations, in view of the use of sensors,
- positioning accuracy, in view of the adoption of feedback control techniques,
- execution repeatability, in view of the programmability of various operations.

During the subsequent decades, industrial robots have gained a wide popularity as essential components for the realization of automated manufacturing



**Fig. 1.20.** Yearly installations of industrial robots worldwide

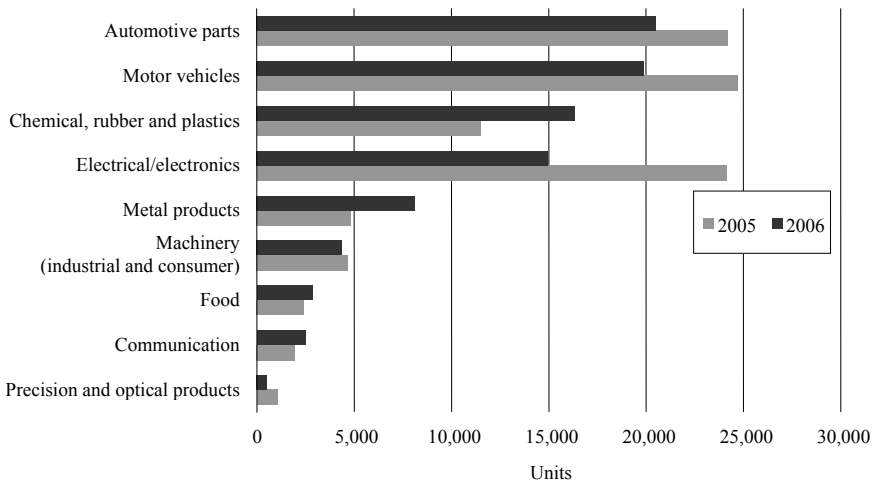
systems. The main factors having determined the spread of robotics technology in an increasingly wider range of applications in the manufacturing industry are reduction of manufacturing costs, increase of productivity, improvement of product quality standards and, last but not least, the possibility of eliminating harmful or off-putting tasks for the human operator in a manufacturing system.

By its usual meaning, the term *automation* denotes a technology aimed at replacing human beings with machines in a manufacturing process, as regards not only the execution of physical operations but also the intelligent processing of information on the status of the process. Automation is then the synthesis of industrial technologies typical of the manufacturing process and computer technology allowing information management. The three levels of automation one may refer to are rigid automation, programmable automation, and flexible automation.

*Rigid automation* deals with a factory context oriented to the mass manufacture of products of the same type. The need to manufacture large numbers of parts with high productivity and quality standards demands the use of fixed operational sequences to be executed on the workpiece by special purpose machines.

*Programmable automation* deals with a factory context oriented to the manufacture of low-to-medium batches of products of different types. A programmable automated system permits changing easy the sequence of operations to be executed on the workpieces in order to vary the range of products. The machines employed are more versatile and are capable of manufacturing different objects belonging to the same group technology. The majority of the products available on the market today are manufactured by programmable automated systems.





**Fig. 1.21.** Yearly supply of industrial robots by main industries

*Flexible automation* represents the evolution of programmable automation. Its goal is to allow manufacturing of variable batches of different products by minimizing the time lost for reprogramming the sequence of operations and the machines employed to pass from one batch to the next. The realization of a flexible manufacturing system (FMS) demands strong integration of computer technology with industrial technology.

The *industrial robot* is a machine with significant characteristics of versatility and flexibility. According to the widely accepted definition of the Robot Institute of America, *a robot is a reprogrammable multifunctional manipulator designed to move materials, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks*. Such a definition, dating back to 1980, reflects the current status of robotics technology.

By virtue of its programmability, the industrial robot is a typical component of programmable automated systems. Nonetheless, robots can be entrusted with tasks in both rigid and flexible automated systems.

According to the above-mentioned IFR report, up to 2006 nearly one million industrial robots are in use worldwide, half of which are in Asia, one third in Europe, and 16% in North America. The four countries with the largest number of robots are Japan, Germany, United States and Italy. The figures for robot installations in the last 15 years are summarized in the graph in Fig. 1.20; by the end of 2007, an increase of 10% in sales with respect to the previous year is foreseen, with milder increase rates in the following years, reaching a worldwide figure of 1,200,000 units at work by the end of 2010.

In the same report it is shown how the average service life of an industrial robot is about 12 years, which may increase to 15 in a few years from now. An interesting statistic is robot density based on the total number of persons employed: this ranges from 349 robots in operation per 10,000 workers to



**Fig. 1.22.** Examples of AGVs for material handling (courtesy of E&K Automation GmbH)

187 in Korea, 186 in Germany, and 13 in Italy. The United States has just 99 robots per 10,000 workers. The average cost of a 6-axis industrial robot, including the control unit and development software, ranges from 20,000 to 60,000 euros, depending on the size and applications.

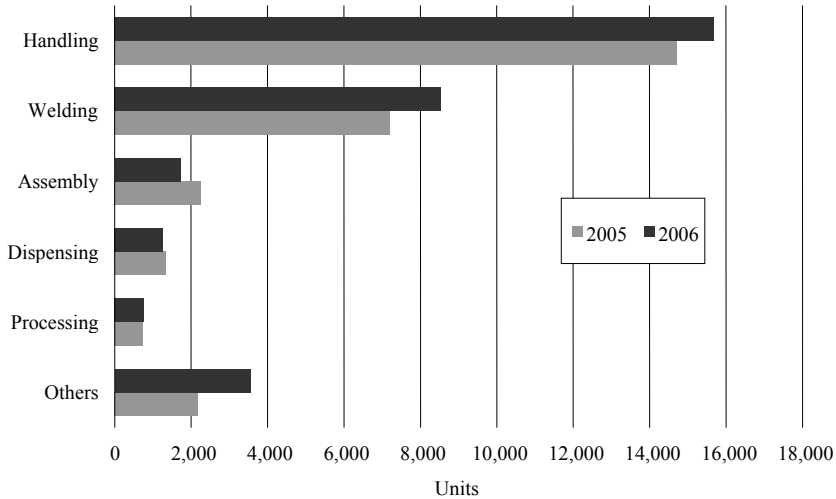
The automotive industry is still the predominant user of industrial robots. The graph in Fig. 1.21 referring to 2005 and 2006, however, reveals how both the chemical industry and the electrical/electronics industry are gaining in importance, and new industrial applications, such as metal products, constitute an area with a high potential investment.

Industrial robots present three fundamental capacities that make them useful for a manufacturing process: *material handling*, *manipulation*, and *measurement*.

In a manufacturing process, each object has to be transferred from one location in the factory to another in order to be stored, manufactured, assembled, and packed. During transfer, the physical characteristics of the object do not undergo any alteration. The robot's capability to pick up an object, move it in space on predefined paths and release it makes the robot itself an ideal candidate for material handling operations. Typical applications include:

- palletizing (placing objects on a pallet in an ordered way),
- warehouse loading and unloading,
- mill and machine tool tending,
- part sorting,
- packaging.

In these applications, besides robots, *Automated Guided Vehicles* (AGV) are utilized which ensure handling of parts and tools around the shop floor



**Fig. 1.23.** Yearly supply of industrial robots in Europe for manufacturing operations

from one manufacturing cell to the next (Fig. 1.22). As compared to the traditional fixed guide paths for vehicles (inductive guide wire, magnetic tape, or optical visible line), modern AGVs utilize high-tech systems with onboard microprocessors and sensors (laser, odometry, GPS) which allow their localization within the plant layout, and manage their work flow and functions, allowing their complete integration in the FMS. The mobile robots employed in advanced applications can be considered as the natural evolution of the AGV systems, as far as enhanced autonomy is concerned.

Manufacturing consists of transforming objects from raw material into finished products; during this process, the part either changes its own physical characteristics as a result of machining, or loses its identity as a result of an assembly of more parts. The robot's capability to manipulate both objects and tools make it suitable to be employed in manufacturing. Typical applications include:

- arc and spot welding,
- painting and coating,
- gluing and sealing,
- laser and water jet cutting,
- milling and drilling,
- casting and die spraying,
- deburring and grinding,
- screwing, wiring and fastening,
- assembly of mechanical and electrical groups,
- assembly of electronic boards.



**Fig. 1.24.** The AdeptOne XL robot (courtesy of Adept Technology Inc)

Besides material handling and manipulation, in a manufacturing process it is necessary to perform measurements to test product quality. The robot's capability to explore 3D space together with the availability of measurements on the manipulator's status allow a robot to be used as a measuring device. Typical applications include:

- object inspection,
- contour finding,
- detection of manufacturing imperfections.

The graph in Fig. 1.23 reports the number of robots employed in Europe in 2005 and 2006 for various operations, which reveals how material handling requires twice as many robots employed for welding, whereas a limited number of robots is still employed for assembly.

In the following some industrial robots are illustrated in terms of their features and application fields.

The AdeptOne XL robot in Fig. 1.24 has a four-joint SCARA structure. Direct drive motors are employed. The maximum reach is 800 mm, with a repeatability of 0.025 mm horizontally and 0.038 mm vertically. Maximum speeds are 1200 mm/s for the prismatic joint, while they range from 650 to 3300 deg/s for the three revolute joints. The maximum payload<sup>3</sup> is 12 kg. Typical industrial applications include small-parts material handling, assembly and packaging.

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<sup>3</sup> Repeatability and payload are classical parameters found in industrial robot data sheets. The former gives a measure of the manipulator's ability to return to a previously reached position, while the latter indicates the average load to be carried at the robot's end-effector.



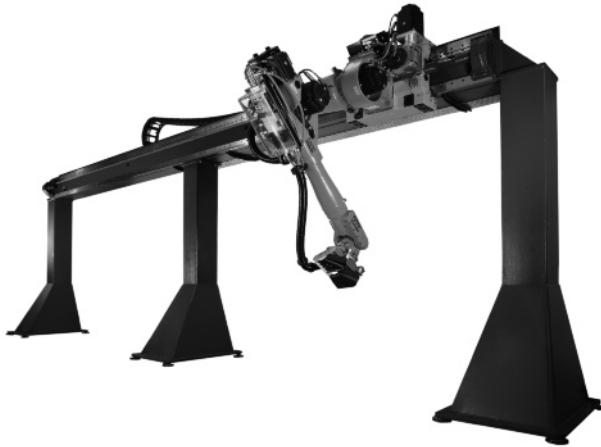
**Fig. 1.25.** The COMAU Smart NS robot (courtesy of COMAU SpA Robotica)



**Fig. 1.26.** The ABB IRB 4400 robot (courtesy of ABB Robotics)

The Comau SMART NS robot in Fig. 1.25 has a six-joint anthropomorphic structure with spherical wrist. In its four versions, the outreach ranges from 1650 and 1850 mm horizontally, with a repeatability of 0.05 mm. Maximum speeds range from 155 to 170 deg/s for the inner three joints, and from 350 to 550 deg/s for the outer three joints. The maximum payload is 16 kg. Both floor and ceiling mounting positions are allowed. Typical industrial applications include arc welding, light handling, assembly and technological processes.

The ABB IRB 4400 robot in Fig. 1.26 also has a six-joint anthropomorphic structure, but unlike the previous open-chain structure, it possesses a closed chain of parallelogram type between the shoulder and elbow joints. The outreach ranges from 1960 to 2550 mm for the various versions, with a



**Fig. 1.27.** The KUKA KR 60 Jet robot (courtesy of KUKA Roboter GmbH)

repeatability from 0.07 to 0.1 mm. The maximum speed at the end-effector is 2200 mm/s. The maximum payload is 60 kg. Floor or shelf-mounting is available. Typical industrial applications include material handling, machine tending, grinding, gluing, casting, die spraying and assembly.

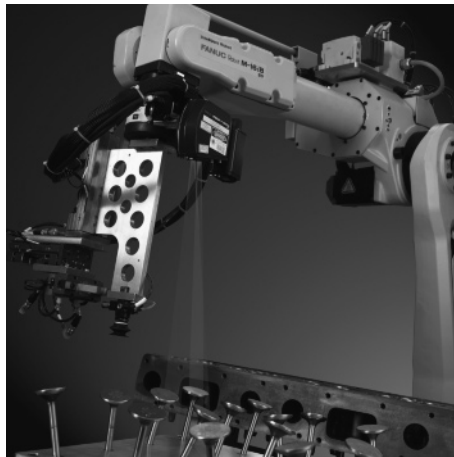
The KUKA KR 60 Jet robot in Fig. 1.27 is composed of a five-axis structure, mounted on a sliding track with a gantry-type installation; the upright installation is also available. The linear unit has a stroke from a minimum of 400 mm to a maximum of 20 m (depending on customer's request), and a maximum speed of 3200 mm/s. On the other hand, the robot has a payload of 60 kg, an outreach of 820 mm and a repeatability of 0.15 mm. Maximum speeds are 120 deg/s and 166 deg/s for the first two joints, while they range from 260 to 322 deg/s for the outer three joints. Typical industrial applications include machine tending, arc welding, deburring, coating, sealing, plasma and waterjet cutting.

The ABB IRB340 FlexPicker robot in Fig. 1.28 adopts a parallel geometry with four axes; in view of its reduced weight and floor mounting, the robot can transport 150 objects a minute (cycle time of just 0.4 s), reaching record speeds of 10 m/s and accelerations of  $100 \text{ m/s}^2$ , for a payload of 1 kg, with a repeatability of 0.1 mm. In its 'clean' aluminum version, it is particularly suitable for packaging in the food and pharmaceutical industries.

The Fanuc M-16iB robot in Fig. 1.29 has a six-joint anthropomorphic structure with a spherical wrist. In its two versions, the outreach varies from 1667 to 1885 mm horizontally, with a repeatability of 0.1 mm. Maximum speeds range from 165 to 175 deg/s for the inner three joints, and from 340 to 520 deg/s for the outer three joints. Payload varies from 10 to 20 kg. The peculiarity of this robot consists of the integrated sensors in the control unit, including a servoing system based on 3D vision and a six-axis force sensor.



**Fig. 1.28.** The ABB IRB 340 FlexPicker robot (courtesy of ABB Robotics)



**Fig. 1.29.** The Fanuc M-16iB robot (courtesy of Fanuc Ltd)

The robot is utilized for handling arbitrarily located objects, deburring, sealing and waterjet cutting.

The Light Weight Robot (LWR) in Fig. 1.30 with a seven-axis structure was introduced in 2006 as the outcome of technology transfer from DLR (the German Aerospace Agency) to KUKA. In view of the adoption of lightweight materials, as well as the adoption of torque sensors at the joints, the robot can manipulate a payload of 7 to 14 kg, in the face of a weight of the structure of just 15 kg. The horizontal outreach is 868 mm, with joint speeds ranging from 110 to 210 deg/s. On the other hand, the presence of the seventh axis of motion confers kinematic redundancy to the robot, which can then be reconfigured into more dexterous postures for the execution of given tasks. Such



**Fig. 1.30.** The KUKA LWR robot (courtesy of KUKA Roboter GmbH)

a manipulator represents one of the most advanced industrial products and, in view of its lightweight feature, it offers interesting performance for interaction with the environment, ensuring an inherent safety in case of contact with human beings.

In most industrial applications requiring object manipulation, typical grippers are utilized as end-effectors. Nevertheless, whenever enhanced manipulability and dexterity is desired, multifingered robot hands are available.

The BarrettHand (Fig. 1.31), endowed with a fixed finger and two mobile fingers around the base of the palm, allows the manipulation of objects of different dimension, shape and orientation.

The SCHUNK Antropomorphic Hand (SAH) in Fig. 1.32 is the outcome of technology transfer from DLR and Harbin Institute of Technology (China) to SCHUNK. Characterized by three independent aligned fingers and an opposing finger which is analogous to the human thumb. The finger joints are endowed with magnetic angular sensors and torque sensors. This hand offers good dexterity and approaches the characteristics of the human hand.

LWR technology has been employed for the realization of the two arms of Justin, a humanoid manipulator made by DLR, composed of a three-joint torso with an anthropomorphic structure, two seven-axis arms and a sensorized head. The robot is illustrated in Fig. 1.33 in the execution of a bimanual manipulation task; the hands employed are previous versions of the SAH anthropomorphic hand.

The applications listed describe the current employment of robots as components of industrial automation systems. They all refer to strongly structured working environments and thus do not exhaust all the possible utilizations of robots for industrial applications. Whenever it is desired to tackle problems requiring the adaptation of the robot to a changeable working environment, the fall-out of advanced robotics products are of concern. In this regard, the





**Fig. 1.31.** The BarrettHand (courtesy of Barrett Technology Inc)



**Fig. 1.32.** The SCHUNK Anthropomorphic Hand (courtesy of SCHUNK Intec Ltd)

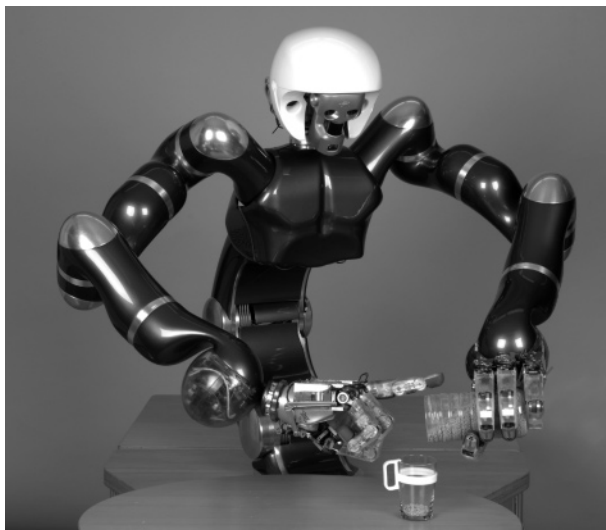
lightweight robot, the hands and the humanoid manipulator presented above are to be considered at the transition from traditional industrial robotics systems toward those innovative systems of advanced robotics.

## 1.4 Advanced Robotics

The expression *advanced robotics* usually refers to the science studying robots with marked characteristics of *autonomy*, operating in scarcely structured or *unstructured environments*, whose geometrical or physical characteristics would not be known a priori.

Nowadays, advanced robotics is still in its youth. It has indeed featured the realization of prototypes only, because the associated technology is not yet mature. There are many motivations which strongly encourage advances in knowledge within this field. They range from the need for automata whenever human operators are not available or are not safe (*field robots*), to the opportunity of developing products for potentially wide markets which are aimed at improving quality of life (*service robots*).

The graph in Fig. 1.34 reports the number of robots in stock for non-industrial applications at the end of 2006 and the forecast to 2010. Such applications are characterized by the complexity level, the uncertainty and variability of the environment with which the robot interacts, as shown in the following examples.

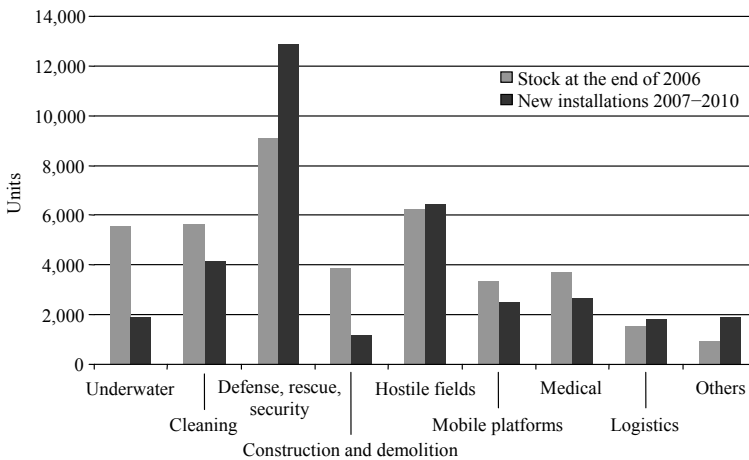


**Fig. 1.33.** The Justin humanoid robot manipulator (courtesy of DLR)

### 1.4.1 Field Robots

The context is that of deploying robots in areas where human beings could not survive or be exposed to unsustainable risks. Such robots should carry out exploration tasks and report useful data on the environment to a remote operator, using suitable onboard sensors. Typical scenarios are the exploration of a volcano, the intervention in areas contaminated by poisonous gas or radiation, or the exploration of the deep ocean or space. As is well known, NASA succeeded in delivering some mobile robots (rovers) to Mars (Fig. 1.35) which navigated on the Martian soil, across rocks, hills and crevasses. Such rovers were partially teleoperated from earth and have successfully explored the environment with sufficient autonomy. Some mini-robots were deployed on September 11, 2001 at Ground Zero after the collapse of the Twin Towers in New York, to penetrate the debris in the search for survivors.

A similar scenario is that of disasters caused by fires in tunnels or earthquakes; in such occurrences, there is a danger of further explosions, escape of harmful gases or collapse, and thus human rescue teams may cooperate with robot rescue teams. Also in the military field, unmanned autonomous aircrafts and missiles are utilized, as well as teleoperated robots with onboard cameras to explore buildings. The ‘Grand Challenge’ of October 2005 (Fig. 1.36) was financially supported by the US Department of Defense (DARPA) with the goal of developing autonomous vehicles to carry weapons and sensors, thus reducing soldier employment.



**Fig. 1.34.** Robots on stock for non-industrial applications



**Fig. 1.35.** The Sojourner rover was deployed by the Pathfinder lander and explored 250 m<sup>2</sup> of Martian soil in 1997 (courtesy of NASA)

### 1.4.2 Service Robots

Autonomous vehicles are also employed for civil applications, i.e., for mass transit systems (Fig. 1.37), thus contributing to the reduction of pollution levels. Such vehicles are part of the so-called Intelligent Transportation Systems (ITS) devoted to traffic management in urban areas. Another feasible application where the adoption of mobile robots offers potential advantages is museum guided tours (Fig. 1.38).

Many countries are investing in establishing the new market of service robots which will co-habitat with human beings in everyday life. According to the above-mentioned IFR report, up to 2005 1.9 million service robots for domestic applications (Fig. 1.39) and 1 million toy robots have been sold.

Technology is ready to transform into commercial products the prototypes of robotic aids to enhance elderly and impaired people's autonomy in everyday life; autonomous wheelchairs, mobility aid lifters, feeding aids and rehabilitation robots allowing tetraplegics to perform manual labor tasks are examples of such service devices. In perspective, other than an all-purpose robot waiter,



**Fig. 1.36.** The unmanned car Stanley autonomously completed a path of 132 miles in the record time of 6 h and 53 min (courtesy of DARPA)



**Fig. 1.37.** The Cycab is an electrically-driven vehicle for autonomous transportation in urban environments (courtesy of INRIA)

assistance, and healthcare systems integrating robotic and telematic modules will be developed for home service management (domotics).

Several robotic systems are employed for medical applications. Surgery assistance systems exploit a robot's high accuracy to position a tool, i.e., for hip prosthesis implant. Yet, in minimally-invasive surgery, i.e., cardiac surgery, the surgeon operates while seated comfortably at a console viewing a 3D image of the surgical field, and operating the surgical instruments remotely by means of a haptic interface (Fig. 1.40).

Further, in diagnostic and endoscopic surgery systems, small teleoperated robots travel through the cavities of human body, i.e., in the gastrointestinal system, bringing live images or intervening in situ for biopsy, dispensing drugs or removing neoplasms.



**Fig. 1.38.** Rhino, employing the synchro-drive mobile base B21 by Real World Interface, was one of the first robots for museum guided tours (courtesy of Deutsches Museum Bonn)



**Fig. 1.39.** The vacuum robot Roomba, employing a differential-drive kinematics, autonomously sweeps and cleans floors (courtesy of I-Robot Corp)

Finally, in motor rehabilitation systems, a hemiplegic patient wears an exoskeleton, which actively interacts, sustains and corrects the movements according to the physiotherapist's programmed plan.

Another wide market segment comes from entertainment, where robots are used as toy companions for children, and life companions for the elderly, such as humanoid robots (Fig. 1.41) and the pet robots (Fig. 1.42) being developed in Japan. It is reasonable to predict that service robots will be naturally integrated into our society. Tomorrow, robots will be as pervasive and personal as today's personal computers, or just as TV sets in the homes of 20 years ago. Robotics will then become ubiquitous, a challenge under discussion within the scientific community.

## 1.5 Robot Modelling, Planning and Control

In all robot applications, completion of a generic task requires the execution of a specific motion prescribed to the robot. The correct execution of such



**Fig. 1.40.** The da Vinci robotic system for laparoscopic surgery (courtesy of Intuitive Surgical Inc)

motion is entrusted to the control system which should provide the robot's actuators with the commands consistent with the desired motion. Motion control demands an accurate analysis of the characteristics of the mechanical structure, actuators, and sensors. The goal of such analysis is the derivation of the mathematical models describing the input/output relationship characterizing the robot components. Modelling a robot manipulator is therefore a necessary premise to finding motion control strategies.

Significant topics in the study of modelling, planning and control of robots which constitute the subject of subsequent chapters are illustrated below.

### 1.5.1 Modelling

Kinematic analysis of the mechanical structure of a robot concerns the description of the motion with respect to a fixed reference Cartesian frame by ignoring the forces and moments that cause motion of the structure. It is meaningful to distinguish between kinematics and differential kinematics. With reference to a robot manipulator, *kinematics* describes the analytical relationship between the joint positions and the end-effector position and orientation. *Differential kinematics* describes the analytical relationship between the joint motion and the end-effector motion in terms of velocities, through the manipulator Jacobian.

The formulation of the kinematics relationship allows the study of two key problems of robotics, namely, the direct kinematics problem and the inverse kinematics problem. The former concerns the determination of a systematic, general method to describe the end-effector motion as a function of the joint motion by means of linear algebra tools. The latter concerns the



**Fig. 1.41.** The Asimo humanoid robot, launched in 1996, has been endowed with even more natural locomotion and human-robot interaction skills (courtesy of Honda Motor Company Ltd)



**Fig. 1.42.** The AIBO dog had been the most widely diffused entertainment robot in the recent years (courtesy of Sony Corp)

inverse problem; its solution is of fundamental importance to transform the desired motion, naturally prescribed to the end-effector in the workspace, into the corresponding joint motion.

The availability of a manipulator's kinematic model is also useful to determine the relationship between the forces and torques applied to the joints and the forces and moments applied to the end-effector in *static* equilibrium configurations.

Chapter 2 is dedicated to the study of kinematics. Chapter 3 is dedicated to the study of differential kinematics and statics, whereas Appendix A provides a useful brush-up on *linear algebra*.

Kinematics of a manipulator represents the basis of a systematic, general derivation of its *dynamics*, i.e., the equations of motion of the manipulator as a function of the forces and moments acting on it. The availability of the dynamic model is very useful for mechanical design of the structure, choice of actuators, determination of control strategies, and computer simulation of

manipulator motion. Chapter 7 is dedicated to the study of dynamics, whereas Appendix B recalls some fundamentals on *rigid body mechanics*.

Modelling of *mobile robots* requires a preliminary analysis of the kinematic constraints imposed by the presence of wheels. Depending on the mechanical structure, such constraints can be integrable or not; this has direct consequence on a robot's mobility. The *kinematic model* of a mobile robot is essentially the description of the admissible instantaneous motions in respect of the constraints. On the other hand, the *dynamic model* accounts for the reaction forces and describes the relationship between the above motions and the generalized forces acting on the robot. These models can be expressed in a canonical form which is convenient for design of planning and control techniques. Kinematic and dynamic analysis of mobile robots is developed in Chap. 11, while Appendix D contains some useful concepts of *differential geometry*.

### 1.5.2 Planning

With reference to the tasks assigned to a manipulator, the issue is whether to specify the motion at the joints or directly at the end-effector. In material handling tasks, it is sufficient to assign only the pick-up and release locations of an object (point-to-point motion), whereas, in machining tasks, the end-effector has to follow a desired trajectory (path motion). The goal of *trajectory planning* is to generate the timing laws for the relevant variables (joint or end-effector) starting from a concise description of the desired motion. Chapter 4 is dedicated to trajectory planning for robot manipulators.

The motion planning problem for a mobile robot concerns the generation of trajectories to take the vehicle from a given initial configuration to a desired final configuration. Such a problem is more complex than that of robot manipulators, since trajectories have to be generated in respect of the kinematic constraints imposed by the wheels. Some solution techniques are presented in Chap. 11, which exploit the specific differential structure of the mobile robots' kinematic models.

Whenever obstacles are present in a mobile robot's workspace, the planned motions must be safe, so as to avoid collisions. Such a problem, known as *motion planning*, can be formulated in an effective fashion for both robot manipulators and mobile robots utilizing the configuration space concept. The solution techniques are essentially of algorithmic nature and include exact, probabilistic and heuristic methods. Chapter 12 is dedicated to motion planning problem, while Appendix E provides some basic concepts on *graph search algorithms*.

### 1.5.3 Control

Realization of the motion specified by the control law requires the employment of *actuators* and *sensors*. The functional characteristics of the most commonly used actuators and sensors for robots are described in Chap. 5.



Chapter 6 is concerned with the hardware/software *architecture* of a robot's *control system* which is in charge of implementation of control laws as well as of interface with the operator.

The trajectories generated constitute the reference inputs to the *motion control* system of the mechanical structure. The problem of *robot manipulator* control is to find the time behaviour of the forces and torques to be delivered by the joint actuators so as to ensure the execution of the reference trajectories. This problem is quite complex, since a manipulator is an articulated system and, as such, the motion of one link influences the motion of the others. Manipulator equations of motion indeed reveal the presence of coupling dynamic effects among the joints, except in the case of a Cartesian structure with mutually orthogonal axes. The synthesis of the joint forces and torques cannot be made on the basis of the sole knowledge of the dynamic model, since this does not completely describe the real structure. Therefore, manipulator control is entrusted to the closure of feedback loops; by computing the deviation between the reference inputs and the data provided by the proprioceptive sensors, a feedback control system is capable of satisfying accuracy requirements on the execution of the prescribed trajectories.

Chapter 8 is dedicated to the presentation of motion control techniques, whereas Appendix C illustrates the basic principles of *feedback control*.

Control of a *mobile robot* substantially differs from the analogous problem for robot manipulators. This is due, in turn, to the availability of fewer control inputs than the robot has configuration variables. An important consequence is that the structure of a controller allowing a robot to follow a trajectory (tracking problem) is unavoidably different from that of a controller aimed at taking the robot to a given configuration (regulation problem). Further, since a mobile robot's proprioceptive sensors do not yield any data on the vehicle's configuration, it is necessary to develop localization methods for the robot in the environment. The control design problem for wheeled mobile robots is treated in Chap. 11.

If a manipulation task requires interaction between the robot and the environment, the control problem should account for the data provided by the exteroceptive sensors; the forces exchanged at the contact with the environment, and the objects' position as detected by suitable cameras. Chapter 9 is dedicated to *force control* techniques for robot manipulators, while Chap. 10 presents *visual control* techniques.

## Bibliography

In the last 30 years, the robotics field has stimulated the interest of an increasing number of scholars. A truly respectable international research community has been established. Literature production has been conspicuous, both in terms of textbooks and scientific monographs and in terms of journals dedicated to robotics. Therefore, it seems appropriate to close this introduction

by offering a selection of *bibliographical reference sources* to those readers who wish to make a thorough study of robotics.

Besides indicating those basic textbooks sharing an affinity of contents with this one, the following lists include specialized books on related subjects, collections of contributions on the state of the art of research, scientific journals, and series of international conferences.

### Basic textbooks

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### Specialized books

Topics of related interest to robot modelling, planning and control are:

- manipulator mechanical design,
- manipulation tools,
- manipulators with elastic members,
- parallel robots,
- locomotion apparatus,
- mobile robots,
- underwater and space robots,
- control architectures
- motion and force control,
- robot vision,
- multisensory data fusion,
- telerobotics,
- human-robot interaction.

The following books are dedicated to these topics:

- G. Antonelli, *Underwater Robots: Motion and Force Control of Vehicle-Manipulator Systems*, 2nd ed., Springer, Heidelberg, Germany, 2006.
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