Chapter 1

Terminology and general definitions

1.1. Introduction

A robot is an automatically controlled, reprogrammable, multipurpose mechanical system with several degrees of freedom, which may be either fixed in place or mobile. It has been widely used so far in various industrial automation applications. Since the last decade, other areas of application have emerged: medical, service (spatial, civil security, ...), transport, underwater, entertainment, ..., where the robot either works in an autonomous manner or in cooperation with an operator to carry out complex tasks in a more or less structured environment. We can distinguish three main classes of robots: *robot manipulators*, which imitate the human arm, *walking robots*, which imitate the locomotion of humans, animals or insects, and *mobile robots*, which look like cars.

The terms *adaptability* and *versatility* are often used to highlight the intrinsic flexibility of a robot. Adaptability means that the robot is capable of adjusting its motion to comply with environmental changes during the execution of tasks. Versatility means that the robot may carry out a variety of tasks – or the same task in different ways – without changing the mechanical structure or the control system.

A robot is composed of the following subsystems:

- *mechanism*: consists of an articulated mechanical structure actuated by electric, pneumatic or hydraulic actuators, which transmit their motion to the joints using suitable transmission systems;
- *perception capabilities*: help the robot to adapt to disturbances and unpredictable changes in its environment. They consist of the internal sensors that provide information about the state of the robot (joint positions and velocities), and the external sensors to obtain the information about the environment (contact detection, distance measurement, artificial vision);

- *controller*: realizes the desired task objectives. It generates the input signals for the actuators as a function of the user's instructions and the sensor outputs;
- *communication interface*: through this the user programs the tasks that the robot must carry out;
- *workcell and peripheral devices*: constitute the environment in which the robot works.

Robotics is thus a multidisciplinary science, which requires a background in mechanics, automatic control, electronics, signal processing, communications, computer engineering, etc.

The objective of this book is to present the techniques of the modeling, identification and control of robots. We restrict our study to rigid robot manipulators with a fixed base. Thus, neither flexible robots for which the deformation of the links cannot be neglected [Cannon 84], [Chedmail 90a], [Boyer 94], nor mobile robots will be addressed in this book.

In this chapter, we will present certain definitions that are necessary to classify the mechanical structures and the characteristics of robot manipulators.

1.2. Mechanical components of a robot

The mechanism of a robot manipulator consists of two distinct subsystems, one (or more) end-effectors and an articulated mechanical structure:

- by the term *end-effector*, we mean any device intended to manipulate objects (magnetic, electric or pneumatic grippers) or to transform them (tools, welding torches, paint guns, etc.). It constitutes the interface with which the robot interacts with its environment. An end-effector may be multipurpose, i.e. equipped with several devices each having different functions;
- the role of *the articulated mechanical structure* is to place the end-effector at a given location (position and orientation) with a desired velocity and acceleration. The mechanical structure is composed of a kinematic chain of articulated rigid links. One end of the chain is fixed and is called the *base*. The end-effector is fixed to the free extremity of the chain. This chain may be *serial (simple open chain)* (Figure 1.1), *tree structured* (Figure 1.2) or *closed* (Figures 1.3 and 1.4). The last two structures are termed *complex chains* since they contain at least one link with more than two joints.

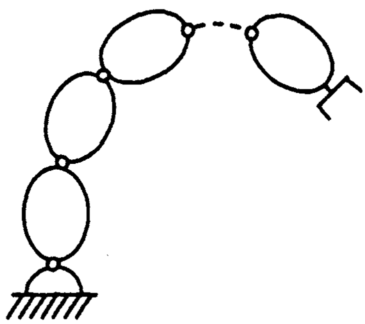

Figure 1.1. *Simple open (or serial) chain*

Serial robots with a simple open chain are the most commonly used. There are also industrial robots with closed kinematic chains, which have the advantage of being more rigid and accurate.

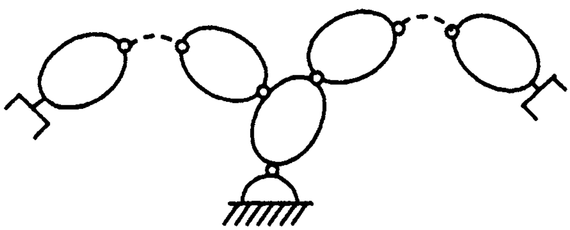

Figure 1.2. *Tree structured chain*

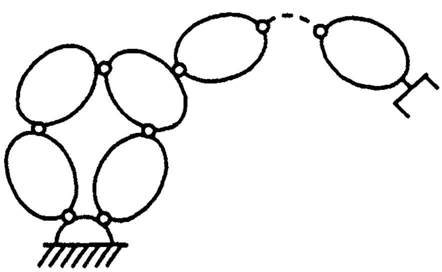

Figure 1.3. *Closed chain*

Figure 1.4 shows a specific architecture with closed chains, which is known as a ***parallel robot***. In this case, the end-effector is connected to the base by several parallel chains [Inoue 85], [Fichter 86], [Reboulet 88], [Gosselin 88], [Clavel 89], [Charentus 90], [Pierrot 91a], [Merlet 00]. The mass ratio of the payload to the robot is much higher compared to serial robots. This structure seems promising in manipulating heavy loads with high accelerations and realizing difficult assembly tasks.

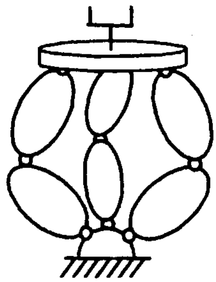

Figure 1.4. *Parallel robot*

1.3. Definitions

1.3.1. *Joints*

A joint connects two successive links, thus limiting the number of degrees of freedom between them. The resulting number of degrees of freedom, m, is also called *joint mobility*, such that $0 \leq m \leq 6$.

When m = 1, which is frequently the case in robotics, the joint is either *revolute* or *prismatic*. A complex joint with several degrees of freedom can be constructed by an equivalent combination of revolute and prismatic joints. For example, a spherical joint can be obtained by using three revolute joints whose axes intersect at a point.

1.3.1.1. *Revolute joint*

This limits the motion between two links to a rotation about a common axis. The relative location between the two links is given by the angle about this axis. The revolute joint, denoted by R, is represented by the symbols shown in Figure 1.5.

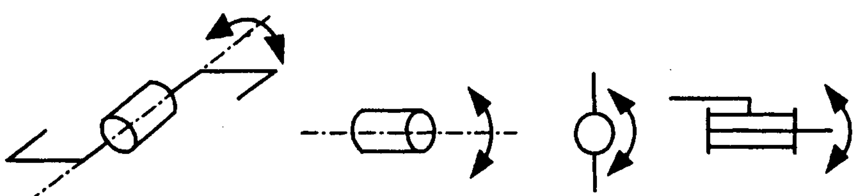

Figure 1.5. *Symbols of a revolute joint*

1.3.1.2. *Prismatic joint*

This limits the motion between two links to a translation along a common axis. The relative location between the two links is determined by the distance along this axis. The prismatic joint, denoted by P, is represented by the symbols shown in Figure 1.6.

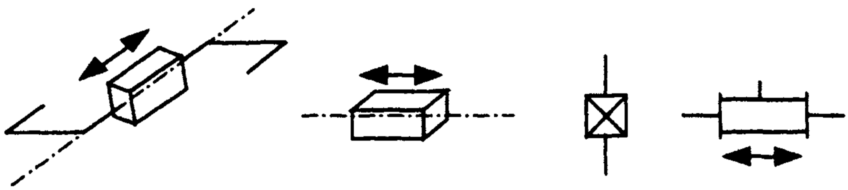

Figure 1.6. *Symbols of a prismatic joint*

1.3.2. *Joint space*

The space in which the location of all the links of a robot are represented is called *joint space*, or *configuration space*. We use the *joint variables*, $\mathbf{q} \in \Re^N$, as the coordinates of this space. Its dimension N is equal to the number of independent joints and corresponds to the number of degrees of freedom of the mechanical structure. In an open chain robot (simple or tree structured), the joint variables are generally independent, whereas a closed chain structure implies constraint relations between the joint variables.

Unless otherwise stated, we will consider that a robot with N degrees of freedom has N actuated joints.

1.3.3. *Task space*

The location, position and orientation, of the end-effector is represented in the *task space*, or *operational space*. We may consider as many task spaces as there are end-effectors. Generally, Cartesian coordinates are used to specify the position in $\Re^3$ and the rotation group SO(3) for the orientation. Thus the task space is equal to $\Re^3 \times SO(3)$. An element of the task space is represented by the vector $\mathbf{X} \in \Re^M$, where M is equal to the maximum number of independent parameters that are necessary to specify the location of the end-effector in space. Consequently, $M \leq 6$ and $M \leq N$.

1.3.4. *Redundancy*

A robot is classified as *redundant* when the number of degrees of freedom of its task space is less than the number of degrees of freedom of its joint space. This property increases the volume of the reachable workspace of the robot and enhances its performance. We will see in Chapter 6 that redundant robots can achieve a secondary objective besides the primary objective of locating and moving the end-effector with desired velocity.

Notice that a simple open chain is redundant if it contains any of the following combinations of joints:

- more than six joints;
- more than three revolute joints whose axes intersect at a point;
- more than three revolute joints with parallel axes;
- more than three prismatic joints;
- prismatic joints with parallel axes;
- revolute joints with collinear axes.

NOTES.–

- for an articulated mechanism with several end-effectors, redundancy is evaluated by comparing the number of degrees of freedom of the joint space acting on each end-effector and the number of degrees of freedom of the corresponding task space;
- another type of redundancy may occur when the number of degrees of freedom of the task is less than the number of degrees of freedom of the robot. We will discuss this case in Chapter 6.

1.3.5. *Singular configurations*

For all robots, redundant or not, it is possible that at some configurations, called *singular configurations*, the number of degrees of freedom of the end-effector becomes less than the dimension of the task space. For example, this may occur when:

- the axes of two prismatic joints become parallel;
- the axes of two revolute joints become collinear;
- the origin of the end-effector lies on a line that intersects all the joint axes.

In Chapter 5, we will present a mathematical condition to determine the number of degrees of freedom of the task space of a mechanism as well as its singular configurations.

1.4. Choosing the number of degrees of freedom of a robot

A non-redundant robot must have six degrees of freedom in order to place an arbitrary object in space. However, if the manipulated object exhibits revolution symmetry, five degrees of freedom are sufficient, since it is not necessary to specify the rotation about the revolution axis. In the same way, to locate a body in a plane, one needs only three degrees of freedom: two for positioning a point in the plane and the third to determine the orientation of the body.

From these observations, we deduce that:

- the number of degrees of freedom of a mechanism is chosen as a function of the shape of the object to be manipulated by the robot and of the class of tasks to be realized;
- a necessary but insufficient condition to have compatibility between the robot and the task is that the number of degrees of freedom of the end-effector of the robot is equal to or more than that of the task.

1.5. Architectures of robot manipulators

Without anticipating the results of the next chapters, we can say that the study of both tree structured and closed chains can be reduced to some equivalent simple open chains. Thus, the classification presented below is relevant for simple open chain architectures, but may also be generalized to the complex chains.

In order to count the possible architectures, we only consider revolute or prismatic joints whose consecutive axes are either parallel or perpendicular. Generally, with some exceptions (in particular, the last three joints of the GMF P150 and Kuka IR600 robots), the consecutive axes of currently used robots are either parallel or perpendicular. The different combinations of these four parameters yield the number of possible architectures with respect to the number of joints as shown in Table 1.1 [Delignières 87], [Chedmail 90a].

The first three joints of a robot are commonly designed in order to perform gross motion of the end-effector, and the remaining joints are used to accomplish orientation. Thus, the first three joints and the associated links constitute the shoulder or regional positioning structure. The other joints and links form the wrist.

Taking into account these considerations and the data of Table 1.1, one can count 36 possible combinations of the shoulder. Among these architectures, only 12 are mathematically distinct and non-redundant (we eliminate, *a priori*, the structures limiting the motion of the terminal point of the shoulder to linear or planar displacement, such as those having three prismatic joints with parallel axes, or three revolute joints with parallel axes). These structures are shown in Figure 1.7.

Table 1.1. *Number of possible architectures as a function of the number of degrees of freedom of the robot*

Number of degrees of freedom of the robot	Number of architectures
2	8
3	36
4	168
5	776
6	3508

A survey of industrial robots has shown that only the following five structures [Liégeois 79] are manufactured:

- anthropomorphic shoulder represented by the first RRR structure shown in Figure 1.7, like PUMA from Unimation, Acma SR400, ABB IRBx400, Comau Smart-3, Fanuc (S-xxx, Arc Mate), Kuka (KR 6 to KR 200), Reis (RV family), Staübli (RX series), etc.;
- spherical shoulder RRP: "Stanford manipulator" and Unimation robots (Series 1000, 2000, 4000);
- RPR shoulder corresponding to the first RPR structure shown in Figure 1.7: Acma-H80, Reis (RH family), etc. The association of a wrist with one revolute degree of freedom of rotation to such a shoulder can be found frequently in the industry. The resulting structure of such a robot is called SCARA (Selective Compliance Assembly Robot Arm) (Figure 1.8). It has several applications, particularly in planar assembly. SCARA, designed by Sankyo, has been manufactured by many other companies: IBM, Bosch, Adept, etc.;
- cylindrical shoulder RPP: Acma-TH8, AFMA (ROV, ROH), etc.;
- Cartesian shoulder PPP: Acma-P80, IBM-7565, Sormel-Cadratic, Olivetti-SIGMA. More recent examples: AFMA (RP, ROP series), Comau P-Mast, Reis (RL family), SEPRO, etc.

The second RRR structure of Figure 1.7, which is equivalent to a spherical joint, is generally used as a wrist. Other types of wrists are shown in Figure 1.9 [Delignières 87].

A robot, composed of a shoulder with three degrees of freedom and a spherical wrist, constitutes a classical six degree-of-freedom structure (Figure 1.10). Note that the position of the center of the spherical joint depends only on the configuration of joints 1, 2 and 3. We will see in Chapter 4 that, due to this property, the inverse geometric model, providing the joint variables for a given location of the end-effector, can be obtained analytically for such robots.

According to the survey carried out by the French Association of Industrial Robotics (AFRI) and RobAut Journal [Fages 98], the classification of robots in France (17794 robots), with respect to the number of degrees of freedom, is as follows: 4.5% of the robots have three degrees of freedom, 27% have four, 9% have five and 59.5% have six or more. As far as the architecture of the shoulder is concerned, there is a clear dominance of the RRR anthropomorphic shoulder (65.5%), followed by the Cartesian shoulder (20.5%), then the cylindrical shoulder (7%) and finally the SCARA shoulder (7%).

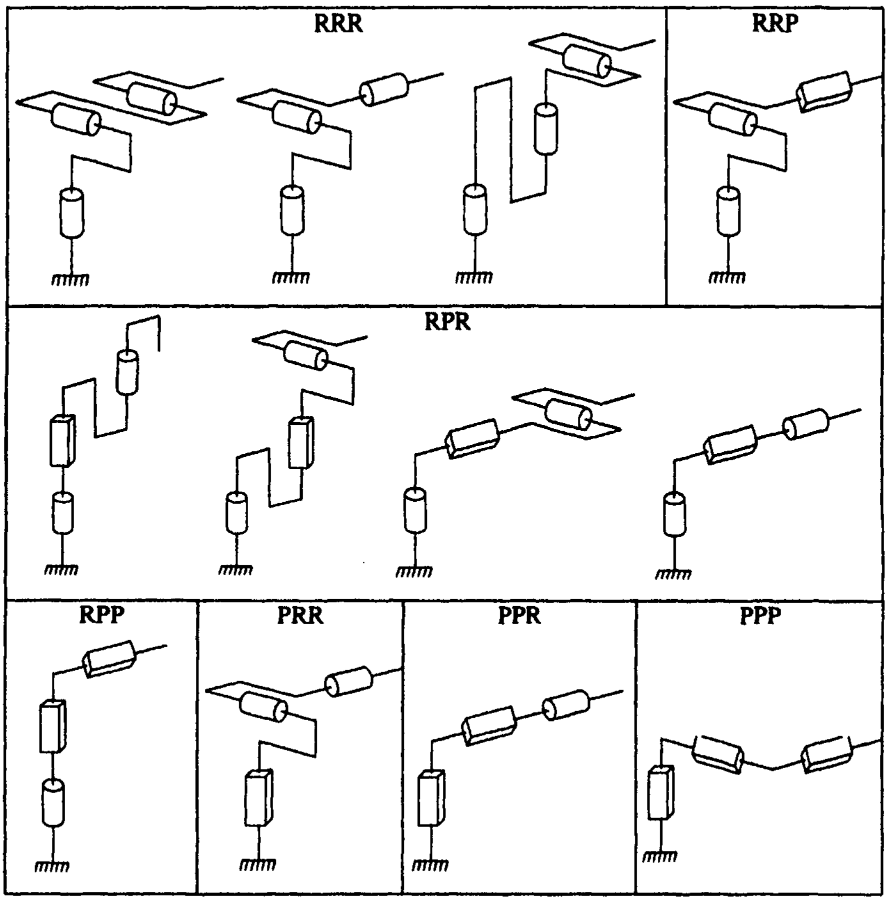

Figure 1.7. *Architectures of the shoulder (from [Milenkovic 83])*

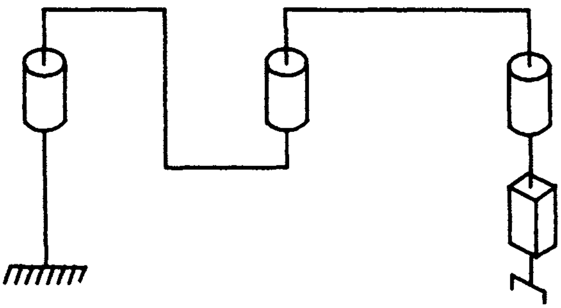

Figure 1.8. *SCARA robot*

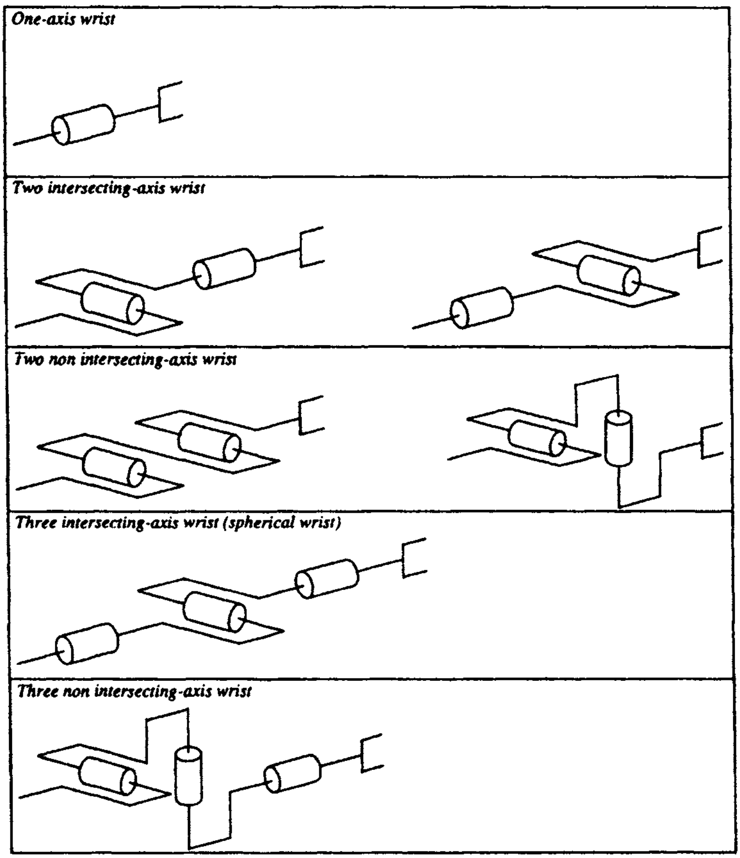

Figure 1.9. *Architectures of the wrist (from [Delignières 87])*

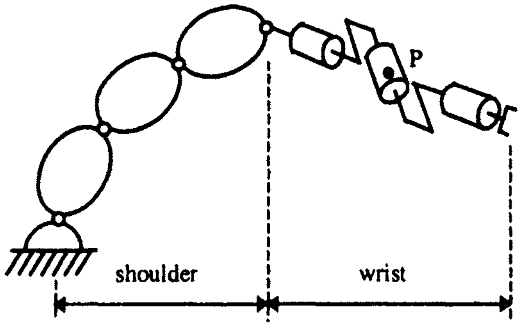

Figure 1.10. *Classical six degree-of-freedom robot*

1.6. Characteristics of a robot

The standard ISO 9946 specifies the characteristics that manufacturers of robots must provide. Here, we describe some of these characteristics that may help the user in choosing an appropriate robot with respect to a given application:

- *workspace*: defines the space that can be swept by the end-effector. Its range depends on the number of degrees of freedom, the joint limits and the length of the links;
- *payload*: maximum load carried by the robot;
- *maximum velocity and acceleration*: determine the cycle time;
- *position accuracy* (Figure 1.11): indicates the difference between a commanded position and the mean of the attained positions when visiting the commanded position several times from different initial positions;
- *position repeatability* (Figure 1.11): specifies the precision with which the robot returns to a commanded position. It is given as the distance between the mean of the attained positions and the furthermost attained position;
- *resolution*: the smallest increment of movement that can be achieved by the joint or the end-effector.

However, other characteristics must also be taken into account: technical (energy, control, programming, etc.) and commercial (price, maintenance, etc.). Thus, the selection criteria are sometimes difficult to formulate and are often contradictory. To a certain extent, the simulation and modeling tools available in Computer Aided Design (CAD) packages may help in making the best choice [Dombre 88b], [Zeghloul 91], [Chedmail 92], [Chedmail 98].

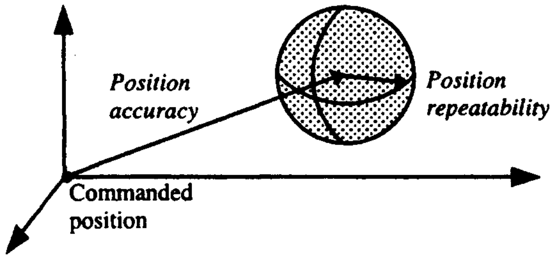

Figure 1.11. *Position accuracy and repeatability (from [Priel 90])*

1.7. Conclusion

In this chapter, we have presented the definitions of some technical terms related to the field of modeling, identification and control of robots. We will frequently come across these terms in this book and some of them will be reformulated in a more analytical or mathematical way. The figures mentioned here justify the choice of the robots that are taken as examples in the following chapters. In the next chapter, we present the transformation matrix concept, which constitutes an important mathematical tool for the modeling of robots.