Robotics

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# Preface

The word "robot" does not originate from a science or engineering vocabulary. It was first used in the Czech drama R.U.R. (Rossum's Universal Robots) written by Karel Čapek and was first played in Prague in 1921 (the word itself was invented by his brother Josef). In the drama the "robot" is an artificial human being which is a brilliant worker, deprived of all unnecessary qualities: feelings, creativity and capacity for feeling pain. In the prologue of the drama the following "definition" of robots is given: *Robots are not people (Roboti nejsou lidé). They are mechanically more perfect than we are, they have an astounding intellectual capacity, but they have no soul. The creation of an engineer is technically more refined than the product of nature.*

The textbook "Robotics" evolved through more than 10 years of teaching robotics at the Faculty of Electrical Engineering, of the University of Ljubljana, Slovenia. The way of presenting the rather demanding subject was successfully tested with several generations of undergraduate students.

The major feature of the book is its simplicity. The basic characteristics of industrial robot mechanisms are presented in the introduction. The position, orientation and displacement of an object are described by homogenous transformation matrices. These matrices, which are the basis for any analysis of robot mechanisms, are introduced through simple geometrical reasoning. Geometrical models of the robot mechanism are explained with the help of an original and friendly vector description. Robot kinematics and dynamics are introduced via a mechanism with only two rotational degrees of freedom, which is however an important part of the most popular industrial SCARA and anthropomorphic robot structures. The presentation of robot dynamics is based on only the knowledge of Newton's law. The robot workspace plays an important role in selecting an appropriate robot for the task planned. Robot sensors and robot trajectory planning are presented. Basic control schemes, resulting in either the desired end-effector trajectory or in the force between the robot and its environment, are also explained. Robot grippers and feeding devices are described together with the planning of robot assembly. The chapter on standardization and measurement of accuracy and repeatability is of interest for users of industrial robots. The textbook is supplemented with a short English–German–French robotic vocabulary.

The book requires minimal advance knowledge of mathematics and physics. Therefore it is appropriate for students of engineering schools (electrical, mechanical, computer, civil) or first-level students according to the two-level Bologna program. It could be of interest also for engineers who did not study robotics, but encounter robots in their working environment and wish to acquire some basic knowledge in a simple and fast manner.

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Ljubljana
July 2009

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# Contents

# Chapter 1
# Introduction

It is appropriate to begin the textbook on robotics with the definition of the industrial robot manipulator as given by the ISO 8373 standard. An industrial robot manipulator is a feedback controlled, reprogrammable, multipurpose system. It is programmable in three or more degrees of freedom. Robot manipulators are used in processes of industrial automation.

The standard stresses feedback control of industrial robots. Robotic mechanisms are actuated by electric and hydraulic motors. Important component parts of any robotic system are sensors. Here, we distinguish between internal and external sensors. Internal sensors assess position and velocity of robot segments and are placed into robotic joints. Among external sensors, the most important are the sensor of contact forces and the robot vision sensors. The aim of the robot control system is to guide the robot end-point with respect to the desired trajectory determined by the user and with respect to information received from the sensors.

In modern industrial production, there are no large stocks of either materials or of products. We say that the production process runs just in time. As a consequence, it may happen that different types of a certain product find themselves on the same production line during the same day. The problem, which is most inconvenient for fixed automation, can be efficiently solved by the use of industrial robotic manipulators. Reprogrammable robots allow us to switch from the production of one type of product to another similar one simply by touching a push-button.

Furthermore, the ISO standard definition characterizes the robot manipulator as a multipurpose mechanism. The robot mechanism is a crude imitation of the human arm. In the same way as we use our arm for both precise and heavy work, we are trying to apply the same robot manipulator to different tasks. This is even more important in view of the economic life span of an industrial robot, which is rather long (12–16 years). It can therefore happen, that we had acquired a robot manipulator for welding purposes, while after certain period of time the robot will be used for a pick and place task.

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The last property, expressed in the definition, describes the robot as a mechanism, which is programmable in three or more degrees of freedom. As this is the most characteristic property of an industrial robot, we shall examine more closely the meaning of a degree of freedom.

## 1.1 Degree of freedom

To begin with, we will introduce the degree of freedom having in mind an infinitesimal mass particle. In this case the number of degrees of freedom is defined as the number of independent coordinates (not including time) which are necessary for the complete description of the position of a mass particle.

A particle moving along a line (infinitesimally small ball on a wire) is a system with one degree of freedom. A pendulum with a rigid segment, which is swinging in a plane, is also a system with one degree of freedom (Figure 1.1). In the first example the position of the particle can be described with the distance, while in the second case it is described with the angle of rotation.

A mass particle moving on a plane has two degrees of freedom (Figure 1.2). The position of the particle can be described with two cartesian coordinates $x$ and $y$. The double pendulum with rigid segments, swinging in a plane, is also a system with two degrees of freedom. The position of the mass particle is described by two angles. A mass particle in space has three degrees of freedom. Usually its position is expressed by three rectangular coordinates $x$, $y$ and $z$. An example of a simple mechanical system with three degrees of freedom is a double pendulum where one segment is represented by an elastic spring and the other by a rigid rod. Also in this case the pendulum is swinging in a plane.

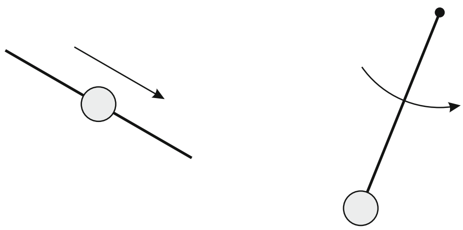

**Fig. 1.1** Two examples of systems with one degree of freedom: mass particle on a wire (left) and rigid pendulum in a plane (right)

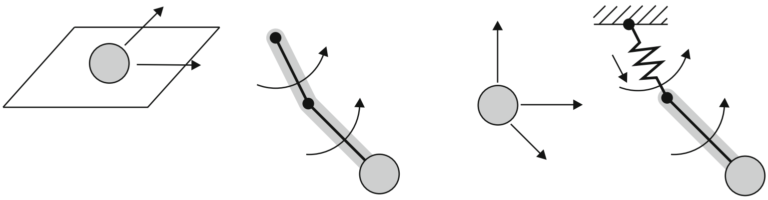

**Fig. 1.2** Examples with two (left) and three degrees of freedom (right)

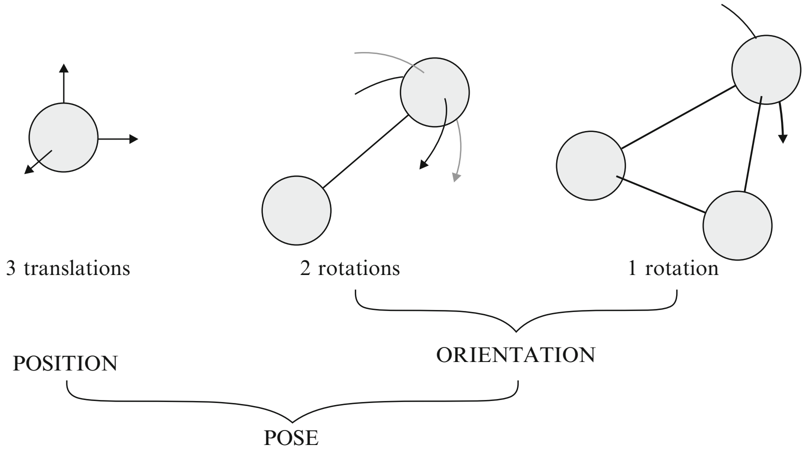


**Fig. 1.3** Degrees of freedom of a rigid body

In robotics we are not interested in mass particles but rather in rigid bodies, which are either robot segments or objects manipulated by the industrial robot. The simplest rigid body consists of three mass particles (Figure 1.3). We already know that a single mass particle has three degrees of freedom, described by three rectangular displacements along a line called translations (T). We add another mass particle to the first one in such a way that there is constant distance between them. The second particle is restricted to move on the surface of a sphere surrounding the first particle. Its position on the sphere can be described by two circles reminding us of meridians and latitudes on a globe. The displacement along a circular line is called rotation (R). The third mass particle is added in such a way that the distances with respect to the first two particles are kept constant. In this way the third particle may move along a circle, a kind of equator, around the axis determined by the first two particles. A rigid body therefore has six degrees of freedom: three translations and three rotations. The first three degrees of freedom describe the position of the body, while the other three degrees of freedom determine its orientation. The term pose is used to include both position and orientation.

## 1.2 Robot manipulator

The robot manipulator consists of a robot arm, wrist, and gripper (Figure 1.4). The task of the robot manipulator is to place an object grasped by the gripper into an arbitrary pose. In this way also the industrial robot needs to have six degrees of freedom. The segments of the robot arm are relatively long. The task of the robot arm is to provide the desired position of the robot end point. The segments of the robot wrist are rather short. The task of the robot wrist is to enable the required orientation of the object grasped by the robot gripper.

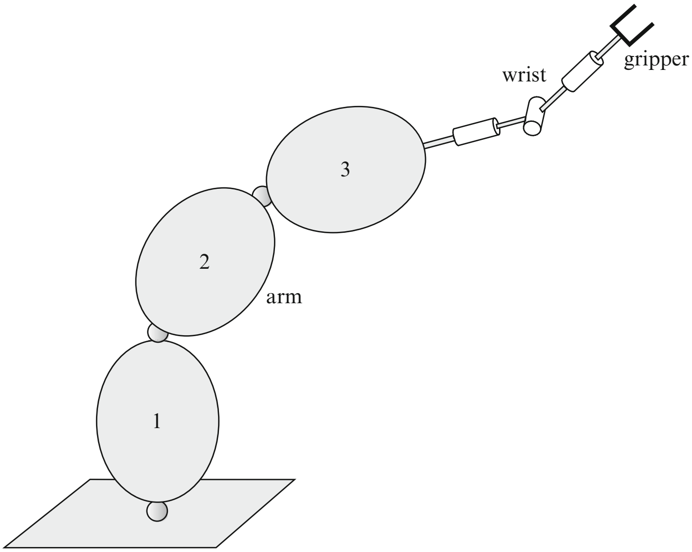


**Fig. 1.4** Robot manipulator

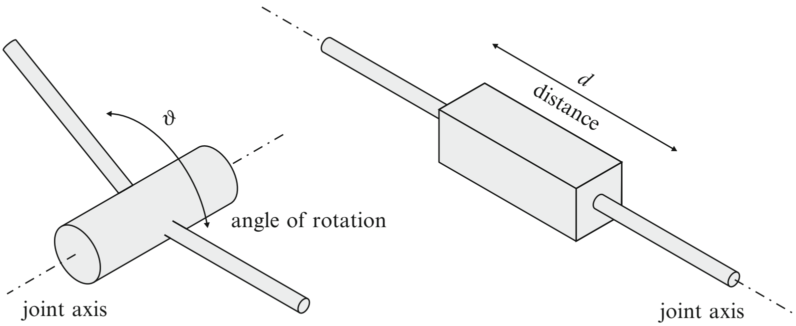


**Fig. 1.5** Rotational (left) and translational (right) robot joint

The robot arm is a serial chain of three rigid bodies called robot segments. Two neighbor segments of a robot manipulator are connected through a robot joint. The joint decreases the number of degrees of freedom which occur between two neighbor segments. The robot joints have only one degree of freedom and are either translational or rotational (Figure 1.5).

The rotational joint has the form of a hinge and limits the motion of two neighbor segments to rotation around the joint axis. The relative position of the segments is given by the angle of rotation around the joint axis. In robotics the joint angles are denoted by the Greek letter $\vartheta$. In simplified robotic models the rotational joint is represented by a cylinder. The translational joint restricts the movement of two neighboring segments to translation. The relative position between the two segments is measured as a distance. The symbol of the translational joint is a prism, while the distance is denoted by the letter $d$.

## 1.3 Robot arms

We have seen that robot joints are either translational or rotational. Robot arms have another important property. The axes of two neighboring joints are either parallel or perpendicular. As the robot arm has only three degrees of freedom, there exist a limited number of possible combinations resulting all together in 36 different structures of robot arms. Among them only 12 are functionally different. On the market we find 5 commercially available structures of robot arms: anthropomorphic, spherical, SCARA, cylindrical, and cartesian.

The anthropomorphic robot arm (Figure 1.6) has all three joints of the rotational type (RRR). Among the robot arms it resembles the human arm to the largest extent. The second joint axis is perpendicular to the first one, while the third joint axis is parallel to the second one. The workspace of the anthropomorphic robot arm, encompassing all the points that can be reached by the robot end point, has a spherical shape.

The spherical robot arm (Figure 1.7) has two rotational and one translational degree of freedom (RRT). The second joint axis is perpendicular to the first one and the third axis is perpendicular to the second one. The workspace of the robot arm has a spherical shape as in the case of the anthropomorphic robot arm.

The SCARA (Selective Compliant Articulated Robot for Assembly) robot arm appeared relatively late in the development of industrial robotics (Figure 1.8). It is predominantly aimed for industrial processes of assembly. Two joints are rotational and one is translational (RRT). The axes of all three joints are parallel. The workspace of SCARA robot arm is of cylindrical shape.

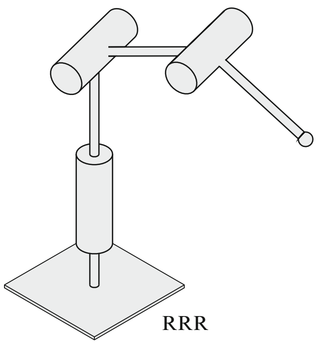


**Fig. 1.6** Anthropomorphic robot arm

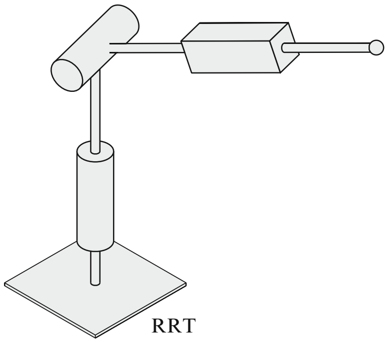


**Fig. 1.7** Spherical robot arm

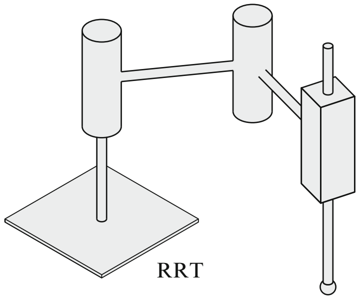


**Fig. 1.8** SCARA robot arm

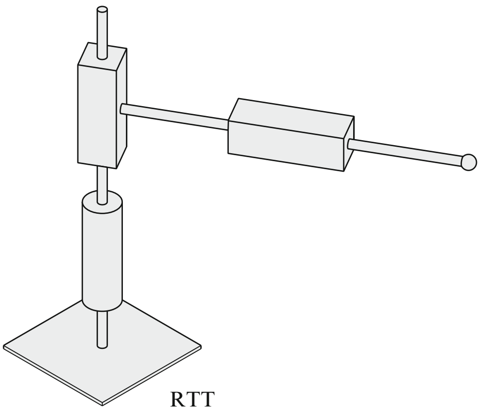


**Fig. 1.9** Cylindrical robot arm

The cylindrical shape of the workspace is even more evident with the cylindrical robot arm (Figure 1.9). This robot has one rotational and two translational degrees of freedom (RTT). The axis of the second joint is parallel to the first axis, while the third joint axis is perpendicular to the second one.

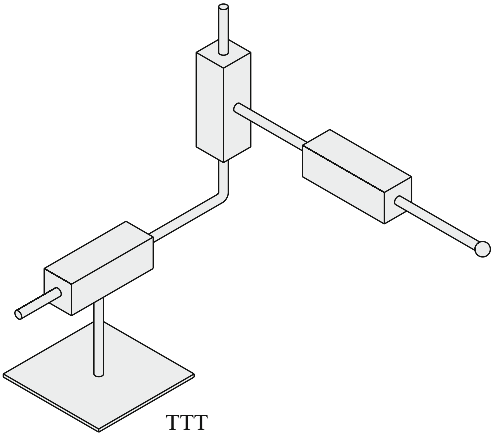


**Fig. 1.10** Cartesian robot arm

The cartesian robot arm (Figure 1.10) has all three joints of the translational type (TTT). The joint axes are perpendicular one to another. Cartesian robot arms are known for high accuracy, while the special structure of gantry robots is suitable for manipulation of heavy objects. The workspace of the cartesian robot arm is a prism.

## 1.4 Robot manipulators in industrial environment

Today we encounter the largest number of industrial robot manipulators in the car industry. They are predominantly used for welding. The ratio of human workers and robots in the car industry is 6:1. In many cases the industrial robots are used for tasks where the robot gripper moves objects from point to point. Such examples are found in the process of palletizing, this means putting in order component parts or products for the purposes of feeding a machine or packaging. Industrial robots are often used in aggressive or dangerous environments, such as spray painting. Robot manipulators are increasingly entering the area of industrial assembly of component parts into a functional system. Robot manipulators are not encountered only in industrial environments. They are of more and more interest in medicine. We find them in surgical applications (hip joint replacement) or in rehabilitation (training of paralyzed extremity after stroke). Special examples of robot manipulators are telemanipulators. These are robots which are controlled by a human operator. They are used in dangerous environments or distant places.

Different from robot manipulators, which represent the main interest of this textbook, are mobile robots. They are either wheeled or legged. The wheeled mobile robots are used on even terrain. As their pose can be described by only three degrees of freedom, they are simpler to control than robot manipulators. Their strength is in the use of robot vision and other sensors assessing distance or contact with objects in the environment. Today they are mainly used for cleaning and mowing purposes. The biologically inspired legged mobile robots usually have six legs and are used on uneven terrain. An efficient representative is the forestry robot which is also capable of cutting trees. A counterpart to industrial robotics is the so called service robotics where robots are used to help people (predominantly graying population) in daily activities. The most advanced examples are humanoid robots capable of biped locomotion. Robots in the air and in the sea are no surprise. They are used for observation of distant terrains or for ocean studies. Sophisticated robotic toys are appreciated by children. Finally, robots are replacing humans also at such a noble occupation as the arts. They are dancing, playing musical instruments, and even painting.