CHAPTER
ONE

INTRODUCTION

> One machine can do the work of a
> hundred ordinary men, but no machine
> can do the work of one extraordinary man.
> *Elbert Hubbard*

1.1 BACKGROUND

With a pressing need for increased productivity and the delivery of end products of uniform quality, industry is turning more and more toward computer-based automation. At the present time, most automated manufacturing tasks are carried out by special-purpose machines designed to perform predetermined functions in a manufacturing process. The inflexibility and generally high cost of these machines, often called *hard automation systems*, have led to a broad-based interest in the use of robots capable of performing a variety of manufacturing functions in a more flexible working environment and at lower production costs.

The word *robot* originated from the Czech word *robota*, meaning work. Webster's dictionary defines robot as "an automatic device that performs functions ordinarily ascribed to human beings." With this definition, washing machines may be considered robots. A definition used by the Robot Institute of America gives a more precise description of industrial robots: "A robot is a *reprogrammable multi-functional* manipulator designed to move materials, parts, tools, or specialized devices, through variable programmed motions for the performance of a variety of tasks." In short, a robot is a reprogrammable general-purpose manipulator with external sensors that can perform various assembly tasks. With this definition, a robot must possess *intelligence*, which is normally due to computer algorithms associated with its control and sensing systems.

An industrial robot is a general-purpose, computer-controlled manipulator consisting of several rigid links connected in series by revolute or prismatic joints. One end of the chain is attached to a supporting base, while the other end is free and equipped with a tool to manipulate objects or perform assembly tasks. The motion of the joints results in relative motion of the links. Mechanically, a robot is composed of an arm (or mainframe) and a wrist subassembly plus a tool. It is designed to reach a workpiece located within its work volume. The work volume is the sphere of influence of a robot whose arm can deliver the wrist subassembly unit to any point within the sphere. The arm subassembly generally can move with three degrees of freedom. The combination of the movements positions the wrist unit at the workpiece. The wrist subassembly unit usually consists of three rotary motions. The combination of these motions orients the tool according to the configuration of the object for ease in pickup. These last three motions are often called *pitch*, *yaw*, and *roll*. Hence, for a six-jointed robot, the arm subassembly is the positioning mechanism, while the wrist subassembly is the orientation mechanism. These concepts are illustrated by the Cincinnati Milacron T^3 robot and the Unimation PUMA robot arm shown in Fig. 1.1.

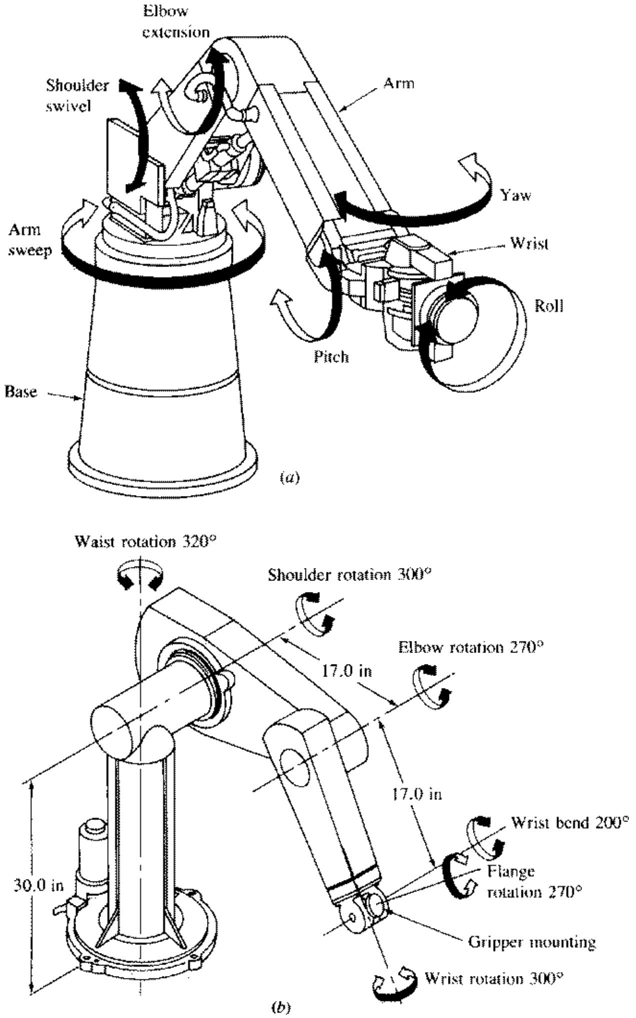
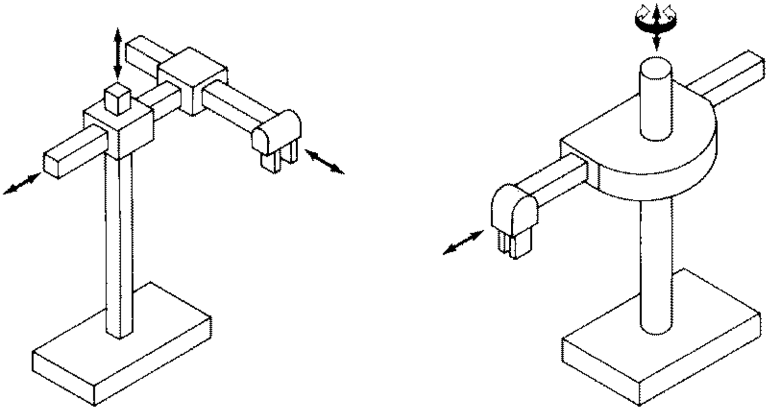


Figure 1.1 (*a*) Cincinnati Milacron T^3 robot arm. (*b*) PUMA 560 series robot arm.

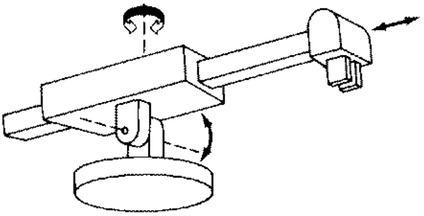
Many commercially available industrial robots are widely used in manufacturing and assembly tasks, such as material handling, spot/arc welding, parts assembly, paint spraying, loading and unloading numerically controlled machines, space and undersea exploration, prosthetic arm research, and in handling hazardous materials. These robots fall into one of the four basic motion-defining categories (Fig. 1.2):

Cartesian coordinates (three linear axes) (e.g., IBM's RS-1 robot and the Sigma robot from Olivetti)
Cylindrical coordinates (two linear and one rotary axes) (e.g., Versatran 600 robot from Prab)
Spherical coordinates (one linear and two rotary axes) (e.g., Unimate 2000B from Unimation Inc.)
Revolute or articulated coordinates (three rotary axes) (e.g., T^3 from Cincinnati Milacron and PUMA from Unimation Inc.)

Most of today's industrial robots, though controlled by mini- and microcomputers, are basically simple positional machines. They execute a given task by



Cartesian or *xyz* Cylindrical



Spherical Revolute

Figure 1.2 Various robot arm categories.

playing back prerecorded or preprogrammed sequences of motions that have been previously guided or taught by a user with a hand-held control-teach box. Moreover, these robots are equipped with little or no external sensors for obtaining the information vital to its working environment. As a result, robots are used mainly in relatively simple, repetitive tasks. More research effort is being directed toward improving the overall performance of the manipulator systems, and one way is through the study of the various important areas covered in this book.

1.2 HISTORICAL DEVELOPMENT

The word *robot* was introduced into the English language in 1921 by the playwright Karel Capek in his satirical drama, *R.U.R.* (Rossum's Universal Robots). In this work, robots are machines that resemble people, but work tirelessly. Initially, the robots were manufactured for profit to replace human workers but, toward the end, the robots turned against their creators, annihilating the entire human race. Capek's play is largely responsible for some of the views popularly held about robots to this day, including the perception of robots as humanlike machines endowed with intelligence and individual personalities. This image was reinforced by the 1926 German robot film *Metropolis,* by the walking robot Electro and his dog Sparko, displayed in 1939 at the New York World's Fair, and more recently by the robot C3PO featured in the 1977 film *Star Wars.* Modern industrial robots certainly appear primitive when compared with the expectations created by the communications media during the past six decades.

Early work leading to today's industrial robots can be traced to the period immediately following World War II. During the late 1940s research programs were started at the Oak Ridge and Argonne National Laboratories to develop remotely controlled mechanical manipulators for handling radioactive materials. These systems were of the "master-slave" type, designed to reproduce faithfully hand and arm motions made by a human operator. The master manipulator was guided by the user through a sequence of motions, while the slave manipulator duplicated the master unit as closely as possible. Later, force feedback was added by mechanically coupling the motion of the master and slave units so that the operator could feel the forces as they developed between the slave manipulator and its environment. In the mid-1950s the mechanical coupling was replaced by electric and hydraulic power in manipulators such as General Electric's Handyman and the Minotaur I built by General Mills.

The work on master-slave manipulators was quickly followed by more sophisticated systems capable of autonomous, repetitive operations. In the mid-1950s George C. Devol developed a device he called a "programmed articulated transfer device," a manipulator whose operation could be programmed (and thus changed) and which could follow a sequence of motion steps determined by the instructions in the program. Further development of this concept by Devol and Joseph F. Engelberger led to the first industrial robot, introduced by Unimation Inc. in 1959. The key to this device was the use of a computer in conjunction with a manipulator to produce a machine that could be "taught" to carry out a variety of tasks automatically. Unlike hard automation machines, these robots could be reprogrammed and retooled at relative low cost to perform other jobs as manufacturing requirements changed.

While programmed robots offered a novel and powerful manufacturing tool, it became evident in the 1960s that the flexibility of these machines could be enhanced significantly by the use of sensory feedback. Early in that decade, H. A. Ernst [1962] reported the development of a computer-controlled mechanical hand with tactile sensors. This device, called the MH-1, could "feel" blocks and use this information to control the hand so that it stacked the blocks without operator assistance. This work is one of the first examples of a robot capable of adaptive behavior in a reasonably unstructured environment. The manipulative system consisted of an ANL Model-8 manipulator with 6 degrees of freedom controlled by a TX-O computer through an interfacing device. This research program later evolved as part of project MAC, and a television camera was added to the manipulator to begin machine perception research. During the same period, Tomovic and Boni [1962] developed a prototype hand equipped with a pressure sensor which sensed the object and supplied an input feedback signal to a motor to initiate one of two grasp patterns. Once the hand was in contact with the object, information proportional to object size and weight was sent to a computer by these pressure-sensitive elements. In 1963, the American Machine and Foundry Company (AMF) introduced the VERSATRAN commercial robot. Starting in this same year, various arm designs for manipulators were developed, such as the Roehampton arm and the Edinburgh arm.

In the late 1960s, McCarthy [1968] and his colleagues at the Stanford Artificial Intelligence Laboratory reported development of a computer with hands, eyes, and ears (i.e., manipulators, TV cameras, and microphones). They demonstrated a system that recognized spoken messages, "saw" blocks scattered on a table, and manipulated them in accordance with instructions. During this period, Pieper [1968] studied the kinematic problem of a computer-controlled manipulator while Kahn and Roth [1971] analyzed the dynamics and control of a restricted arm using bang-bang (near minimum time) control.

Meanwhile, other countries (Japan in particular) began to see the potential of industrial robots. As early as 1968, the Japanese company Kawasaki Heavy Industries negotiated a license with Unimation for its robots. One of the more unusual developments in robots occurred in 1969, when an experimental walking truck was developed by the General Electric Company for the U.S. Army. In the same year, the Boston arm was developed, and in the following year the Stanford arm was developed, which was equipped with a camera and computer controller. Some of the most serious work in robotics began as these arms were used as robot manipulators. One experiment with the Stanford arm consisted of automatically stacking blocks according to various strategies. This was very sophisticated work for an automated robot at that time. In 1974, Cincinnati Milacron introduced its first computer-controlled industrial robot. Called "The Tomorrow Tool," or T^3, it could lift over 100 lb as well as track moving objects on an assembly line.

During the 1970s a great deal of research work focused on the use of external sensors to facilitate manipulative operations. At Stanford, Bolles and Paul [1973], using both visual and force feedback, demonstrated a computer-controlled Stanford arm connected to a PDP-10 computer for assembling automotive water pumps. At about the same time, Will and Grossman [1975] at IBM developed a computer-controlled manipulator with touch and force sensors to perform mechanical assembly of a 20-part typewriter. Inoue [1974] at the MIT Artificial Intelligence Laboratory worked on the artificial intelligence aspects of force feedback. A landfall navigation search technique was used to perform initial positioning in a precise assembly task. At the Draper Laboratory Nevins et al. [1974] investigated sensing techniques based on compliance. This work developed into the instrumentation of a passive compliance device called *remote center compliance* (RCC) which was attached to the mounting plate of the last joint of the manipulator for close parts-mating assembly. Bejczy [1974], at the Jet Propulsion Laboratory, implemented a computer-based torque-control technique on his extended Stanford arm for space exploration projects. Since then, various control methods have been proposed for servoing mechanical manipulators.

Today, we view robotics as a much broader field of work than we did just a few years ago, dealing with research and development in a number of interdisciplinary areas, including kinematics, dynamics, planning systems, control, sensing, programming languages, and machine intelligence. These topics, introduced briefly in the following sections, constitute the core of the material in this book.

1.3 ROBOT ARM KINEMATICS AND DYNAMICS

Robot arm kinematics deals with the analytical study of the geometry of motion of a robot arm with respect to a fixed reference coordinate system without regard to the forces/moments that cause the motion. Thus, kinematics deals with the analytical description of the spatial displacement of the robot as a function of time, in particular the relations between the joint-variable space and the position and orientation of the end-effector of a robot arm.

There are two fundamental problems in robot arm kinematics. The first problem is usually referred to as the *direct* (or *forward*) *kinematics* problem, while the second problem is the *inverse kinematics* (or *arm solution*) problem. Since the independent variables in a robot arm are the joint variables, and a task is usually stated in terms of the reference coordinate frame, the inverse kinematics problem is used more frequently. Denavit and Hartenberg [1955] proposed a systematic and generalized approach of utilizing matrix algebra to describe and represent the spatial geometry of the links of a robot arm with respect to a fixed reference frame. This method uses a 4×4 homogeneous transformation matrix to describe the spatial relationship between two adjacent rigid mechanical links and reduces the direct kinematics problem to finding an equivalent 4×4 homogeneous transformation matrix that relates the spatial displacement of the hand coordinate frame to the reference coordinate frame. These homogeneous transformation matrices are also useful in deriving the dynamic equations of motion of a robot arm. In general, the inverse kinematics problem can be solved by several techniques. The most commonly used methods are the matrix algebraic, iterative, or geometric approach. Detailed treatments of direct kinematics and inverse kinematics problems are given in Chap. 2.

Robot arm dynamics, on the other hand, deals with the mathematical formulations of the equations of robot arm motion. The dynamic equations of motion of a manipulator are a set of mathematical equations describing the dynamic behavior of the manipulator. Such equations of motion are useful for computer simulation of the robot arm motion, the design of suitable control equations for a robot arm, and the evaluation of the kinematic design and structure of a robot arm. The actual dynamic model of an arm can be obtained from known physical laws such as the laws of newtonian and lagrangian mechanics. This leads to the development of dynamic equations of motion for the various articulated joints of the manipulator in terms of specified geometric and inertial parameters of the links. Conventional approaches like the Lagrange-Euler and the Newton-Euler formulations can then be applied systematically to develop the actual robot arm motion equations. Detailed discussions of robot arm dynamics are presented in Chap. 3.

1.4 MANIPULATOR TRAJECTORY PLANNING AND MOTION CONTROL

With the knowledge of kinematics and dynamics of a serial link manipulator, one would like to servo the manipulator's joint actuators to accomplish a desired task by controlling the manipulator to follow a desired path. Before moving the robot arm, it is of interest to know whether there are any obstacles present in the path that the robot arm has to traverse (obstacle constraint) and whether the manipulator hand needs to traverse along a specified path (path constraint). The control problem of a manipulator can be conveniently divided into two coherent subproblems—the motion (or trajectory) planning subproblem and the motion control subproblem.

The space curve that the manipulator hand moves along from an initial location (position and orientation) to the final location is called the *path*. The trajectory planning (or trajectory planner) interpolates and/or approximates the desired path by a class of polynomial functions and generates a sequence of time-based "control set points" for the control of the manipulator from the initial location to the destination location. Chapter 4 discusses the various trajectory planning schemes for obstacle-free motion, as well as the formalism for describing desired manipulator motion in terms of sequences of points in space through which the manipulator must pass and the space curve that it traverses.

In general, the motion control problem consists of (1) obtaining dynamic models of the manipulator, and (2) using these models to determine control laws or strategies to achieve the desired system response and performance. Since the first part of the control problem is discussed extensively in Chap. 3, Chap. 5 concentrates on the second part of the control problem. From the control analysis point of view, the movement of a robot arm is usually performed in two distinct control phases. The first is the gross motion control in which the arm moves from an initial position/orientation to the vicinity of the desired target position/orientation along a planned trajectory. The second is the fine motion control in which the end-effector of the arm dynamically interacts with the object using sensory feedback information from the sensors to complete the task.

Current industrial approaches to robot arm control treat each joint of the robot arm as a simple joint servomechanism. The servomechanism approach models the varying dynamics of a manipulator inadequately because it neglects the motion and configuration of the whole arm mechanism. These changes in the parameters of the controlled system sometimes are significant enough to render conventional feedback control strategies ineffective. The result is reduced servo response speed and damping, limiting the precision and speed of the end-effector and making it appropriate only for limited-precision tasks. Manipulators controlled in this manner move at slow speeds with unnecessary vibrations. Any significant performance gain in this and other areas of robot arm control require the consideration of more efficient dynamic models, sophisticated control approaches, and the use of dedicated computer architectures and parallel processing techniques. Chapter 5 focuses on deriving gross motion control laws and strategies which utilize the dynamic models discussed in Chap. 3 to efficiently control a manipulator.

1.5 ROBOT SENSING

The use of external sensing mechanisms allows a robot to interact with its environment in a flexible manner. This is in contrast to preprogrammed operations in which a robot is "taught" to perform repetitive tasks via a set of programmed functions. Although the latter is by far the most predominant form of operation of present industrial robots, the use of sensing technology to endow machines with a greater degree of intelligence in dealing with their environment is indeed an active topic of research and development in the robotics field.

The function of robot sensors may be divided into two principal categories: *internal state* and *external state*. Internal state sensors deal with the detection of variables such as arm joint position, which are used for robot control. External state sensors, on the other hand, deal with the detection of variables such as range, proximity, and touch. External sensing, the topic of Chaps. 6 through 8, is used for robot guidance, as well as for object identification and handling. The focus of Chap. 6 is on range, proximity, touch, and force-torque sensing. Vision sensors and techniques are discussed in detail in Chaps. 7 and 8. Although proximity, touch, and force sensing play a significant role in the improvement of robot performance, vision is recognized as the most powerful of robot sensory capabilities. Robot vision may be defined as the process of extracting, characterizing, and interpreting information from images of a three-dimensional world. This process, also commonly referred to as *machine* or *computer vision*, may be subdivided into six principal areas: (1) sensing, (2) preprocessing, (3) segmentation, (4) description, (5) recognition, and (6) interpretation.

It is convenient to group these various areas of vision according to the sophistication involved in their implementation. We consider three levels of processing: low-, medium-, and high-level vision. While there are no clearcut boundaries between these subdivisions, they do provide a useful framework for categorizing the various processes that are inherent components of a machine vision system. In our discussion, we shall treat sensing and preprocessing as low-level vision functions. This will take us from the image formation process itself to compensations such as noise reduction, and finally to the extraction of primitive image features such as intensity discontinuities. We will associate with medium-level vision those processes that extract, characterize, and label components in an image resulting from low-level vision. In terms of our six subdivisions, we will treat segmentation, description, and recognition of individual objects as medium-level vision functions. High-level vision refers to processes that attempt to emulate cognition. The material in Chap. 7 deals with sensing, preprocessing, and with concepts and techniques required to implement low-level vision functions. Topics in higher-level vision are discussed in Chap. 8.

1.6 ROBOT PROGRAMMING LANGUAGES

One major obstacle in using manipulators as general-purpose assembly machines is the lack of suitable and efficient communication between the user and the robotic system so that the user can direct the manipulator to accomplish a given task. There are several ways to communicate with a robot, and the three major approaches to achieve it are discrete word recognition, teach and playback, and high-level programming languages.

Current state-of-the-art speech recognition is quite primitive and generally speaker-dependent. It can recognize a set of discrete words from a limited vocabulary and usually requires the user to pause between words. Although it is now possible to recognize words in real time due to faster computer components and efficient processing algorithms, the usefulness of discrete word recognition to describe a task is limited. Moreover, it requires a large memory space to store speech data, and it usually requires a training period to build up speech templates for recognition.

The method of teach and playback involves teaching the robot by leading it through the motions to be performed. This is usually accomplished in the following steps: (1) leading the robot in slow motion using manual control through the entire assembly task, with the joint angles of the robot at appropriate locations being recorded in order to replay the motion; (2) editing and playing back the taught motion; and (3) if the taught motion is correct, then the robot is run at an appropriate speed in a repetitive motion. This method is also known as guiding and is the most commonly used approach in present-day industrial robots.

A more general approach to solve the human-robot communication problem is the use of high-level programming. Robots are commonly used in areas such as arc welding, spot welding, and paint spraying. These tasks require no interaction between the robot and the environment and can be easily programmed by guiding. However, the use of robots to perform assembly tasks generally requires high-level programming techniques. This effort is warranted because the manipulator is usually controlled by a computer, and the most effective way for humans to communicate with computers is through a high-level programming language. Furthermore, using programs to describe assembly tasks allows a robot to perform different jobs by simply executing the appropriate program. This increases the flexibility and versatility of the robot. Chapter 9 discusses the use of high-level programming techniques for achieving effective communication with a robotic system.

1.7 ROBOT INTELLIGENCE

A basic problem in robotics is *planning* motions to solve some prespecified task, and then *controlling* the robot as it executes the commands necessary to achieve those actions. Here, planning means deciding on a course of action before acting. This action synthesis part of the robot problem can be solved by a problem-solving system that will achieve some stated goal, given some initial situation. A plan is, thus, a representation of a course of action for achieving a stated goal.

Research on robot problem solving has led to many ideas about problem-solving systems in artificial intelligence. In a typical formulation of a robot problem we have a robot that is equipped with sensors and a set of primitive actions that it can perform in some easy-to-understand world. Robot actions change one state, or configuration, of the world into another. In the "blocks world," for example, we imagine a world of several labeled blocks resting on a table or on each other and a robot consisting of a TV camera and a movable arm and hand that is able to pick up and move blocks. In some situations, the robot is a mobile vehicle with a TV camera that performs tasks such as pushing objects from place to place in an environment containing other objects.

In Chap. 10, we introduce several basic methods for problem solving and their applications to robot planning. The discussion emphasizes the problem-solving or planning aspect of a robot. A robot planner attempts to find a path from our initial robot world to a final robot world. The path consists of a sequence of operations that are considered primitive to the system. A solution to a problem could be the basis of a corresponding sequence of physical actions in the physical world. Robot planning, which provides the intelligence and problem-solving capability to a robot system, is still a very active area of research. For real-time robot applications, we still need powerful and efficient planning algorithms that will be executed by high-speed special-purpose computer systems.

1.8 REFERENCES

The general references cited below are representative of publications dealing with topics of interest in robotics and related fields. References given at the end of later chapters are keyed to specific topics discussed in the text. The bibliography at the end of the book is organized in alphabetical order by author, and it contains all the pertinent information for each reference cited in the text.

Some of the major journals and conference proceedings that routinely contain articles on various aspects of robotics include: *IEEE Journal of Robotics and Automation*; *International Journal of Robotics Research*; *Journal of Robotic Systems*; *Robotica*; *IEEE Transactions on Systems, Man and Cybernetics*; *Artificial Intelligence*; *IEEE Transactions on Pattern Analysis and Machine Intelligence*; *Computer Graphics, Vision, and Image Processing*; *Proceedings of the International Symposium on Industrial Robots*; *Proceedings of the International Joint Conference on Artificial Intelligence*; *Proceedings of IEEE International Conference on Robotics and Automation; IEEE Transactions on Automatic Control*; *Mechanism and Machine Theory*; *Proceedings of the Society of Photo-Optical and Instrumentation Engineers*; *ASME Journal of Mechanical Design*; *ASME Journal of Applied Mechanics*; *ASME Journal of Dynamic Systems, Measurement and Control*; and *ASME Journal of Mechanisms, Transmissions, and Automation in Design.*

Complementary reading for the material in this book may be found in the books by Dodd and Rossol [1979], Engelberger [1980], Paul [1981], Dorf [1983], Snyder [1985], Lee, Gonzalez, and Fu [1986], Tou [1985], and Craig [1986].