CHAPTER

# TWO

# FUNDAMENTALS OF ROBOT TECHNOLOGY, PROGRAMMING, AND APPLICATIONS

Robotics is an applied engineering science that has been referred to as a combination of machine tool technology and computer science. It includes such seemingly diverse fields as machine design, control theory, microelectronics, computer programming, artificial intelligence, human factors, and production theory. Research and development are proceeding in all of these areas to improve the way robots work and think. It is likely that the research efforts will result in future robots that will make today's machines seem quite primitive. Advancements in technology will enlarge the scope of the industrial applications of robots.

Our problem in this chapter is to define the basic technology, programming, and applications of current day industrial robotics. The technical fields listed above are highly interdependent in the manner in which they are used in robotics. In order to appreciate robotics technology and programming, one must be aware of the way robots are applied in industry. In order to understand the use of sensors in robotics, one must be familiar with the way robots are programmed. To comprehend the use of an end effector, one must know that a fundamental function of a robot is to handle parts and tools. In this chapter, therefore, we provide that survey of the entire field of robotics to establish the necessary framework for the reader to relate the various topics in the chapters that follow.

To describe the technology of a robot, we must define a variety of technical features about the way the robot is constructed and the way it operates. Robots work with sensors, tools, and grippers, and these terms must be defined. The programming of robots is accomplished in several ways.

Although we discuss this subject in considerable detail later in the book, a concise description is presented in this chapter. Finally, robots are used to perform work in industry, and we provide a survey of these industrial applications. To survey these various topics, this chapter is organized into the following sections:

Robot anatomy
Work volume
Drive systems
Control systems and dynamic performance
Precision of movement
End effectors
Sensors
Robot programming and work cell control
Applications

For many of these topics, it is appropriate to delve much deeper into the subject, well beyond the basic introduction intended by this chapter. We discuss these topics in greater depth in subsequent chapters of the book.

## 2-1 ROBOT ANATOMY

Robot anatomy is concerned with the physical construction of the body, arm, and wrist of the machine. Most robots used in plants today are mounted on a base which is fastened to the floor. The body is attached to the base and the arm assembly is attached to the body. At the end of the arm is the wrist. The wrist consists of a number of components that allow it to be oriented in a variety of positions. Relative movements between the various components of the body, arm, and wrist are provided by a series of joints. These joint movements usually involve either rotating or sliding motions, which we will describe later in this section. The body, arm, and wrist assembly is sometimes called the manipulator.

Attached to the robot's wrist is a hand. The technical name for the hand is "end effector" and we will discuss end effectors later in this chapter and in much greater detail in a later chapter. The end effector is not considered as part of the robot's anatomy. The arm and body joints of the manipulator are used to position the end effector, and the wrist joints of the manipulator are used to orient the end effector.

### Four Common Robot Configurations

Industrial robots are available in a wide variety of sizes, shapes, and physical configurations. The vast majority of today's commercially available robots possess one of four basic configurations:

1. Polar configuration
2. Cylindrical configuration
3. Cartesian coordinate configuration
4. Jointed-arm configuration

The four basic configurations are illustrated in the schematic diagrams of Fig. 2-1.

The polar configuration is pictured in part (*a*) of Fig. 2-1. It uses a telescoping arm that can be raised or lowered about a horizontal pivot. The pivot is mounted on a rotating base. These various joints provide the robot

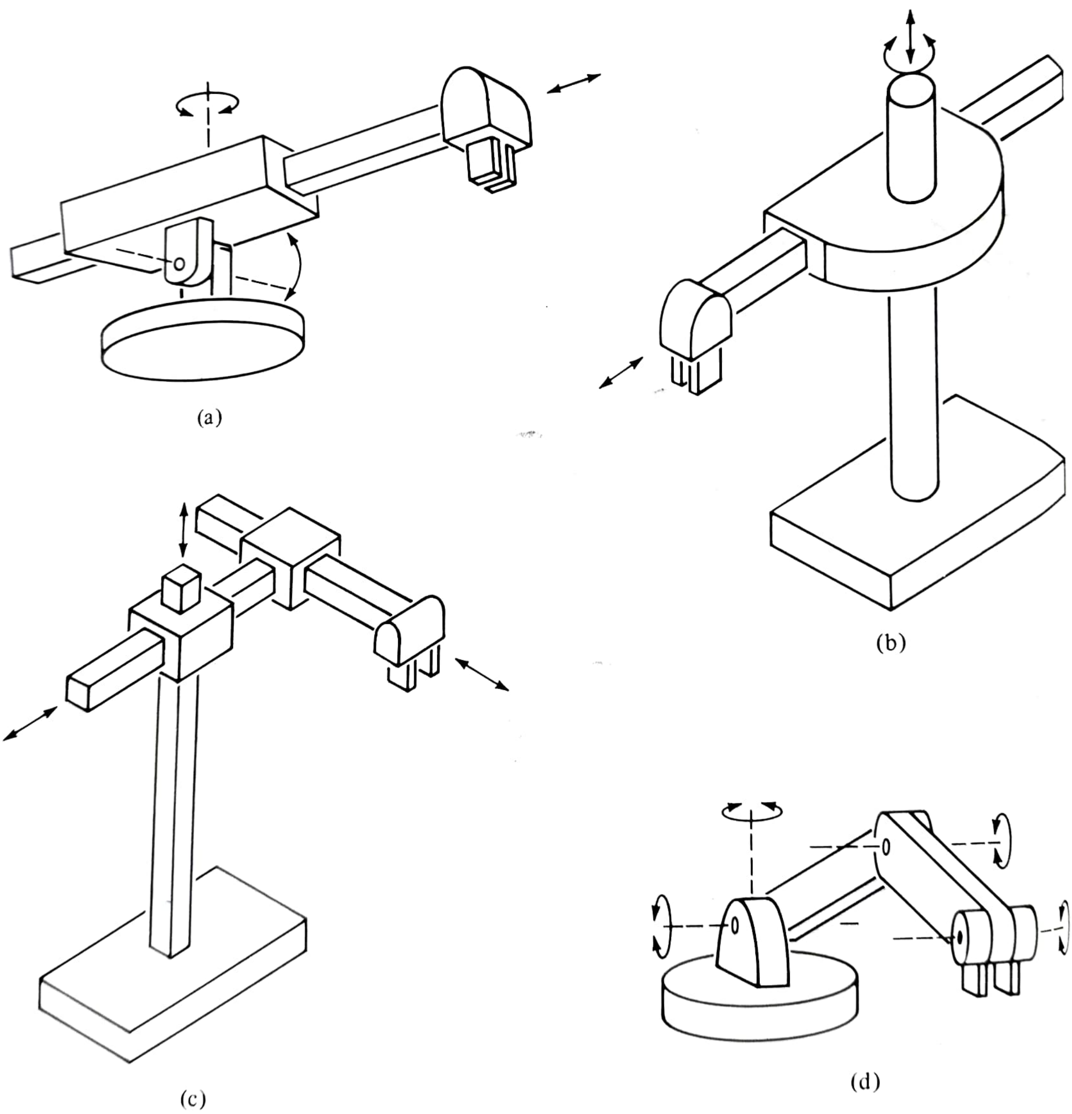

**Figure 2-1** The four basic robot anatomies: (a) polar, (b) cylindrical, (c) cartesian, and (d) jointed-arm. (Reprinted from Reference [7].)

with the capability to move its arm within a spherical space, and hence the name "spherical coordinate" robot is sometimes applied to this type. A number of commercial robots possess the polar configuration. These include the familiar Unimate 2000 series, pictured in Fig. 2-2. Another robot which is much smaller than the Unimate is the MAKER 110, made by United States Robots, and illustrated in Fig. 2-3.

The cylindrical configuration, as shown in Fig. 2-1(*b*), uses a vertical column and a slide that can be moved up or down along the column. The robot arm is attached to the slide so that it can be moved radially with respect to the column. By rotating the column, the robot is capable of achieving a work space that approximates a cylinder. An example of the cylindrical configuration is pictured in Fig. 2-4.

The cartesian coordinate robot, illustrated in part (*c*) of Fig. 2-1, uses three perpendicular slides to construct the *x*, *y*, and *z* axes. Other names are sometimes applied to this configuration, including *xyz* robot and rectilinear robot. By moving the three slides relative to one another, the robot is capable

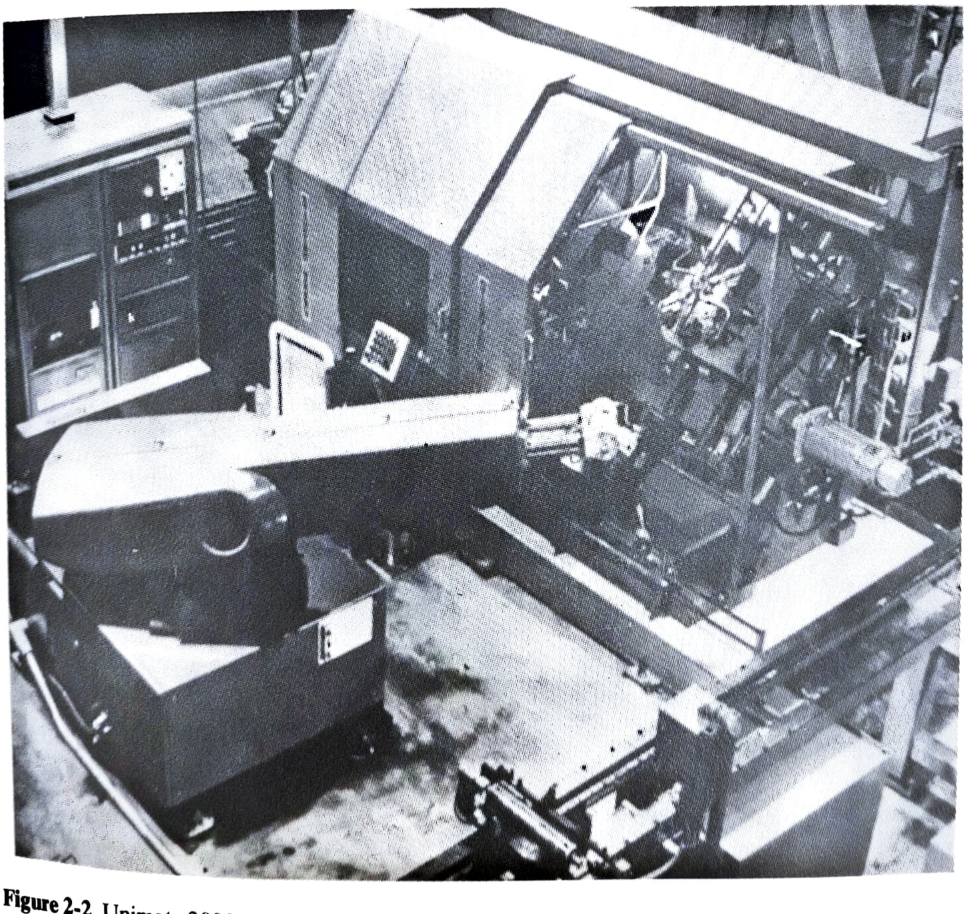

**Figure 2-2** Unimate 2000—polar configuration. Here, the Unimate performs a machine loading and unloading operation. The 2000 series robots have provided many years of service. (Photo courtesy of Unimation, Inc.)

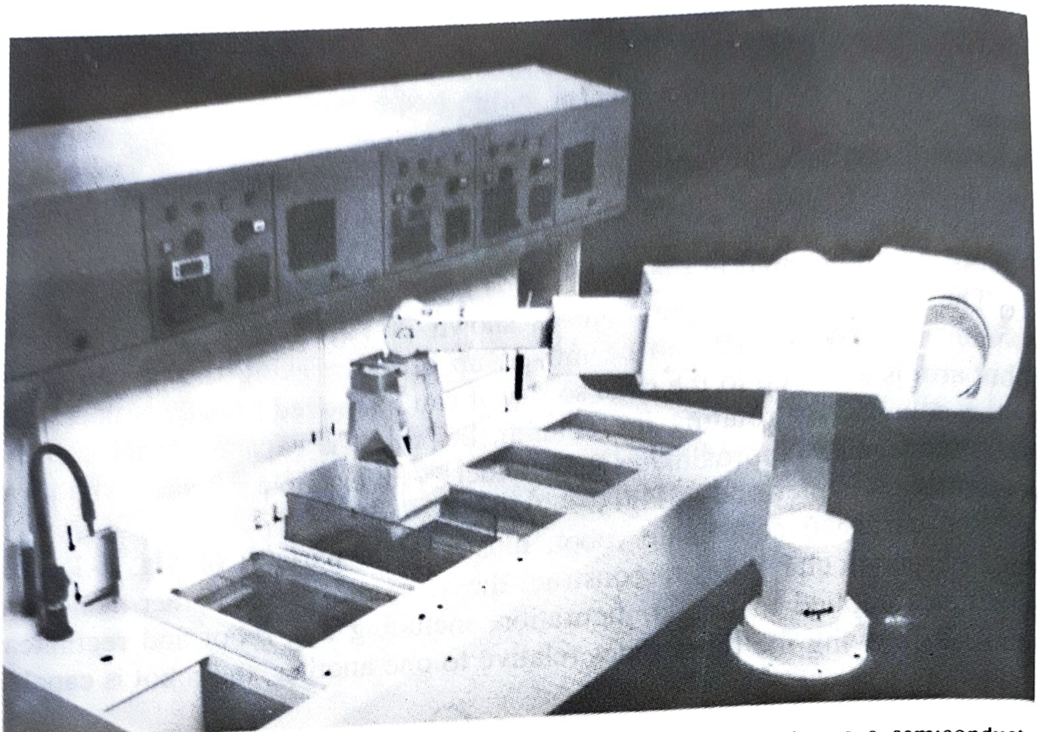

**Figure 2-3** The MAKER 110—polar configuration. The MAKER performs a semiconductor wafer-etching application in the electronics industry. (Photo courtesy of United States Robots.)

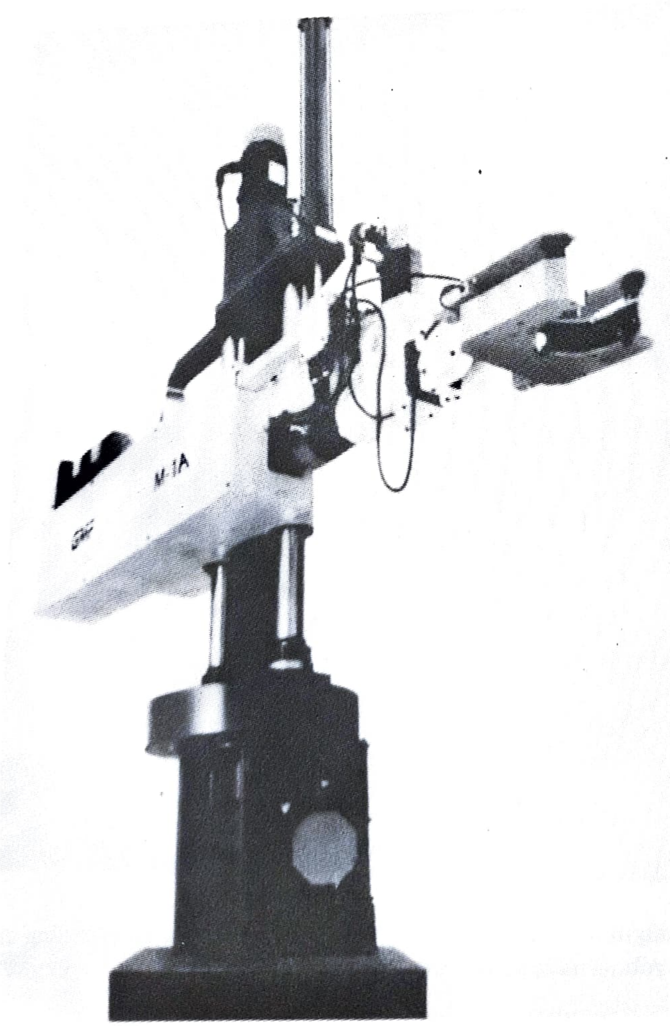


**Figure 2-4** GMF Model M-1A—cylindrical configuration. (Photo courtesy of GMF Robotics.)

of operating within a rectangular work envelope. An example of this configuration is the IBM RS-1 robot (currently called the Model 7565), pictured in Fig. 2-5. The RS-1, because of its appearance and construction, is occasionally referred to as a "box" configuration. "Gantry" robot is another name used for cartesian robots that are generally large and possess the appearance of a gantry-type crane. An example is shown in Fig. 2-6.

The jointed-arm robot is pictured in Fig. 2-1(*d*). Its configuration is similar to that of the human arm. It consists of two straight components, corresponding to the human forearm and upper arm, mounted on a vertical pedestal. These components are connected by two rotary joints corresponding to the shoulder and elbow. A wrist is attached to the end of the forearm, thus providing several additional joints. Several commercially available robots possess the jointed-arm configuration, including the Cincinnati Milacron T3 (Model 776) robot, illustrated in Fig. 2-7. A special version of the jointed arm robot is the SCARA, whose shoulder and elbow joints rotate about vertical axes. SCARA stands for Selective Compliance Assembly Robot Arm, and this configuration provides substantial rigidity for the robot in the vertical direction, but compliance in the horizontal plane. This makes it ideal for many assembly tasks. A SCARA robot is pictured in Fig. 2-8.

There are relative advantages and disadvantages to the four basic robot anatomies simply because of their geometries. In terms of repeatability of

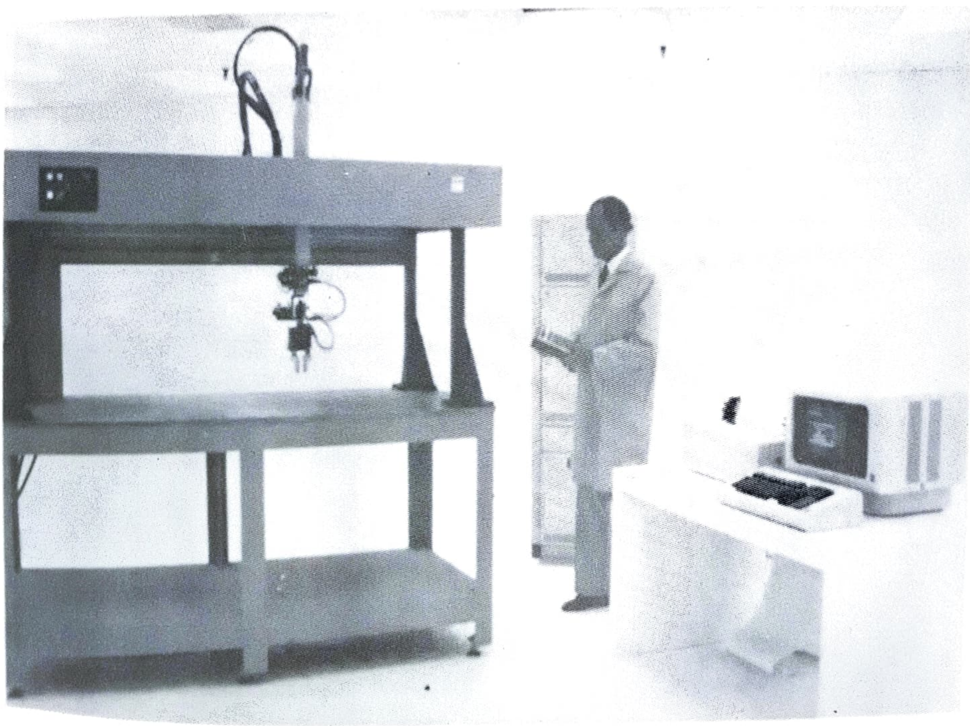

**Figure 2-5** The RS-1 (Model 7565)—cartesian coordinate robot. (Photo courtesy of IBM Corporation.)

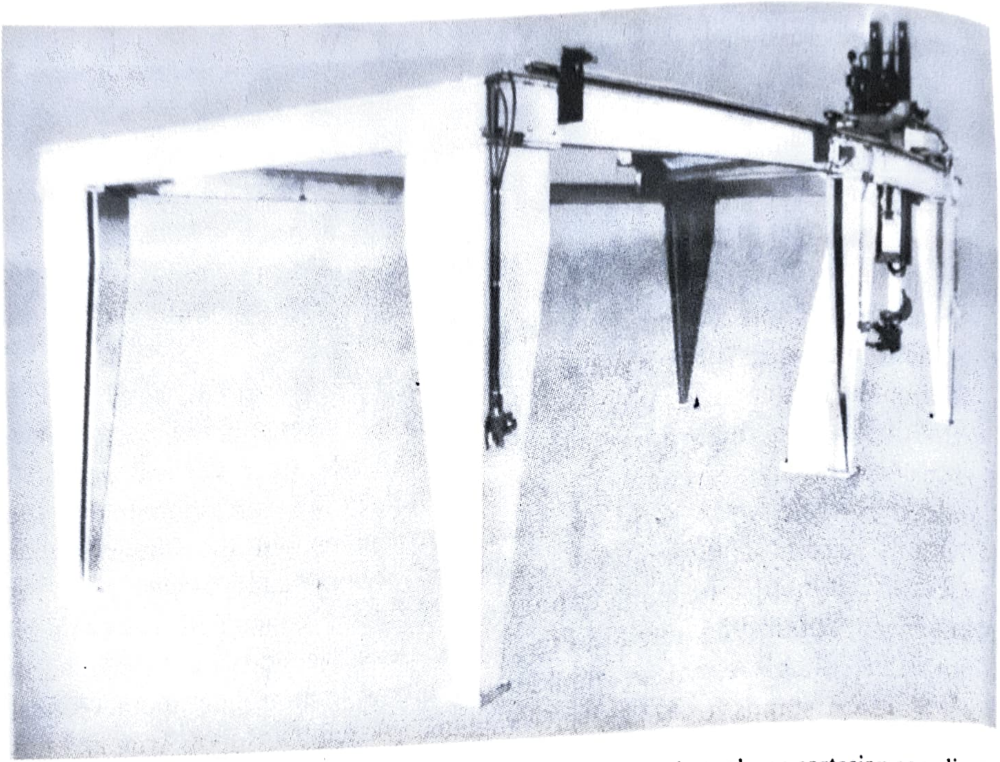

**Figure 2-6** Cincinnati Milacron T3-800 series robot—gantry type robot, a large cartesian coordinate configuration. (Photo courtesy of Cincinnati Milacron.)

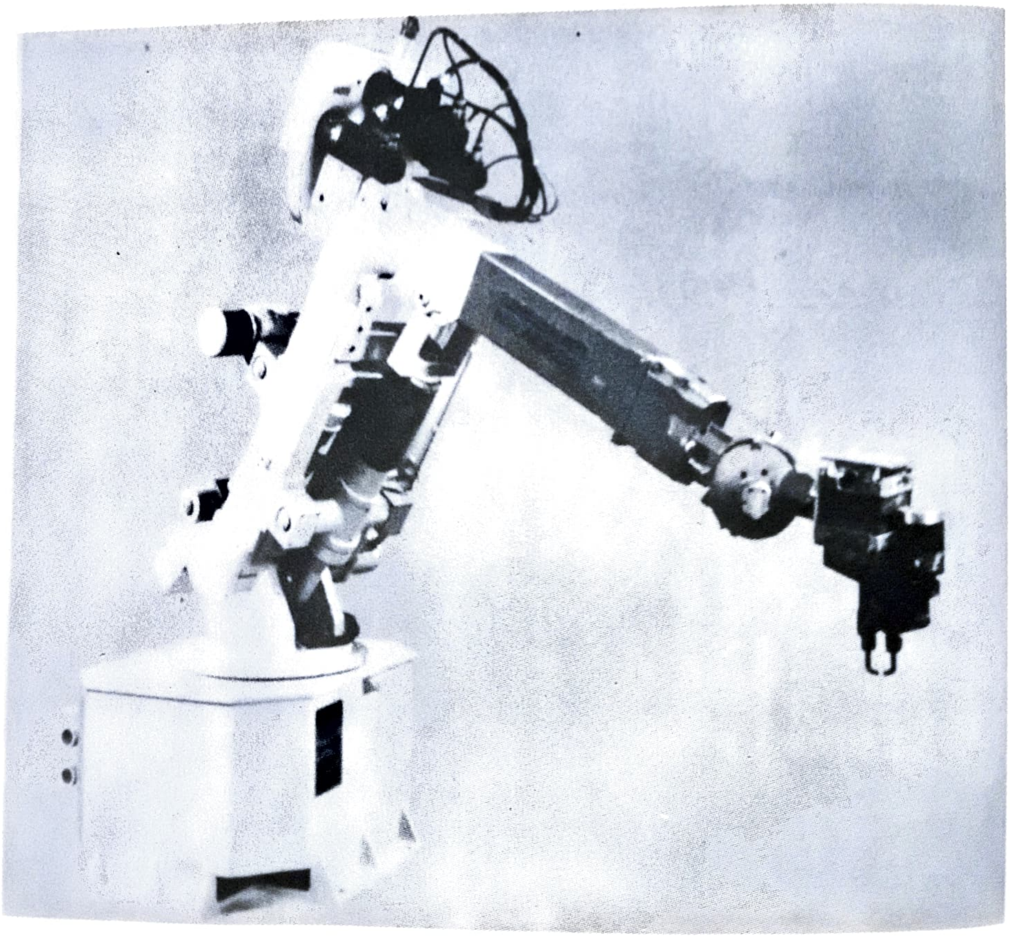

**Figure 2-7** The T3-776 robot jointed-arm configuration. (Photo courtesy of Cincinnati Milacron.)

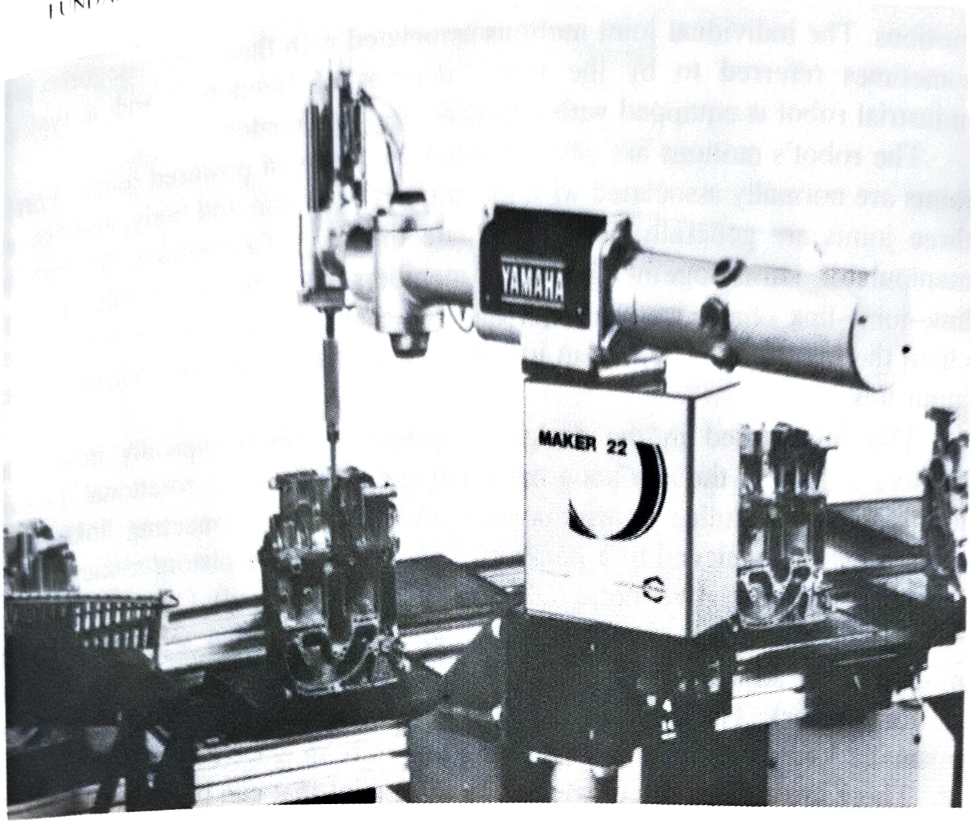


**Figure 2-8** SCARA (Selective Compliance Assembly Robotic Arm) robot. (Photo courtesy of United States Robots.)

motion (the capability to move to a taught point in space with minimum error), the box-frame cartesian robot probably possesses the advantage because of its inherently rigid structure. (We will define repeatability and other related terms in Sec. 2-5.) In terms of reach (the ability of the robot to extend its arm significantly beyond its base), the polar and jointed arm configurations have the advantage. The lift capacity of the robot is important in many applications. The cylindrical configuration and the gantry *xyz* robot can be designed for high-rigidity and load-carrying capacity. For machine-loading applications, the ability of the robot to reach into a small opening without interference with the sides of the opening is important. The polar configuration and the cylindrical configuration possess a natural geometric advantage in terms of this capability.

## Robot Motions

Industrial robots are designed to perform productive work. The work is accomplished by enabling the robot to move its body, arm, and wrist through a series of motions and positions. Attached to the wrist is the end effector which is used by the robot to perform a specific work task. The robot's movements can be divided into two general categories: arm and body motions, and wrist motions. The individual joint motions associated with these two categories are sometimes referred to by the term "degrees of freedom," and a typical industrial robot is equipped with 4 to 6 degrees of freedom.

The robot's motions are accomplished by means of powered joints. Three joints are normally associated with the action of the arm and body, and two or three joints are generally used to actuate the wrist. Connecting the various manipulator joints together are rigid members that are called links. In any link–joint–link chain, we shall call the link that is closest to the base in the chain the input link. The output link is the one that moves with respect to the input link.

The joints used in the design of industrial robots typically involve a relative motion of the adjoining links that is either linear or rotational. Linear joints involve a sliding or translational motion of the connecting links. This motion can be achieved in a number of ways (e.g., by a piston, a telescoping mechanism, and relative motion along a linear track or rail). Our concern here is not with the mechanical details of the joint, but rather with the relative motion of the adjacent links. We shall refer to the linear joint as a type *L* joint (*L* for *L*inear). The table of Fig. 2-9 illustrates the linear joint. The term prismatic joint is sometimes used in the literature in place of linear joint.

There are at least three types of rotating joint that can be distinguished in robot manipulators. The three types are illustrated in Fig. 2-9. We shall refer to the first as a type *R* joint (*R* for *R*otational). In the type *R* joint the axis of rotation is perpendicular to the axes of the two connecting links. The second type of rotating joint involves a twisting motion between the input and output links. The axis of rotation of the twisting joint is parallel to the axes of both links. We shall call this a type *T* joint (*T* for *T*wisting). The third type of rotating joint is a revolving joint in which the input link is parallel to the axis of rotation and the output link is perpendicular to the axis of rotation. In essence, the output link revolves about the input link, as if it were in orbit. This joint will be designated as a type *V* joint (*V* for re*V*olving).

The arm and body joints are designed to enable the robot to move its end effector to a desired position within the limits of the robot's size and joint movements. For robots of polar, cylindrical, or jointed-arm configuration, the 3 degrees of freedom associated with the arm and body motions are:

1. Vertical traverse—This is the capability to move the wrist up or down to provide the desired vertical attitude.
2. Radial traverse—This involves the extension or retraction (in or out movement) of the arm from the vertical center of the robot.
3. Rotational traverse—This is the rotation of the arm about the vertical axis.

The degrees of freedom associated with the arm and body of the robot are shown in Fig. 2-10 for a polar configuration robot. Similar degrees of freedom are associated with the cylindrical configuration and jointed-arm robot. For a cartesian coordinate robot, the three degrees of freedom are vertical move-

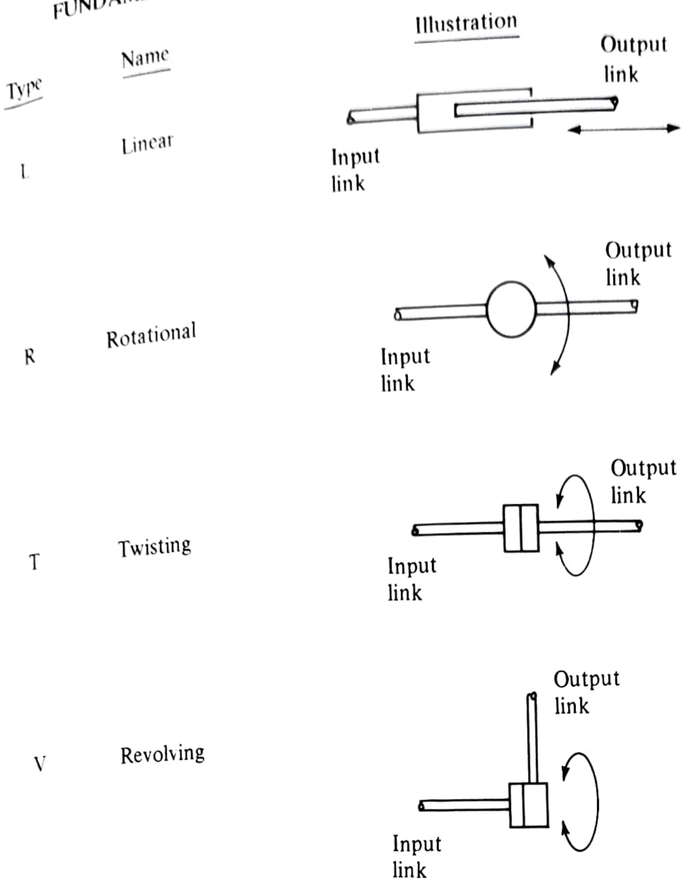


**Figure 2-9** Several types of joints used in robots: (a) rotational joint with rotation along an axis perpendicular to arm member axes, (b) rotational joint with twisting action, (c) linear motion joint, usually achieved by a sliding action.

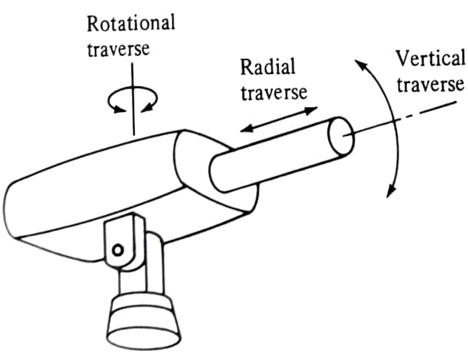


**Figure 2-10** Three degrees of freedom associated with arm and body of a polar coordinate robot.

ment ($z$-axis motion), in-and-out movement ($y$-axis motion), and right-or-left movement ($x$-axis motion). These are achieved by corresponding movements of the three orthogonal slides of the robot arm.

The wrist movement is designed to enable the robot to orient the end effector properly with respect to the task to be performed. For example, the hand must be oriented at the appropriate angle with respect to the workpiece

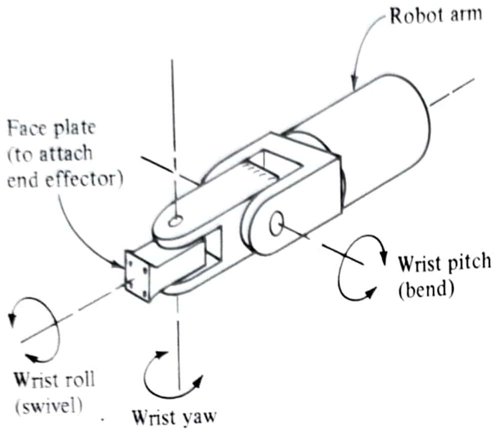


**Figure 2-11** Three degrees of freedom associated with the robot wrist.

in order to grasp it. To solve this orientation problem, the wrist is normally provided with up to 3 degrees of freedom (the following is a typical configuration):

1. Wrist roll—Also called wrist swivel, this involves rotation of the wrist mechanism about the arm axis.
2. Wrist pitch—Given that the wrist roll is in its center position, the pitch would involve the up or down rotation of the wrist. Wrist pitch is also sometimes called wrist bend.
3. Wrist yaw—Again, given that the wrist swivel is in the center position of its range, wrist yaw would involve the right or left rotation of the wrist.

These degrees of freedom for the wrist are illustrated in Fig. 2-11. The reason for specifying that the wrist roll be in its center position in the definitions of pitch and yaw is because rotation of the wrist about the arm axis will alter the orientation of the pitch and yaw movements.

## Joint Notation Scheme

The physical configuration of the robot manipulator can be described by means of a joint notation scheme, using the joint types defined earlier in this section ($L$, $R$, $T$, and $V$). Considering the arm and body joints first, the letters can be used to designate the particular robot configuration starting with the joint closest to the base and proceeding to the joint that connects to the wrist. Accordingly, a jointed-arm robot (excluding the wrist assembly) would have three rotational joints and would be designated as either TRR or VVR. Typical notations for the four basic configurations are summarized in Table 2-1.

The joint notation scheme permits the designation of more or less than the three joints typical of the basic configurations indicated in the table. It can also be used to explore other possibilities for configuring robots, beyond the four basic types.

**Table 2-1 Notation scheme for designating robot configurations**

| Robot configuration (arm and body) | Symbol |
|---|---|
| Polar configuration | *TRL* |
| Cylindrical configuration | *TLL*, *LTL*, *LVL* |
| Cartesian coordinate robot | *LLL* |
| Jointed arm configuration | *TRR*, *VVR* |
| **Robot configuration (wrist)** | **Symbol** |
| Two-axis wrist (typical) | :*RT* |
| Three-axis wrist (typical) | :*TRT* |

The notation system can be expanded to include wrist motions by designating the two or three (or more) types of wrist joint. The notation starts with the joint closest to the arm interface, and proceeds to the mounting plate for the end effector. Wrist joints are predominantly rotating joints of type *R* and *T*. Hence, a typical wrist mechanism with three rotational joints would be indicated by *TRR* (Fig. 2-11). This notation is simply added to the notation for the arm and body configuration. For example, a polar coordinate robot with a three-axis wrist might be designated as *TRL*:*TRT*.

The scheme can also provide for the possibility of robots that move on a track in the floor or along an overhead rail system in the factory. As an illustration, a *TRL*:*TRT* robot fastened to a platform on wheels that can be driven along a track between several machine tools would be designated by the following notation: *L*-*TRL*:*TRT*. In this case, even though the wheels of the platform rotate, the motion of the robot is linear.

## 2-2 WORK VOLUME

Work volume is the term that refers to the space within which the robot can manipulate its wrist end. The convention of using the wrist end to define the robot's work volume is adopted to avoid the complication of different sizes of end effectors that might be attached to the robot's wrist. The end effector is an addition to the basic robot and should not be counted as part of the robot's working space. A long end effector mounted on the wrist would add significantly to the extension of the robot compared to a smaller end effector. Also, the end effector attached to the wrist might not be capable of reaching certain points within the robot's normal work volume because of the particular combination of joint limits of the arm.

The work volume is determined by the following physical characteristics

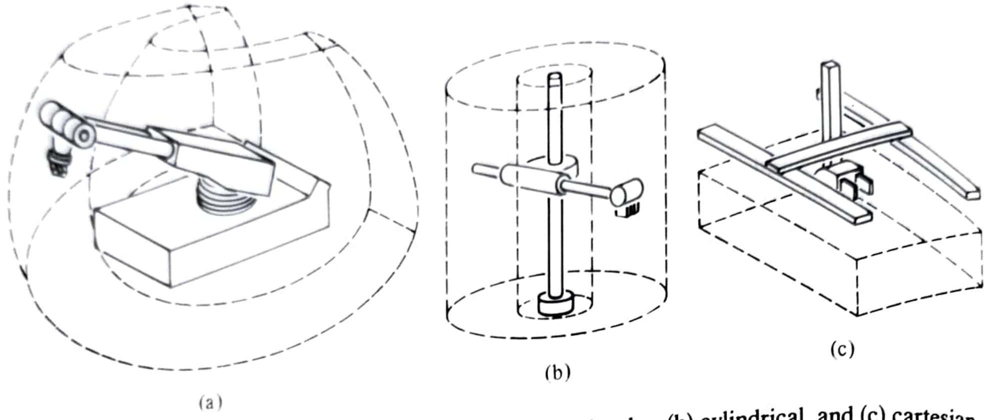


**Figure 2-12** Work volumes for various robot anatomies: (a) polar, (b) cylindrical, and (c) cartesian. (Reprinted from Reference [7].)

of the robot:

The robot's physical configuration
The sizes of the body, arm, and wrist components
The limits of the robot's joint movements

The influence of the physical configuration on the shape of the work volume is illustrated in Fig. 2-12. A polar coordinate robot has a work volume that is a partial sphere, a cylindrical coordinate robot has a cylindrical work envelope, a cartesian coordinate robot has a rectangularly shaped work space, and a jointed-arm robot approximates a work volume that is spherical. The size of each work volume shape is influenced by the dimensions of the arm components and by the limits of its joint movements. Using the cylindrical configuration as an example, limits on the rotation of the column about the base would determine what portion of a complete cylinder the robot could reach with its wrist end.

## 2-3 ROBOT DRIVE SYSTEMS

The robot's capacity to move its body, arm, and wrist is provided by the drive system used to power the robot. The drive system determines the speed of the arm movements, the strength of the robot, and its dynamic performance. To some extent, the drive system determines the kinds of applications that the robot can accomplish. In this and the following sections, we will discuss some of these technical features.

## Types of Drive Systems

Commercially available industrial robots are powered by one of three types of drive systems. These three systems are:

1. Hydraulic drive
2. Electric drive
3. Pneumatic drive

Hydraulic drive and electric drive are the two main types of drives used on more sophisticated robots.

Hydraulic drive is generally associated with larger robots, such as the Unimate 2000 series (Fig. 2-2). The usual advantages of the hydraulic drive system are that it provides the robot with greater speed and strength. The disadvantages of the hydraulic drive system are that it typically adds to the floor space required by the robot, and that a hydraulic system is inclined to leak oil which is a nuisance. Hydraulic drive systems can be designed to actuate either rotational joints or linear joints. Rotary vane actuators can be utilized to provide rotary motion, and hydraulic pistons can be used to accomplish linear motion.

Electric drive systems do not generally provide as much speed or power as hydraulic systems. However, the accuracy and repeatability of electric drive robots are usually better. Consequently, electric robots tend to be smaller, requiring less floor space, and their applications tend toward more precise work such as assembly. The MAKER 110 (Fig. 2-3) is an example of an electric drive robot that is consistent with these tendencies. Electric drive robots are actuated by dc stepping motors or dc servomotors. These motors are ideally suited to the actuation of rotational joints through appropriate drive train and gear systems. Electric motors can also be used to actuate linear joints (e.g., telescoping arms) by means of pulley systems or other translational mechanisms.

The economics of the two types of drive systems are also a factor in the decision to utilize hydraulic drive on large robots and electric drive on smaller robots. It turns out that the cost of an electric motor is much more proportional to its size, whereas the cost of a hydraulic drive system is somewhat less dependent on its size. These relationships are displayed conceptually in Fig. 2-13. As the illustration suggests, there is a hypothetical break-even point, below which it is advantageous to use electric drive and above which it is appropriate to use hydraulic drive. Having explained these factors, it should be noted that there is a trend in the design of industrial robots toward all electric drives, and away from hydraulic robots because of the disadvantages discussed above.

Pneumatic drive is generally reserved for smaller robots that possess fewer degrees of freedom (two- to four-joint motions). These robots are often limited to simple "pick-and-place" operations with fast cycles. Pneumatic power can

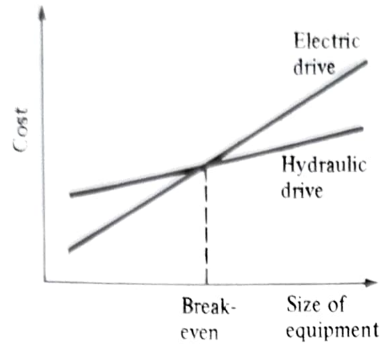


**Figure 2-13** Cost vs. size for electric drive and hydraulic drive.

be readily adapted to the actuation of piston devices to provide translational movement of sliding joints. It can also be used to operate rotary actuators for rotational joints.

## Speed of Motion

The speed capabilities of current industrial robots range up to a maximum of about 1.7 m/s (about 5 ft/sec). This speed would be measured at the wrist. Accordingly, the highest speeds can be obtained by large robots with the arm extended to its maximum distance from the vertical axis of the robot. As mentioned previously, hydraulic robots tend to be faster than electric drive robots.

The speed, of course, determines how quickly the robot can accomplish a given work cycle. It is generally desirable in production to minimize the cycle time of a given task. Nearly all robots have some means by which adjustments in the speed can be made. Determination of the most desirable speed, in addition to merely attempting to minimize the production cycle time, would also depend on other factors, such as:

The accuracy with which the wrist (end effector) must be positioned
The weight of the object being manipulated
The distances to be moved.

There is generally an inverse relationship between the accuracy and the speed of robot motions. As the required accuracy is increased, the robot needs more time to reduce the location errors in its various joints to achieve the desired final position. The weight of the object moved also influences the operational speed. Heavier objects mean greater inertia and momentum, and the robot must be operated more slowly to safely deal with these factors. The influence of the distance to be moved by the robot manipulator is illustrated in Fig. 2-14. Because of acceleration and deceleration problems, a robot is capable of traveling one long distance in less time than a sequence of short distances whose sum is equal to the long distance. The short distances may not permit the robot to ever reach the programmed operating speed.

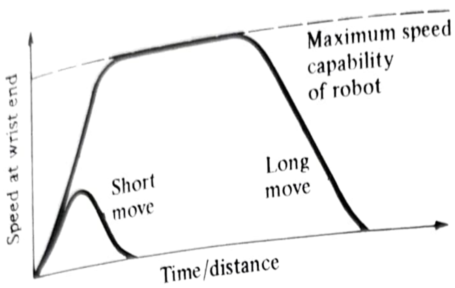


**Figure 2-14** Influence of distance versus speed.

### Load-Carrying Capacity

The size, configuration, construction, and drive system determine the load-carrying capacity of the robot. This load capacity should be specified under the condition that the robot's arm is in its weakest position. In the case of a polar, cylindrical, or jointed-arm configuration, this would mean that the robot arm is at maximum extension. Just as in the case of a human, it is more difficult to lift a heavy load with arms fully extended than when the arms are held in close to the body.

The rated weight-carrying capacities of industrial robots ranges from less than a pound for some of the small robots up to several thousand pounds for very large robots. An example is the Prab Versatran Model FC which has a rated load capacity of 2000 lb. The small assembly robots, such as the MAKER 110, have weight-carrying capabilities in the vicinity of 5 lb. The manufacturer's specification of this feature is the gross weight capacity. To use this specification, the user must consider the weight of the end effector. For example, if the rated load capacity of a given robot were 5 lb, and the end effector weighed 2 lb, then the net weight-carrying capacity of the robot would be only 3 lb.

## 2-4 CONTROL SYSTEMS AND DYNAMIC PERFORMANCE

In order to operate, a robot must have a means of controlling its drive system to properly regulate its motions. In this section we briefly describe the various types of control systems and the associated performance characteristics which are determined by the control system. A more thorough treatment of these topics is provided in Chaps. 3 and 4.

### Four Types of Robot Controls

Commercially available industrial robots can be classified into four categories according to their control systems. The four categories are:

1. Limited-sequence robots
2. Playback robots with point-to-point control

3. Playback robots with continuous path control
4. Intelligent robots

Of the four categories, the limited-sequence robots represent the lowest level of control and the intelligent robots are the most sophisticated.

Limited-sequence robots do not use servo-control to indicate relative positions of the joints. Instead, they are controlled by setting limit switches and/or mechanical stops to establish the endpoints of travel for each of their joints. Establishing the positions and sequence of these stops involves a mechanical setup of the manipulator rather than robot programming in the usual sense of the term. With this method of control, the individual joints can only be moved to their extreme limits of travel. This has the effect of severely limiting the number of distinct points that can be specified in a program for these robots. The sequence in which the motion cycle is played out is defined by a pegboard or stepping switch or other sequencing device. This device, which constitutes the robot controller, signals each of the particular actuators to operate in the proper succession. There is generally no feedback associated with a limited sequence robot to indicate that the desired position has been achieved. Any of the three drive systems can be used with this type of control system; however, pneumatic drive seems to be the type most commonly employed. Applications for this type of robot generally involve simple motions, such as pick-and-place operations.

Playback robots use a more sophisticated control unit in which a series of positions or motions are "taught" to the robot, recorded into memory, and then repeated by the robot under its own control. The term "playback" is descriptive of this general mode of operation. The procedure of teaching and recording into memory is referred to as programming the robot. Playback robots usually have some form of servo-control (e.g., closed loop feedback system) to ensure that the positions achieved by the robot are the positions that have been taught.

Playback robots can be classified into two categories: point-to-point (PTP) robots and continuous-path (CP) robots. Point-to-point robots are capable of performing motion cycles that consist of a series of desired point locations and related actions. The robot is taught each point, and these points are recorded into the robot's control unit. During playback, the robot is controlled to move from one point to another in the proper sequence. Point-to-point robots do not control the path taken by the robot to get from one point to the next. If the programmer wants to exercise a limited amount of control over the path followed, this must be done by programming a series of points along the desired path. Control of the sequence of positions is quite adequate for many kinds of applications, including loading and unloading machines and spot welding.

Continuous-path robots are capable of performing motion cycles in which the path followed by the robot is controlled. This is usually accomplished by making the robot move through a series of closely spaced points which describe the desired path. The individual points are defined by the control unit rather than the programmer. Straight line motion is a common form of continuous-path control for industrial robots. The programmer specifies the starting point and the end point of the path, and the control unit calculates the sequence of individual points that permit the robot to follow a straight line trajectory. Some robots have the capability to follow a smooth, curved path that has been defined by a programmer who manually moves the arm through the desired motion cycle. To achieve continuous-path control to more than a limited extent requires that the controller unit be capable of storing a large number of individual point locations that define the compound curved path. Today this usually involves the use of a digital computer (a microprocessor is typically used as the central processing unit for the computer) as the robot controller. CP control is required for certain types of industrial applications such as spray coating and arc welding.

Intelligent robots constitute a growing class of industrial robot that possesses the capability not only to play back a programmed motion cycle but to also interact with its environment in a way that seems intelligent. Invariably, the controller unit consists of a digital computer or similar device (e.g., programmable controller). Intelligent robots can alter their programmed cycle in response to conditions that occur in the workplace. They can make logical decisions based on sensor data received from the operation. The robots in this class have the capacity to communicate during the work cycle with humans or computer-based systems. Intelligent robots are usually programmed using an English-like and symbolic language not unlike a computer programming language. Indeed, the kinds of applications that are performed by intelligent robots rely on the use of a high-level language to accomplish the complex and sophisticated activities that can be accomplished by these robots. Typical applications for intelligent robots are assembly tasks and arc-welding operations.

## Speed of Response and Stability

Speed of response and stability are two important characteristics of dynamic performance related to control systems design. The speed of response refers to the capability of the robot to move to the next position in a short amount of time. This response time is obviously related to the robot's motion speed, a feature that we have already discussed. It is also a function of the control system. In robotics, stability is generally defined as a measure of the oscillations which occur in the arm during movement from one position to the next. A robot with good stability will exhibit little or no oscillations either during or at the termination of the arm movement. Poor stability would be indicated by a large amount of oscillation. It is generally desirable in control systems design for the system to have good stability and a fast response time. Unfortunately, these are competing objectives.

The stability of a robot can be controlled to a certain extent by incorporating damping elements into the robot's design. A high level of damping will increase the robot's stability (reduce its tendency toward oscillation).

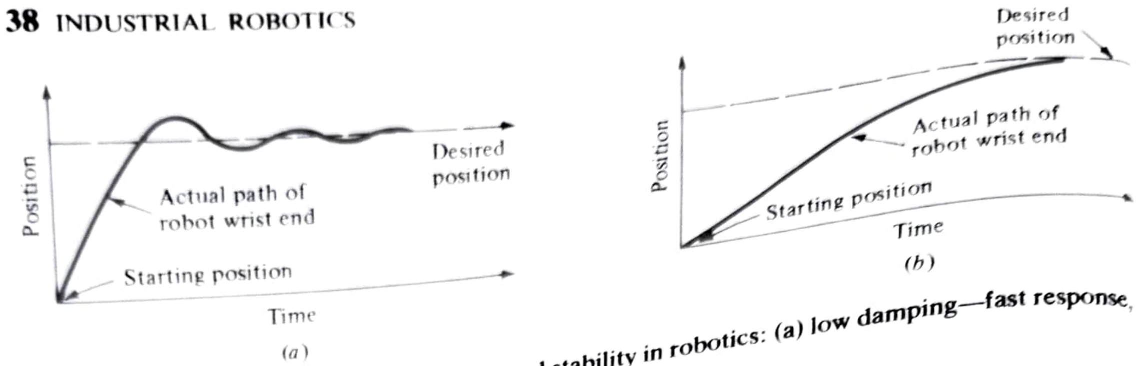


**Figure 2-15** Concept of speed of response and stability in robotics: (a) low damping—fast response, (b) high damping—slow response.

The problem with high damping is that it reduces the speed of response. Accordingly, there is a compromise that must be struck between the stability of the robot and its ability to operate at high speeds.

The concept of stability and its relation to damping is illustrated in Fig. 2-15. In the two diagrams of the figure, the position of the robot's wrist is shown as a function of time for two cases: small damping and large damping. With low damping, the robot arm moves to the programmed position quickly, but exhibits considerable oscillation about the position. With a large amount of damping built into the system, the arm movement to the desired position is very sluggish but there is no oscillatory motion about the final position.

with Application

## 2.5 PRECISION OF MOVEMENT

The preceding discussion of response speed and stability is concerned with the dynamic performance of the robot. Another measure of performance is precision of the robot's movement. We will define precision as a function of three features:

1. Spatial resolution
2. Accuracy
3. Repeatability

These terms will be defined with the following assumptions. First, the definitions will apply at the robot's wrist end with no hand attached to the wrist. Second, the terms apply to the worst case conditions, the conditions under which the robot's precision will be at its worst. This generally means that the robot's arm is fully extended in the case of a jointed arm or polar configuration. Third, our definitions will be developed in the context of a point-to-point robot. That is, we will be concerned with the robot's capability to achieve a given position within its work volume. It is easier to define the various precision features in a static context rather than a dynamic context. It is considerably more difficult to define, and measure, the robot's capacity to achieve a defined motion path in space because it would be complicated by speed and other factors.

## Spatial Resolution

The spatial resolution of a robot is the smallest increment of movement into which the robot can divide its work volume. Spatial resolution depends on two factors: the system's control resolution and the robot's mechanical inaccuracies. It is easiest to conceptualize these factors in terms of a robot with 1 degree of freedom.

The control resolution is determined by the robot's position control system and its feedback measurement system. It is the controller's ability to divide the total range of movement for the particular joint into individual increments that can be addressed in the controller. The increments are sometimes referred to as "addressable points." The ability to divide the joint range into increments depends on the bit storage capacity in the control memory. The number of separate, identifiable increments (addressable points) for a particular axis is given by

$$\text{Number of increments} = 2^n$$

where $n$ = the number of bits in the control memory.

For example, a robot with 8 bits of storage can divide the range into 256 discrete positions. The control resolution would be defined as the total motion range divided by the number of increments. We assume that the system designer will make all of the increments equal.

**Example 2-1** Using our robot with 1 degree of freedom as an illustration, we will assume it has one sliding joint with a full range of 1.0 m (39.37 in.). The robot's control memory has a 12-bit storage capacity. The problem is to determine the control resolution for this axis of motion.

The number of control increments can be determined as follows:

$$\text{Number of increments} = 2^{12} = 4096$$

The total range of 1 m is divided into 4096 increments. Each position will be separated by

$$1\text{ m}/4096 = 0.000244\text{ m} \qquad \text{or} \qquad 0.244\text{ mm}$$

The control resolution is 0.244 mm (0.0096 in.).

This example deals with only one joint. A robot with several degrees of freedom would have a control resolution for each joint of motion. To obtain the control resolution for the entire robot, component resolutions for each joint would have to be summed vectorially. The total control resolution would depend on the wrist motions as well as the arm and body motions. Since some of the joints are likely to be rotary while others are sliding, the robot's control resolution can be a complicated quantity to determine.

Mechanical inaccuracies in the robot's links and joint components and its feedback measurement system (if it is a servo-controlled robot) constitute the other factor that contributes to spatial resolution. Mechanical inaccuracies come from elastic deflection in the structural members, gear backlash, stretching of pulley cords, leakage of hydraulic fluids, and other imperfections in the mechanical system. These inaccuracies tend to be worse for larger robots simply because the errors are magnified by the larger components. The inaccuracies would also be influenced by such factors as the load being handled, the speed with which the arm is moving, the condition of maintenance of the robot, and other similar factors.

The spatial resolution of the robot is the control resolution degraded by these mechanical inaccuracies. Spatial resolution can be improved by increasing the bit capacity of the control memory. However, a point is reached where it provides little additional benefit to increase the bit capacity further because the mechanical inaccuracies of the system become the dominant component in the spatial resolution.

## Accuracy

Accuracy refers to a robot's ability to position its wrist end at a desired target point within the work volume. The accuracy of a robot can be defined in terms of spatial resolution because the ability to achieve a given target point depends on how closely the robot can define the control increments for each of its joint motions. In the worst case, the desired point would lie in the middle between two adjacent control increments. Ignoring for the moment the mechanical inaccuracies which would reduce the robot's accuracy, we could initially define accuracy under this worst case assumption as one-half of the control resolution. This relationship is illustrated in Fig. 2-16. In fact, the mechanical inaccuracies would affect the ability to reach the target position. Accordingly, we define the robot's accuracy to be one-half of its spatial resolution as portrayed in Fig. 2-17.

Our definition of accuracy applies to the worst case, where the target point is directly between two control points. Our definition also implies that the accuracy is the same anywhere in the robot's work volume. In fact, the

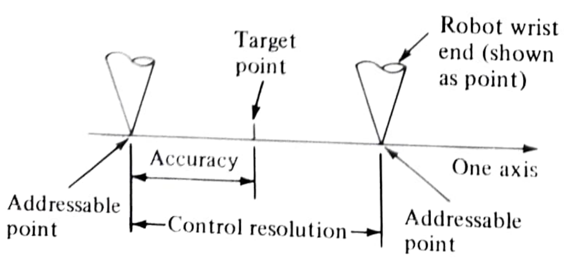


**Figure 2-16** Illustration of accuracy and control resolution when mechanical inaccuracies are assumed to be zero.

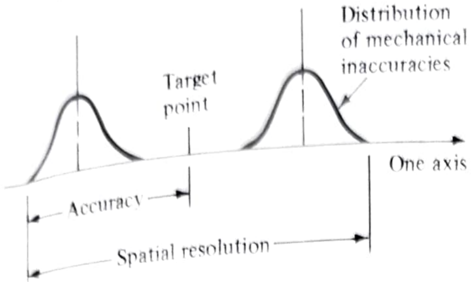


**Figure 2-17** Illustration of accuracy and spatial resolution in which mechanical inaccuracies are represented by a statistical distribution.

accuracy of a robot is affected by several factors. First, the accuracy varies within the work volume, tending to be worse when the arm is in the outer range of its work volume and better when the arm is closer to its base. The reason for this is that the mechanical inaccuracies are magnified with the robot's arm fully extended. The term error map is used to characterize the level of accuracy possessed by the robot as a function of location in the work volume. Second, the accuracy is improved if the motion cycle is restricted to a limited work range. The mechanical errors will tend to be reduced when the robot is exercised through a restricted range of motions. The robot's ability to reach a particular reference point within the limited work space is sometimes called its local accuracy. When the accuracy is assessed within the robot's full work volume, the term global accuracy is used. A third factor influencing accuracy is the load being carried by the robot. Heavier workloads cause greater deflection of the mechanical links of the robot, resulting in lower accuracy.

## Repeatability

Repeatability is concerned with the robot's ability to position its wrist or an end effector attached to its wrist at a point in space that had previously been taught to the robot. Repeatability and accuracy refer to two different aspects of the robot's precision. Accuracy relates to the robot's capacity to be programmed to achieve a given target point. The actual programmed point will probably be different from the target point due to limitations of control resolution. Repeatability refers to the robot's ability to return to the programmed point when commanded to do so.

These concepts are illustrated in Figure 2-18. The desired target point is denoted by the letter $T$. During the teach procedure, the robot is commanded to move to point $T$, but because of the limitations on its accuracy, the programmed position becomes point $P$. The distance between points $T$ and $P$ is a manifestation of the robot's accuracy in this case. Subsequently, the robot is instructed to return to the programmed point $P$; however, it does not return to the exact same position. Instead, it returns to position $R$. The difference between $P$ and $R$ is a result of limitations on the robot's repeatability. The robot will not always return to the same position $R$ on subsequent repetitions of the motion cycle. Instead, it will form a cluster of points on both sides of the position $P$ in Fig. 2-18.

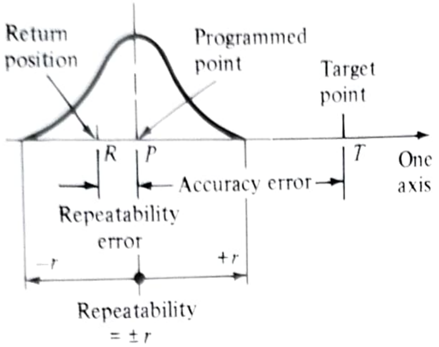


**Figure 2-18** Illustration of repeatability and accuracy.

Repeatability errors form a random variable and constitute a statistical distribution as shown in the figure. It would be convenient if the repeatability errors formed a nice bell-shaped curve, suggesting a normally distributed random variable. What is closer to reality is that for each joint, the mechanical inaccuracies that are principally responsible for repeatability errors do not form the nice symmetric bell-shaped distribution shown in the figure. However, when the errors from several axes of motion are combined together, the resulting aggregate error is influenced by the central limit theorem in probability. This theorem states that the sums of random variables tend to form a normally distributed variable, even though the individuals come from a distribution other than the normal. Accordingly, we can infer that the repeatability error of a robot with five or six axes is approximately normal, even if the error due to each individual axis is not normal.

In three-dimensional space, the repeatability errors will surround the programmed point $P$, forming a distribution whose outer boundary can be conceptualized as a sphere. A robot manufacturer typically quotes the repeatability of its manipulator as the radius of the idealized sphere, usually expressing the specification as plus or minus a particular value. The size of the sphere will tend to be larger in the regions of the work volume that are further away from the center of the robot. It is likely that the shape of the sphere is not perfectly round, but instead is oblong in certain directions due to compliance of the robot arm.

## Compliance

A feature of the robot that is related to our preceding discussion is compliance. The compliance of the robot manipulator refers to the displacement of the wrist end in response to a force or torque exerted against it. A high compliance means that the wrist is displaced a large amount by a relatively small force. The term "springy" is sometimes used to describe a robot with high compliance. A low compliance means that the manipulator is relatively stiff and is not displaced by a significant amount.

Robot manipulator compliance is a directional feature. That is, the compliance of the robot arm will be greater in certain directions than in other directions because of the mechanical construction of the arm.

Compliance is important because it reduces the robot's precision of movement under load. If the robot is handling a heavy load, the weight of the load will cause the robot arm to deflect. If the robot is pressing a tool against a workpart, the reaction force of the part may cause deflection of the manipulator. If the robot has been programmed under no-load conditions to position its end effector, and accuracy of position is important in the application, the robot's performance will be degraded because of compliance when it operates under loaded conditions.

## 2-6 END EFFECTORS

For industrial applications, the capabilities of the basic robot must be augmented by means of additional devices. We might refer to these devices as the robot's peripherals. They include the tooling which attaches to the robot's wrist and the sensor systems which allow the robot to interact with its environment. We provide a more comprehensive treatment of these robot technology areas in Chaps. 5, 6, and 7.

In robotics, the term end effector is used to describe the hand or tool that is attached to the wrist. The end effector represents the special tooling that permits the general-purpose robot to perform a particular application. This special tooling must usually be designed specifically for the application.

End effectors can be divided into two categories: grippers and tools. Grippers would be utilized to grasp an object, usually the workpart, and hold it during the robot work cycle. There are a variety of holding methods that can be used in addition to the obvious mechanical means of grasping the part between two or more fingers. These additional methods include the use of suction cups, magnets, hooks, and scoops. A tool would be used as an end effector in applications where the robot is required to perform some operation on the workpart. These applications include spot welding, arc welding, spray painting, and drilling. In each case, the particular tool is attached to the robot's wrist to accomplish the application.

## 2-7 ROBOTIC SENSORS

Sensors used as peripheral devices in robotics include both simple types such as limit switches and sophisticated types such as machine vision systems. Of course, sensors are also used as integral components of the robot's position feedback control system. We discuss this use in Chap. 3. Their function as peripheral devices in a robotic work cell is to permit the robot's activities to be coordinated with other activities in the cell. The sensors used in robotics include the following general categories:

1. Tactile sensors. These are sensors which respond to contact forces with another object. Some of these devices are capable of measuring the level of force involved.
2. Proximity and range sensors. A proximity sensor is a device that indicates when an object is close to another object but before contact has been made. When the distance between the objects can be sensed, the device is called a range sensor.
3. Miscellaneous types. The miscellaneous category includes the remaining kinds of sensors that are used in robotics. These include sensors for temperature, pressure, and other variables.
4. Machine vision. A machine vision system is capable of viewing the work-space and interpreting what it sees. These systems are used in robotics to perform inspection, parts recognition, and other similar tasks.

Sensors are an important component in work cell control and in safety monitoring systems.

## 2-8 ROBOT PROGRAMMING AND WORK CELL CONTROL

In its most basic form, a robot program can be defined as a path in space through which the manipulator is directed to move. This path also includes other actions such as controlling the end effector and receiving signals from sensors. The purpose of robot programming is to teach these actions to the robot.

There are various methods used for programming robots. The two basic categories of greatest commercial importance today are leadthrough programming and textual language programming. Chapters 8 and 9 describe these two methods, respectively.

Leadthrough programming consists of forcing the robot arm to move through the required motion sequence and recording the motions into the controller memory. Leadthrough methods are used to program playback robots. In the case of point-to-point playback robots, the usual procedure is to use a control box (called a teach pendant) to drive the robot joints to each of the desired points in the workspace, and record the points into memory for subsequent playback. The teach pendant is equipped with a series of switches and dials to control the robot's movements during the teach procedure. Owing to its ease and convenience and the wide range of applications suited to it, this leadthrough method is the most common programming method for playback-type robots.

Continuous-path playback robots also use leadthrough programming. For well-defined paths, such as moving along a straight line between two points, a teach pendant can be employed to teach the locations of the two points, and the robot controller then computes the trajectory to be followed in order to move along the straight line path. For more complex motions (e.g., those encountered in spray-painting operations), it is usually more convenient for the programmer to physically move the robot arm and end effector through the desired motion path and record the positions at closely spaced sampling intervals. Certain parameters of the motion cycle, such as the robot's speed, would be controlled independently when the job is set up to operate. Accordingly, the programmer does not need to be concerned with these aspects of the program. The programmer's principal concern is to make sure that the motion sequence is correct.

Textual programming methods use an English-like language to establish the logic and sequence of the work cycle. A computer terminal is used to input the program instructions into the controller but a teach pendant is also used to define the locations of the various points in the workspace. The robot programming language names the points as symbols in the program and these symbols are subsequently defined by showing the robot their locations. In addition to identifying points in the workspace, the robot languages permit the use of calculations, more detailed logic flow, and subroutines in the programs, and greater use of sensors and communications. Accordingly, the use of the textual languages corresponds largely to the so-called intelligent robots.

Some examples of the kinds of programming statements that would be found in the textual robot languages include the following sequence:

```
SPEED 35 IPS
MOVE P1
CLOSE 40 MM
WAIT 1 SEC
DEPART 60 MM
```

The series of commands tells the robot that its velocity at the wrist should be 35 in./sec in the motions which follow. The MOVE statement indicates that the robot is to move its gripper to point P1 and close to an opening of 40 mm. It is directed to wait 1.0 s before departing from P1 by a distance of 60 mm above the point.

A future enhancement of textual language programming will be to enter the program completely off-line, without the need for a teach pendant to define point locations in the program. The potential advantage of this method is that the programming can be accomplished without taking the robot out of production. All of the current methods of programming require the participation of the robot in order to perform the programming function. With off-line programming, the entire program can be entered into a computer for later downloading to the robot. Off-line programming would hasten the changeover from one robot work cycle to a new work cycle without a major time delay for reprogramming. Unfortunately, there are certain technical problems associated with off-line programming. These problems are mainly concerned with defining the spatial locations of the positions to be used in the work cycle, and that is why the teach pendant is required in today's textual robot languages.

In addition to the leadthrough and textual language programming methods, there is another form of programming for the low-technology-limited sequence robots. These robots are programmed by setting limit switches, mechanical stops, and other similar means to establish the endpoints of travel for each of the joints. This is sometimes called mechanical programming; it really involves more of a manual setup procedure rather than a programming method. The work cycles for these kinds of robots generally consist of a limited number of simple motions (e.g., pick-and-place applications), for which this manual programming method is adequate.

Work cell control deals with the problem of coordinating the robot to operate with other equipment in the work cell. A robot cell usually consists of not only the robot, but also conveyors, machine tools, inspection devices, and possibly human operators. Some of the activities in the robot work cell occur sequentially, while other activities occur simultaneously. A method of controlling and synchronizing these various activities is required, and that is the purpose of the work cell controller. Work cell control is accomplished either by the robot controller or a separate small computer or programmable controller. During operation, the controller communicates signals to the equipment in the cell and receives signals back from the equipment. These signals are sometimes called interlocks. By communicating back and forth with the different components of the work cell, the various activities in the cell are accomplished in the proper sequence.

## 2-9 ROBOT APPLICATIONS

Robots are employed in a wide assortment of applications in industry. Today most of the applications are in manufacturing to move materials, parts, and tools of various types. Future applications will include nonmanufacturing tasks, such as construction work, exploration of space, and medical care. At some time in the distant future, a household robot may become a mass produced item, perhaps as commonplace as the automobile is today.

For the present, most industrial applications of robots can be divided into the following three categories:

1. Material-handling and machine-loading and -unloading applications. In these applications the robot's function is to move materials or parts from one location in the work cell to some other location. The MAKER 110 in Figure 2-3 is shown performing a material-handling operation. Loading and/or unloading of a production machine is included within the scope of this material-handling activity. The Unimate 2000 in Fig. 2-2 is performing a machine load/unload operation for a machine tool.
2. Processing applications. This category includes spot welding, arc welding, spray painting, and other operations in which the function of the robot is to manipulate a tool to accomplish some manufacturing process in the work