CHAPTER

2 Robot Technology

2.0 OBJECTIVES

After studying this chapter, the reader should:

1. Realize the fundamentals of robot technology
2. Know the general characteristics of robots
3. Understand the basic components of robots
4. Recognize robot anatomy
5. Be informed of robot generations
6. Be aware of robot selection

2.1 FUNDAMENTALS

Robot technology is an applied science that is referred to as a combination of machine tools and computer applications. It includes such diverse fields as machine design, control theory, microelectronics, computer programming, artificial intelligence, human factors, and production theory.

Research and development are proceeding in all these areas to improve the way robots work and behave. Advancements in technology will enlarge the scope and future applications of robots.

To describe the technology of a robot, it is necessary to define a variety of technical features about the way a robot is constructed and the way it works. To accomplish this, the following topics as applied to the industrial robot are discussed:

- General characteristics
- Basic components
- Robot anatomy
- Robot generations
- Robot selection

Although these topics are discussed in detail later in the book, a concise description is necessary here to help the reader become familiar with the terms and practical aspects of this subject.

2.2 GENERAL CHARACTERISTICS

The development of the **industrial robot** represents a logical evolution of automated equipment, combining certain features of fixed automation and human labor. Robots can be thought of as specialized machine tools with a degree of flexibility that distinguishes them from fixed-purpose automation. By the addition of sensory devices, robots are gaining the ability to adapt to their work environment and modify their actions based on work-condition variations. Industrial robots are becoming "smarter" mechanical workers and are now widely accepted as valuable productivity-improvement tools.

Industrial robots are properly thought of as machines or mechanical arms. It is inappropriate to think of them as mechanical people. A robot is essentially a mechanical arm that is bolted to the floor, a machine, the ceiling, or, in some cases, the wall, fitted with its mechanical hand, and taught to do repetitive tasks in a controlled, ordered environment. In most cases, it possesses neither the ability to move about the plant nor the ability to see or feel the part it is working on. Exceptions to these general rules exist in certain instances. However, even with these limitations, robots make outstanding contributions toward the improvement of manufacturing operations. Robots fill the gap between the specialized and limited capabilities normally associated with fixed automation and the extreme flexibility of human labor.

Robots offer many benefits simply because they are machines. As such, they are not as susceptible to fatigue, discomfort, boredom, or similar factors that negatively impact a human worker's job performance in harsh, noisy, hot, or hazardous environments. Robots can perform well and consistently where strenuous, dangerous, dirty, or repetitive work is required.

Robots have the ability to move their mechanical **arm** (or arms) to perform work. The set of points representing the maximum extent or reach of the robot hand or working tool in all directions is its **work envelope**. The motion characteristics of robots vary depending upon their mechanical design. There are five distinct design configurations for robots, which are discussed later in the robot anatomy section.

Robots interface with their work environment once a mechanical hand (end effector) has been attached to the robot's **tool-mounting plate. End effectors** (also commonly called end-of-arm-tooling, **EOAT**) are the **grippers**, tools, special devices, or **fixtures** attached to the robot arm that actually perform the work. The ability to carry, continuously and satisfactorily, a given maximum weight at a given speed defines a robot's **payload**, usually expressed in pounds or kilograms. Payload, in other words, is the weight that the robot is designed to lift, hold, and position repeatedly with the same accuracy.

The maximum **speed** at which the tip of a robot is capable of moving at full arm extension is its **velocity**, usually expressed in inches or millimeters per second. There are two components of its speed: its **acceleration** and **deceleration** rate, and its **slew rate**. The acceleration/deceleration rate is the time it takes to go from rest to full speed and the time it takes to go from full speed to a complete stop. The slew rate is the velocity once the robot is at full speed.

Cycle time is the time it takes for the robot to complete one cycle of picking up a given object at a given height, moving it to a given distance, lowering it, releasing it, and returning to the starting point.

Accuracy defines a robot's ability to position the end effector at a specified point in space upon receiving a control command without previously having attained that position. **Repeatability** refers to the ability of a robot to return consistently to a previously defined and achieved location. **Resolution** of a robot is the smallest incremental change in position that it can make or its control system can measure.

Size refers to the physical size of a robot, which influences its capacity and its capabilities. There are robots as large as gantry cranes and as small as grains of salt—the latter being made by micromachining, which is the same process used to make integrated circuits and computer chips. Some robots intended for light assembly work are designed to be approximately the size of a human so as to make the installation of the robot into the space vacated by the replaced human as easy and as undisruptive as possible. In general, industrial robots vary widely in size, configuration, and capabilities, yet they share a common family structure. All robots are made up of four basic components.

2.3 BASIC COMPONENTS

The most complex robot can be broken down into a few basic parts. This section provides an overview of the parts that make up an industrial robot and their function. It also introduces much of the terminology related to these parts and explains their origin.

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The basic components of an industrial robot, labeled in Figure 2.3.1, are the **manipulator**, the end effector (which is part of the manipulator), the **power supply**, and the **controller**. Figure 2.3.2 illustrates clearly the relationship of these four components at a typical industrial robot installation.

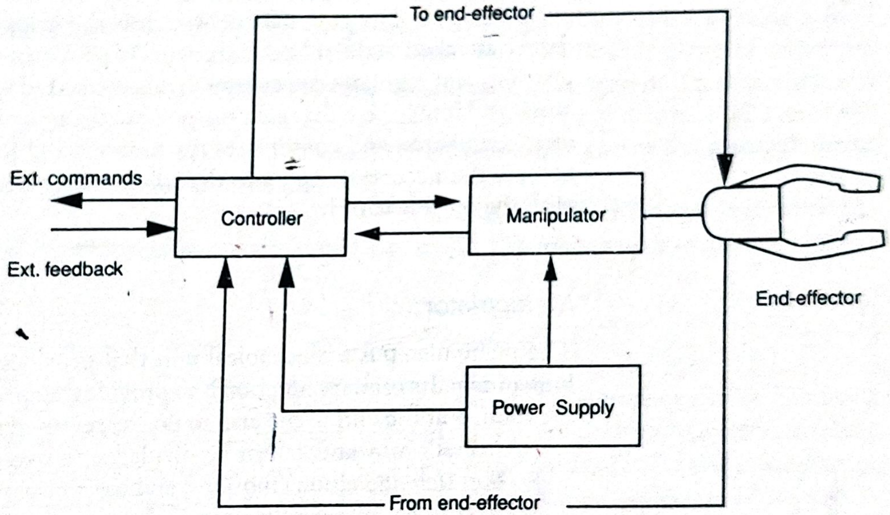

Figure 2.3.1 Basic components of an industrial robot

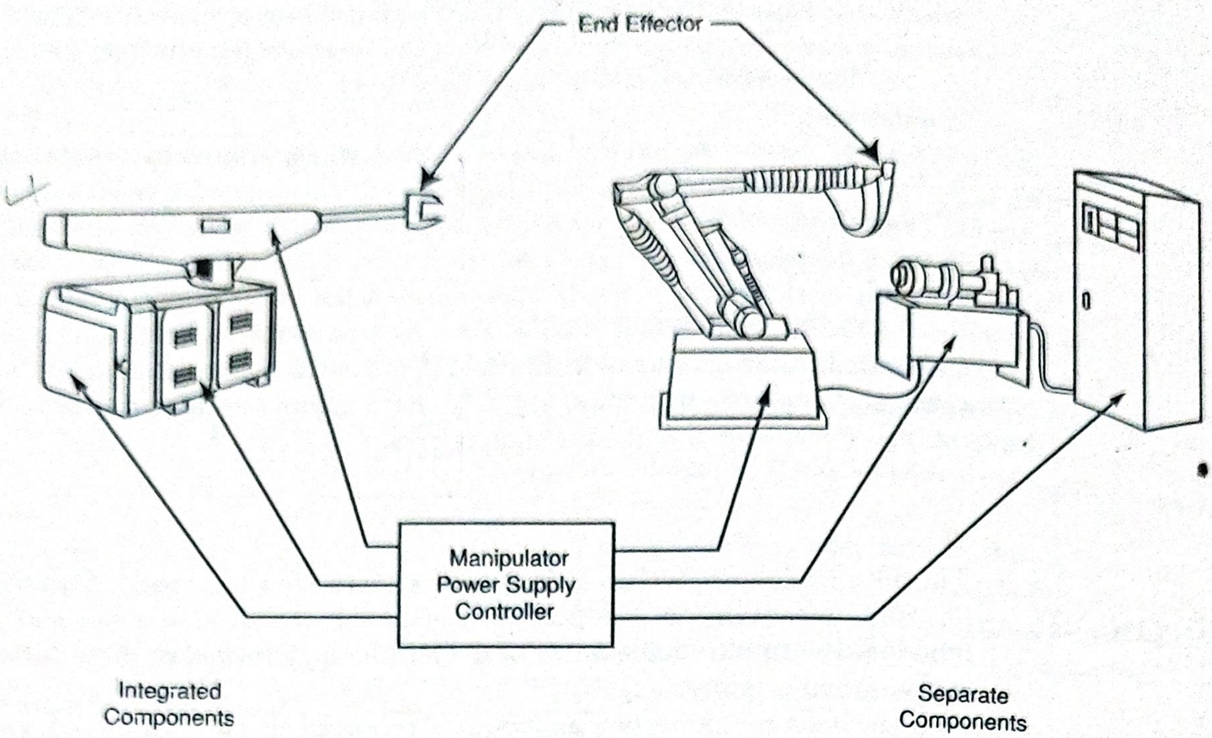

Figure 2.3.2 Industrial robot with integrated and nonintegrated components

The manipulator, which is the robot's arm, consists of segments jointed together with axes capable of motion in various directions allowing the robot to perform work. The end effector, which is the gripper tool, a special device, or fixture attached to the robot's arm, actually performs the work. The power supply provides and regulates the energy that is converted to motion by the robot actuators, and it may be either electric, pneumatic, or hydraulic. The controller initiates, terminates, and coordinates the motions and sequences of a robot. Also, it accepts the necessary inputs to the robot and provides the outputs to interface with the outside world.

Manipulator

The manipulator is a mechanical unit that provides motion similar to that of a human arm. Its primary function is to provide the specific motions that will enable the tooling at the end of the arm to do the required work.

A robot's movements can be divided into two general categories: arm and body (shoulder and elbow) motions, and wrist motions. The individual **joint** motions associated with these two categories are referred to as **degrees of freedom**. Each axis is equal to one degree of freedom. Typically, industrial robots are equipped with 4–6 degrees of freedom. The wrist can reach a point in space with

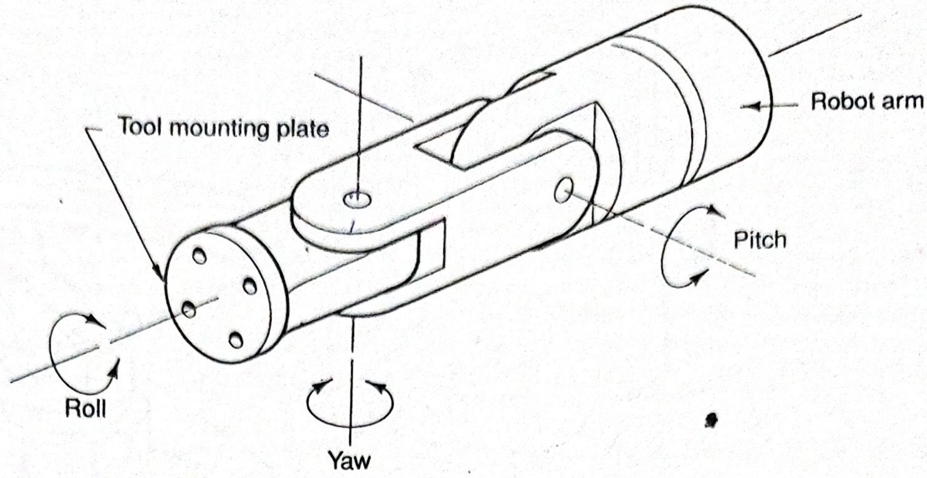

Figure 2.3.3 The three degrees of freedom associated with the robot wrist: roll, pitch, and yaw

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specific orientation by any of three motions: a **pitch**, or up-and-down motion; a **yaw**, or side-to-side motion; and a **roll**, or rotating motion. The joints labeled pitch, yaw, and roll are called **orientation axes**. Figure 2.3.3 shows these three motions as associated with the robot wrist.

The manipulator, therefore, is the part of the robot that physically performs the work. The points that a manipulator bends, slides, or rotates are called joints or **position axes**. Manipulation is carried out using mechanical devices, such as linkages, gears, actuators, and feedback devices. Position axes are also called the world coordinates. The **world coordinate system** is identified as being a fixed location within the manipulator that serves as an absolute frame of reference. Figure 2.3.4 shows the location of the world coordinate system. The x axis of travel moves the manipulator in an in-and-out motion; the y axis motion causes the manipulator to move side-to-side; the z axis motion causes the manipulator to move in an up-and-down motion.

The mechanical design of a robot manipulator relates directly to its work envelope and motion characteristics. Figure 2.3.5 shows the parts of a manipulator.

End Effector

A robot can become a production machine only if a **tool** or device has been attached to its mechanical arm by means of the tool-mounting plate. Robot tooling is referred to by several names. The most frequently used is the end effector, but the term end-of-arm-tooling (EOAT) is commonly used both by industry and in publications. If the end effector is a device that is mechanically opened and closed, similar to the one shown in Figure 2.3.6, it is called a gripper. If the end effector

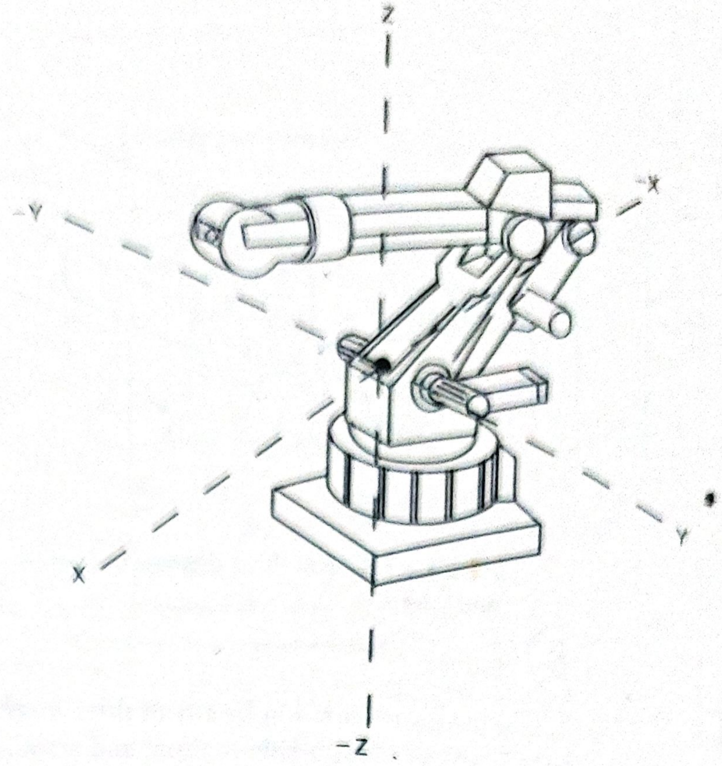

Figure 2.3.4 World coordinates identified on an articulator-style manipulator

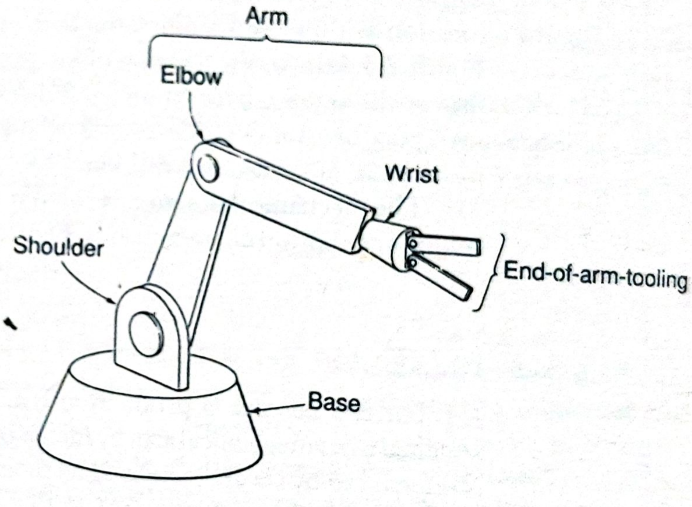

Figure 2.3.5 Parts of a manipulator: The industrial robot manipulator has a body, arm, and wrist. Names match those of the corresponding human parts.

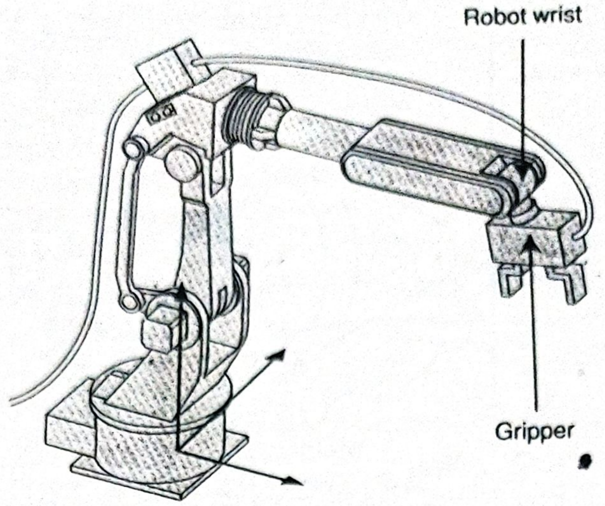

Figure 2.3.6 The Motoman-SK16 electrically controlled industrial robot illustrates here its six degrees of freedom and gripper. It is an articulated robot primarily designed for welding, assembly, and material-handling operations. *(Courtesy of Motoman, Inc.)*

is a tool or a special attachment similar to the ones shown in Figure 2.3.7, it is called **process tooling**.

Depending on the type of operation, conventional end effectors are equipped with various devices and tool attachments, as follows:

- Grippers, hooks, scoops, electromagnets, vacuum cups, and adhesive fingers for materials handling
- Spray gun for painting
- Attachments for spot and arc welding and arc cutting
- Power tools, such as drills, nut drivers, and burrs
- Special devices and fixtures for machining and assembly
- Measuring instruments, such as dial indicators, depth gauges, and the like.

Figure 2.3.8 illustrates various devices and tools attached to the end effector to perform a variety of operations.

The **tool center point (TCP)** is the origin of the coordinate system or the point of action of the tool attached to the robot arm. Notice in Figure 2.3.9 that the origin of the coordinate system is located on the tool-mounting plate of the manipulator. From this location, we can see the direction of the x, y, and z axes. All movements of the manipulator are referenced from this location in space. In Figure 2.3.10 a tool has been added to the mounted plate. Therefore the origin of the coordinate system moved to a new location, which is called the tool center point.

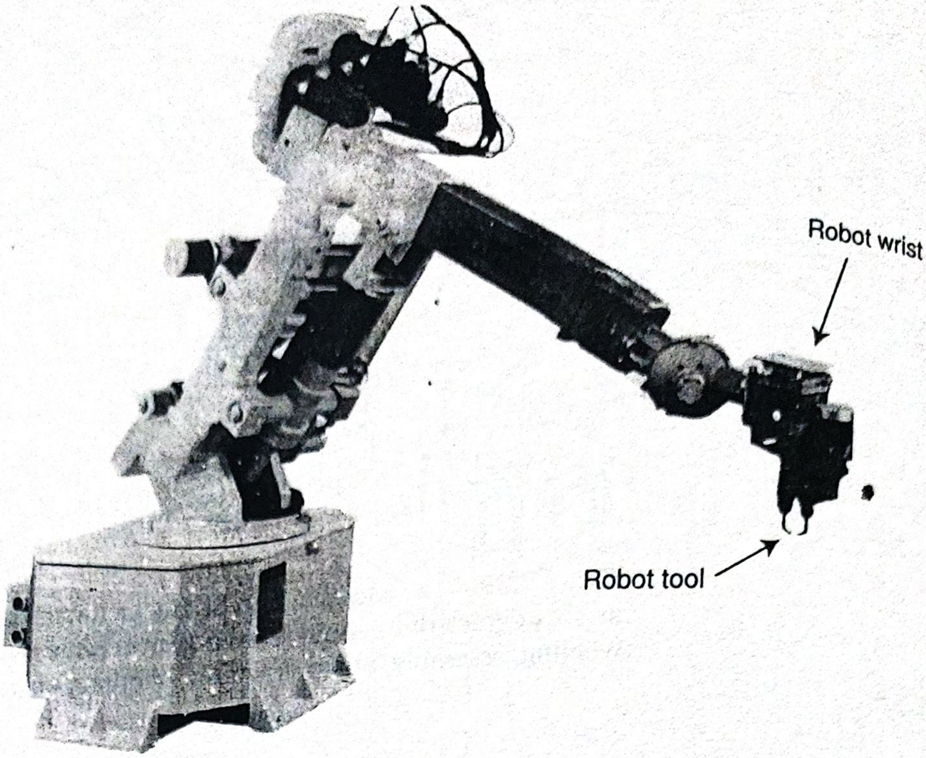

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Figure 2.3.7 The Cincinnati Milacron T^3 776 industrial robot illustrates here its wrist and process tool. It is primarily designed for heavy-payload process applications.

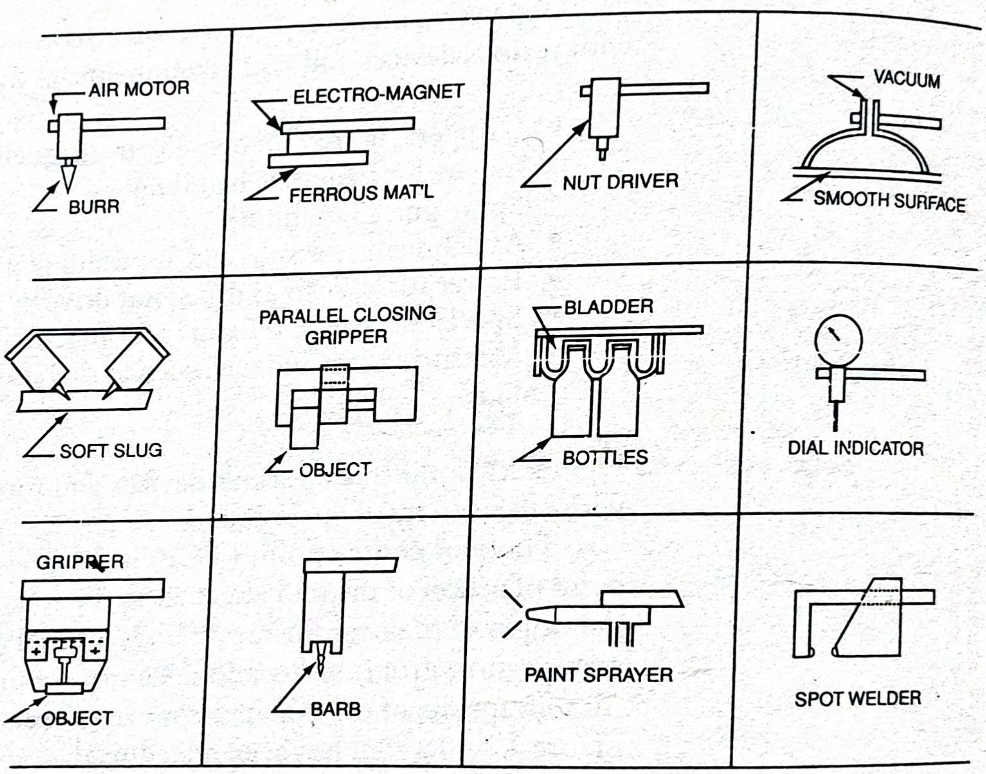

Figure 2.3.8 Various devices and tools attached to end effectors to perform a variety of operations *(Courtesy of Mack Corp.)*

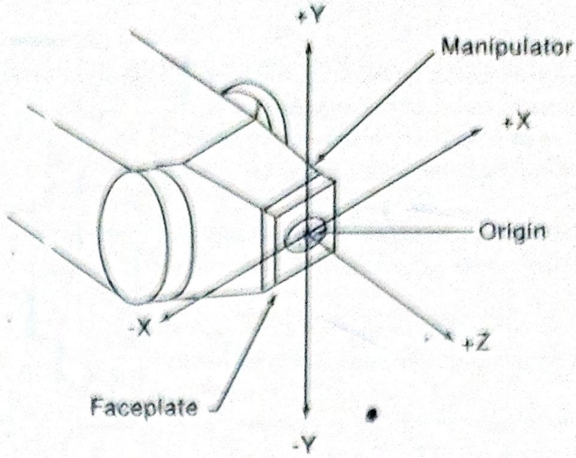

Figure 2.3.9 The origin of the coordinate system is located at the center of the tool-mounting plate of the manipulator.

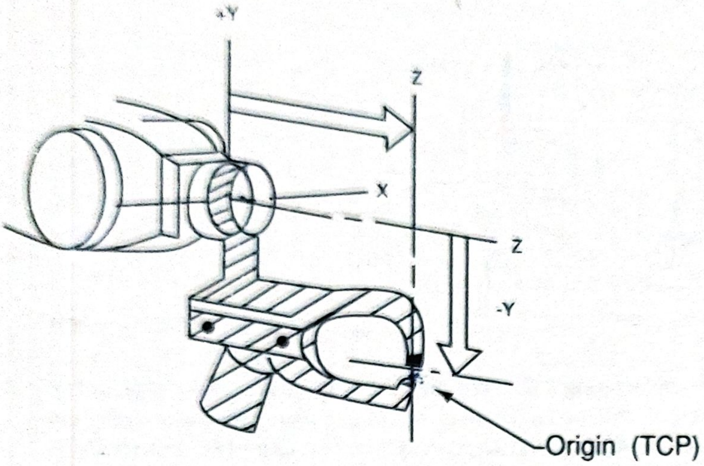

Figure 2.3.10 The location of origin is changed by the addition of a tool to the manipulator. This new origin is called the tool center point (TCP).

End effectors are generally custom-made to meet special handling requirements. Mechanical grippers are the most commonly used and are equipped with two or more fingers. The selection of an appropriate end effector for a specific application depends upon factors such as the payload, environment, reliability, and cost. (Chapter 5 is devoted to the various types of end effectors with their classification, selection, and applications.)

Power Supply

The function of the power supply is to provide and regulate the energy that is required for a robot to be operated. The three basic types of power supplies are electric, hydraulic, and pneumatic.

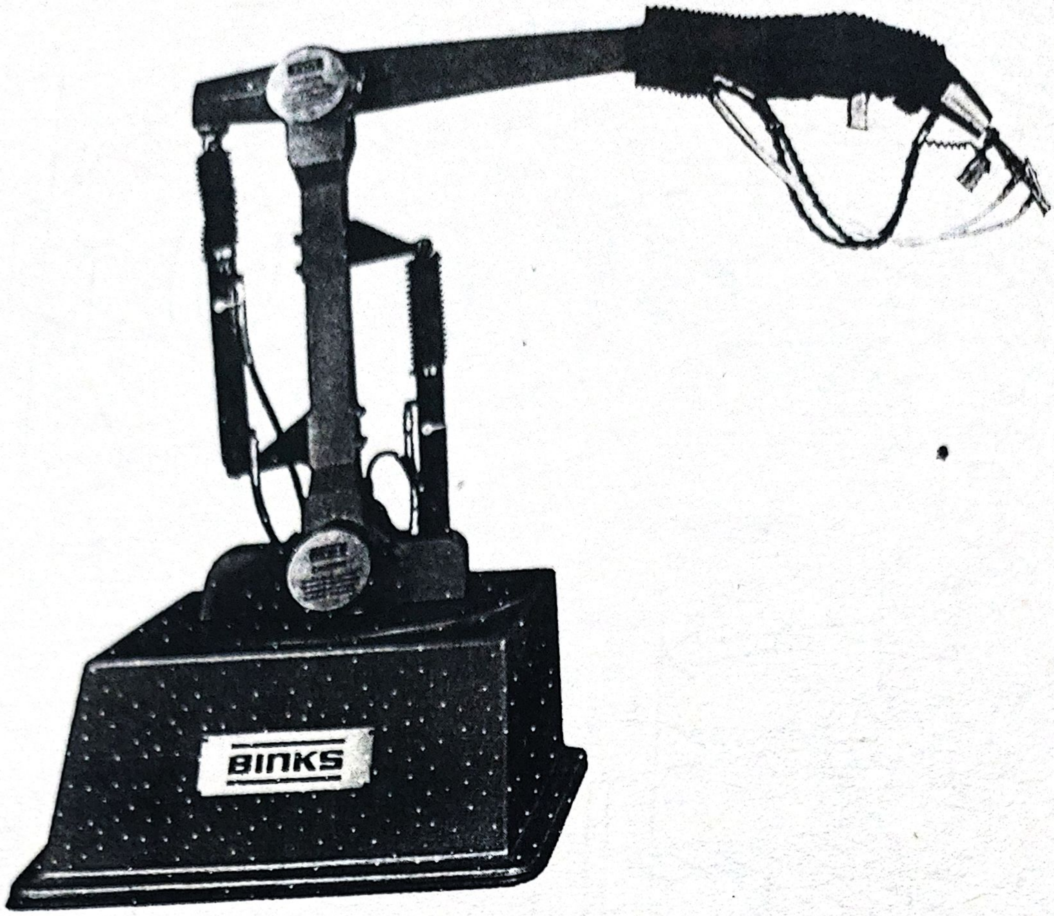

Figure 2.3.11 Binks Manufacturing Co. robot model 88-800 with power supply: Hydraulic on first three axes, electric on last three axes and pneumatic for the end effector. Maximum speeds 60°/s on θ_1, 45°/s on θ_2, 32°/s on θ_3, 90°/s on λ_4 and θ_5, and 150°/s on λ_6. Lead-through controller for spray painting applications. *(Source: Binks Manufacturing Co.)*

Electricity is the most common source of power and is used extensively with industrial robots. The second most common is **pneumatic**, and the least common is **hydraulic** power. Some robot systems require a combination of the three sources. For example, the robot shown in Figure 2.3.11 requires hydraulic power for the first three axes, electric power for the last three axes, and pneumatic power for the end effector. This robot is manufactured by Binks Manufacturing Co., and its application is for spray painting.

The power supply has a direct relation to the payload rating of a robot. Each source of energy and the **actuators** and controls involved have their own characteristics, advantages, and limitations. (Robot power supplies are discussed in detail in Chapter 3.)

Controller

The controller is a communication and information processing device that initiates, terminates, and coordinates the motions and sequences of a robot. It accepts the necessary inputs to the robot and provides the output drive signals to a controlling motor or actuator to correspond with the robot movements and outside world.

Controllers vary greatly in complexity and design. They have a great deal to do with the functional capabilities of a robot and, therefore, the complexity of tasks that robots must be able to fulfill.

The block diagram in Figure 2.3.12a illustrates the many different parts of a robot controller. Figure 2.3.12b illustrates the layout of an actual system installation of a Yamaha loading robot model structure.

The heart of the controller is the computer and its solid-state memory. In many robot controllers, such as the one shown in Figure 2.3.13, the computer includes a network of microprocessors.

The **input** and **output** section of a control system must provide a communication interface between the robot controller computer and the following parts:

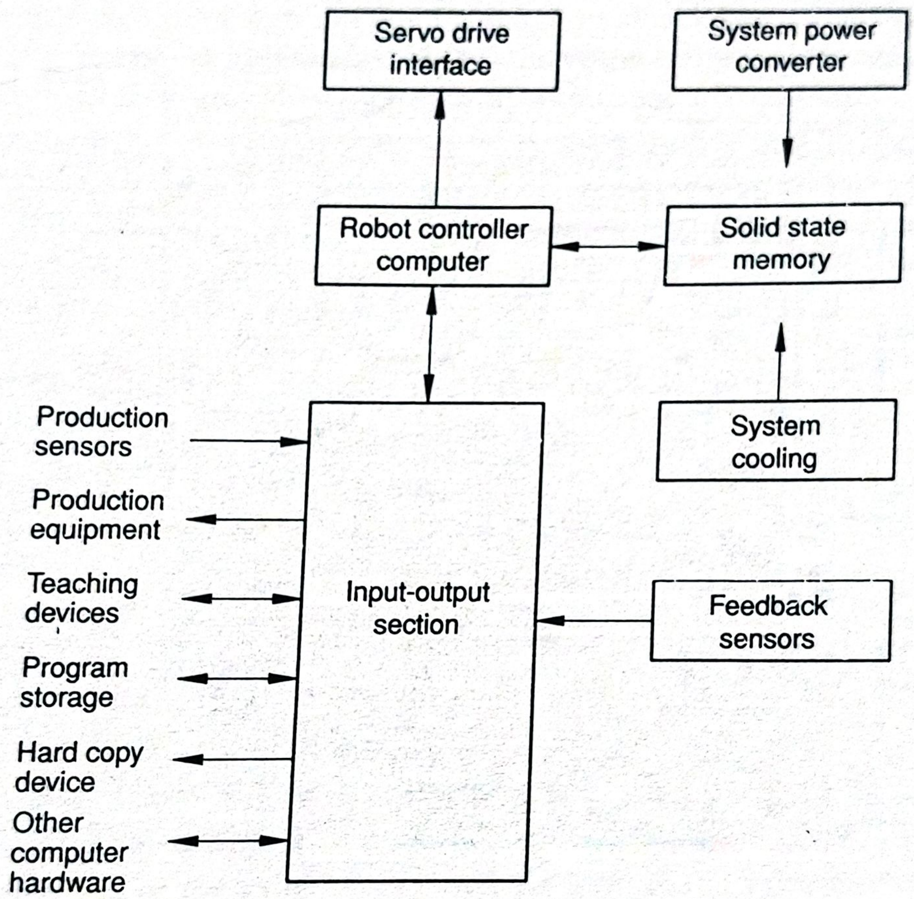

Figure 2.3.12a Robot controller block diagram.

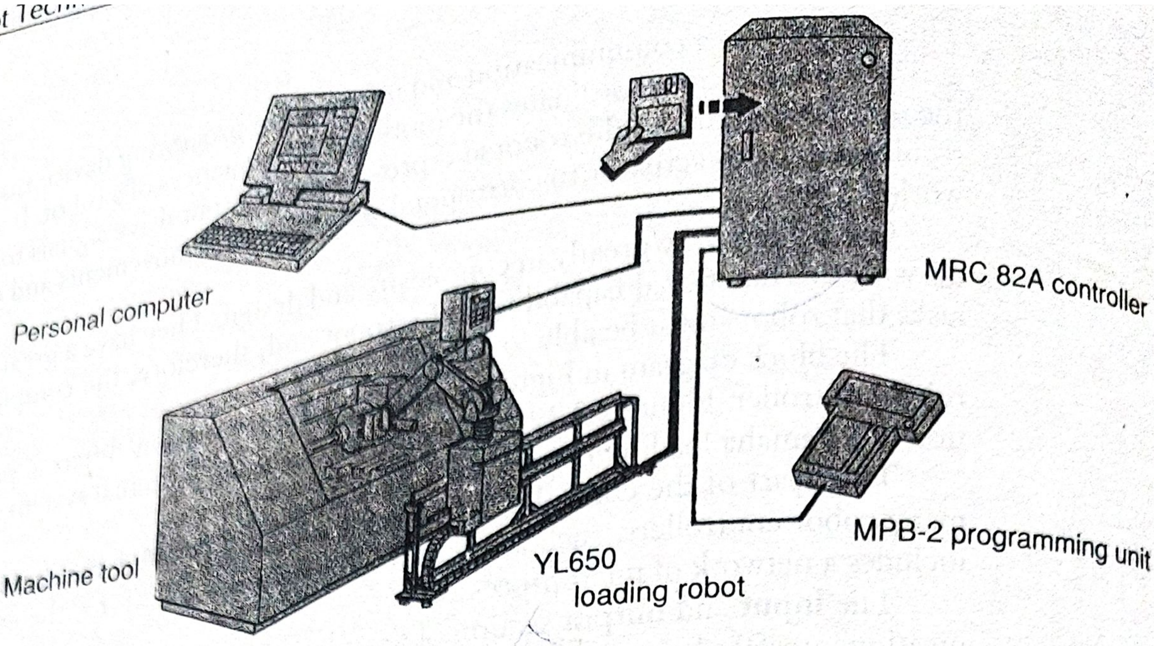

Figure 2.3.12b The Yamaha robot model YL650 is composed of the loading robot, controller, programming box (MPB-2), a[...] I/F equipment for loading and unloading operations. *(Courtesy of Yamaha Robotics Corp.)*

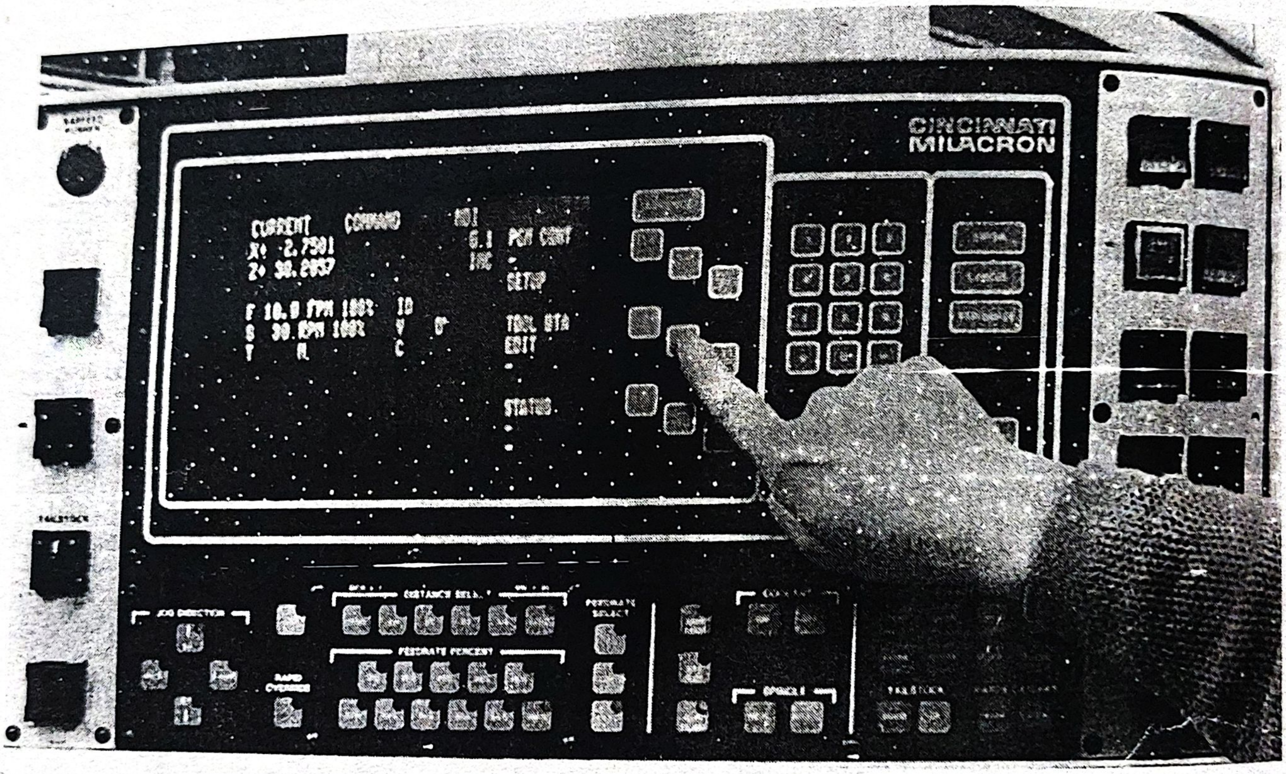

Figure 2.3.13 Microprocessor controller *(Source: Cincinnati Milacron)*

- Feedback sensors
- Production sensors
- Production machine tools
- Teaching devices
- Program storage devices
- Hard copy devices
- Other computer-device hardware

The computer controls the motion of the robot arm by means of drive signals that pass through the drive interface to the actuators on the arm.

In the United States, robots are often classified under three major categories, according to the type of control system used:

1. Nonservo
2. Servo
3. Servo-controlled

The **nonservo** is an **open loop** system, whereas the **servo** is a **closed loop** system. In an open loop system, the output signal is not dependent upon the output input of the system, whereas in the closed loop system, the output of the control is constantly compared with the input through **feedback** devices so that the two quantities can be used simultaneously to achieve the desired performance. **Servo-controlled** robots are closed loop systems with continuously controlled path.

Nonservo robots are the simplest form in construction and operation. They are often referred to as limited-sequence robots, pick-and-place, fixed-stops, or bang-bang robots. Feedback devices, such as **transducers**, are also an important part of the controller. They transmit information to the controller on the position of various robot joints and linkages. A robot with either a closed-loop or an open-loop system controls the motion of its arm as it moves through a **programmable** path.

The primary difference between the three categories is that an open loop system has no sensors on the robot arm to provide feedback. Feedback signals indicate the arm position to the controller. Therefore, in an open loop system the controller continues adjusting the arm until it reaches a permanent stop.

Nonservo (open loop). A nonservo robot system is shown in Figure 2.3.14. The diagram is used to represent a four-axis pneumatic robot. At the beginning of the cycle, the controller starts to move the robot through its various sequential steps. At the first step, the controller sends a signal to the control valve of the manipulator.

As the control valve opens, air is allowed to pass to the actuator or cylinder causing the rod of the cylinder to move. As long as the valve remains open, this segment of the manipulator continues to move until it is restrained by the end stops on the rod of the cylinder. After the rod of the cylinder reaches

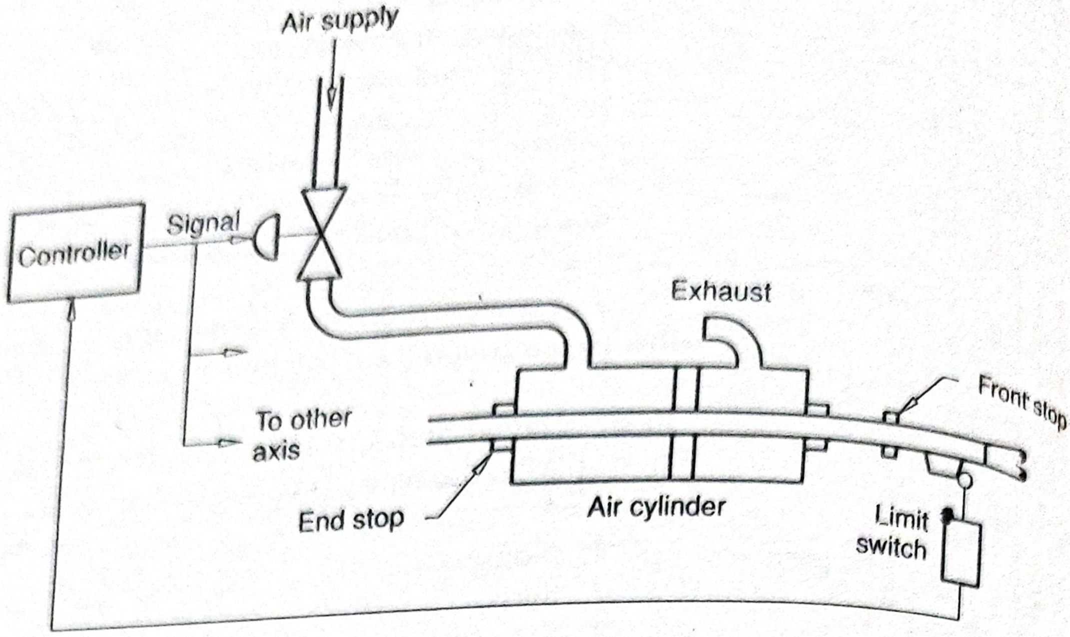

Figure 2.3.14 Nonservo robotic system (open loop)

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its length of travel, a limit switch is activated. This tells the controller to close the control valve.

The controller then sends a signal to the control valve to close it, and from there moves to the next step in the program and initiates the necessary signals. The process is repeated until all the steps in the program have been completed.

This is a simple controller—an open loop device, commonly one that relies on sequences and mechanical stops to control the end-point positions along each axis. These robots have no provision for trajectory control between the end points.

For each motion in a nonservo robot, the manipulator members move to a full tilt until the limits of travel are reached. The robot's arm stops at that achieved position by one of the following methods:

- Actuator
- Fixed stop
- Variable stop
- Stepper motors

The actuator is a device in robots that converts energy into motion. Such devices are hydraulic and pneumatic cylinders and linear electric solenoids or motors in which their stroke from full retraction to full extension positions the robot's arm. A linear actuator is shown in Figure 2.3.15 and Figure 2.3.16.

Pneumatic and hydraulic actuators are both powered by moving fluids. In the first case, the fluid is compressed air; in the second case, the fluid is usually pressurized oil. The operation of these actuators is generally similar except in their ability to contain the pressure of the fluid. Pneumatic systems typically operate

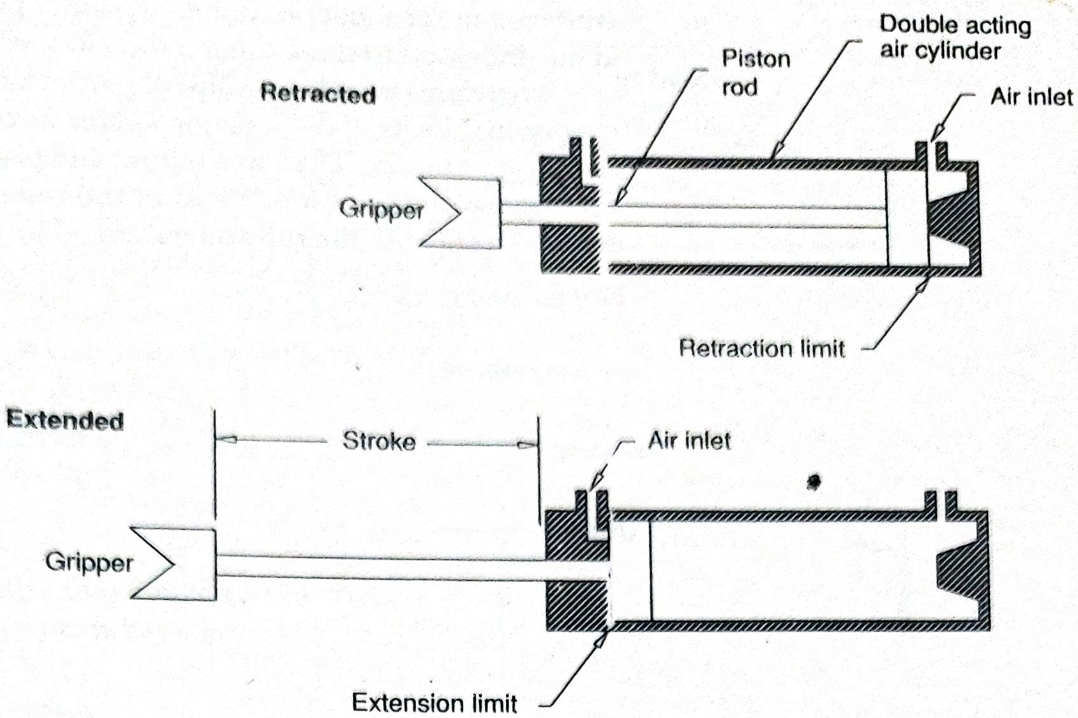

Figure 2.3.15 Linear actuator for motion position.

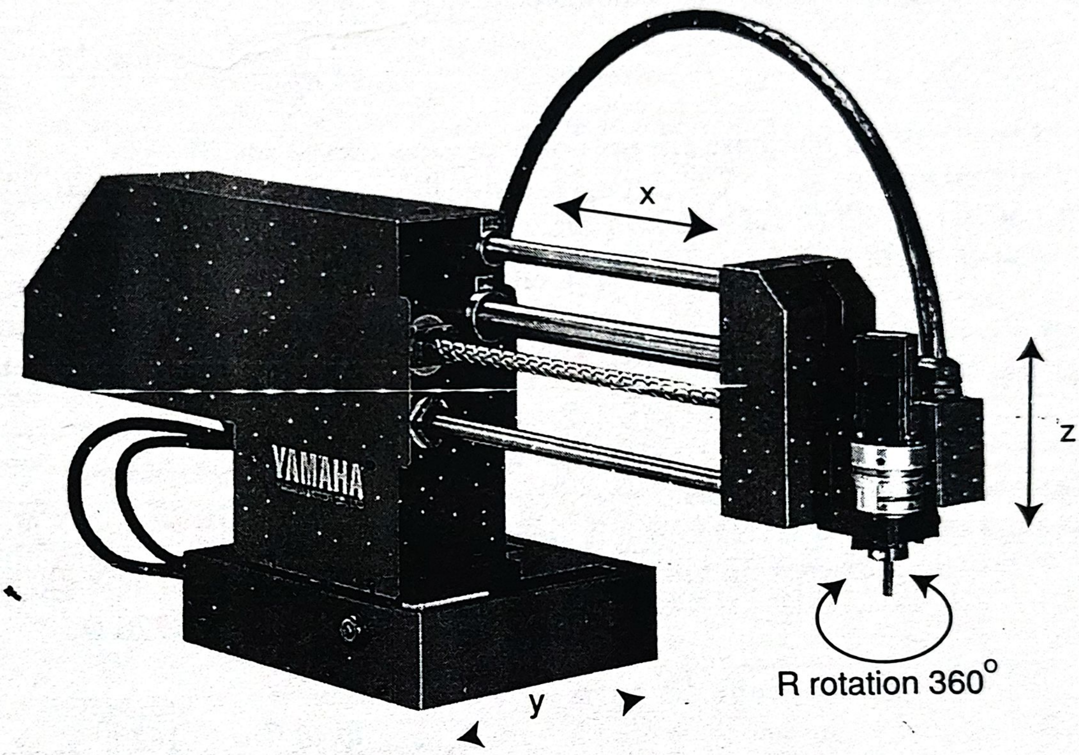

Figure 2.3.16 The Yamaha model YP304A Pick & Place-type robot is a four-axis unit that uses actuator stroke to position the end-of-arm tooling. *(Courtesy of Yamaha Robotics, Inc.)*

with pressure at about one hundred pounds per square inch and hydraulic systems at one thousand to three thousand pounds per square inch.

There are two relationships of particular interest when discussing actuators: the piston velocity of the actuator and the force output of the actuator with respect to the input power. The force output and piston velocity of double-acting cylinders are not the same for extension and retraction strokes. This phenomenon is due to the effect of the rod and is defined by Equations 2.3.1 through 2.3.4.

Extension stroke:

$$\text{force (lb)} = \text{pressure (psi)} \times \text{piston area (in.}^2\text{)} \qquad \text{(Equation 2.3.1)}$$

$$\text{velocity (ft/sec)} = \frac{\text{input flow (ft}^3\text{/sec)}}{\text{piston area (ft}^2\text{)}} \qquad \text{(Equation 2.3.2)}$$

Retraction stroke:

$$\text{force (lb)} = \text{pressure (psi)} \times [\text{piston area (in.}^2\text{)} - \text{rod area (in.}^2\text{)}] \qquad \text{(Equation 2.3.3)}$$

$$\text{velocity (ft/sec)} = \frac{\text{input flow (ft}^3\text{/sec)}}{[\text{piston area (ft}^2\text{)} - (\text{rod area (ft}^2\text{)}]} \qquad \text{(Equation 2.3.4)}$$

The horsepower developed by a cylinder can be found using Equations 2.3.5 or 2.3.6.

$$\text{horsepower} = \frac{\text{piston velocity (ft/sec)} \times \text{force (lb)}}{550} \qquad \text{(Equation 2.3.5)}$$

$$\text{horsepower} = \frac{\text{input flow (gpm)} \times \text{pressure (lb/in.}^2\text{)}}{1714} \qquad \text{(Equation 2.3.6)}$$

Example: A hydraulic cylinder has a piston diameter of 2.0 in., a fluid pressure of 1200 lb/in.^{2}, a flow rate of 142 in.^{3}/min, and a stroke of 10 in. Find the force and the velocity generated by the piston.

Solution

Using Equation 2.3.1:

$$\begin{aligned} \text{force} &= \text{pressure} \times \text{piston area} \\ &= 1200 \times (0.785 \times 2^2) \\ &= 3770\ lb \end{aligned}$$

Using Equation 2.3.2:

$$\text{velocity} = \frac{\text{input flow}}{\text{piston area}} = \frac{142}{3.14} = 45.2\ inch/min = 0.0628\ ft/sec$$

Note: The length of the stroke has no bearing on the operating force and velocity.

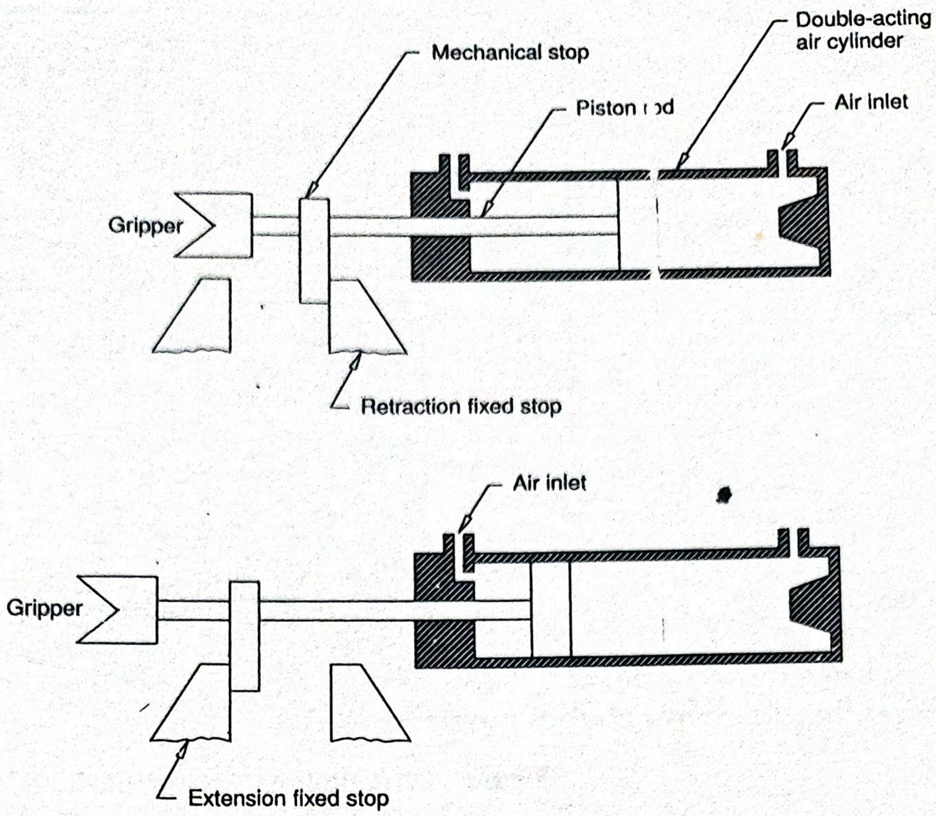

Figure 2.3.17 Fixed stops arrangement for motion position

Fixed stops are often blocks used to stop the extension or retraction of an actuator before it reaches its full stroke. Figure 2.3.17 shows such an installation.

Variable stops are often screws, collars, or sliding blocks that can be adjusted so that they can vary the stroke of the actuator. Figure 2.3.18 shows an example of this type of robot stop.

A **stepper motor** is a DC motor that rotates through a cycle or through part of a cycle in response to an electrical pulse. Stepper motors are designed to output incremental motion with readily available range from 90° down to 0.72°. Their positioning accuracy is 1%–5% of the step angle, with 3% being a common stated accuracy. Stepper motor speed is usually specified as steps per second (sps) as opposed to revolutions per minute (rpm). Equations 2.3.7 to 2.3.9 show the conversion from step angle to steps per revolution and from sps to rpm:

$$\text{Steps / revolution} = \frac{360}{\text{step angle (degrees)}} \qquad \text{(Equation 2.3.7)}$$

$$\text{rpm} = \frac{60\ (\text{sps})}{\text{steps/revolution}} = 1/6\ (\text{sps})\ (\text{step angle}) \qquad \text{(Equation 2.3.8)}$$

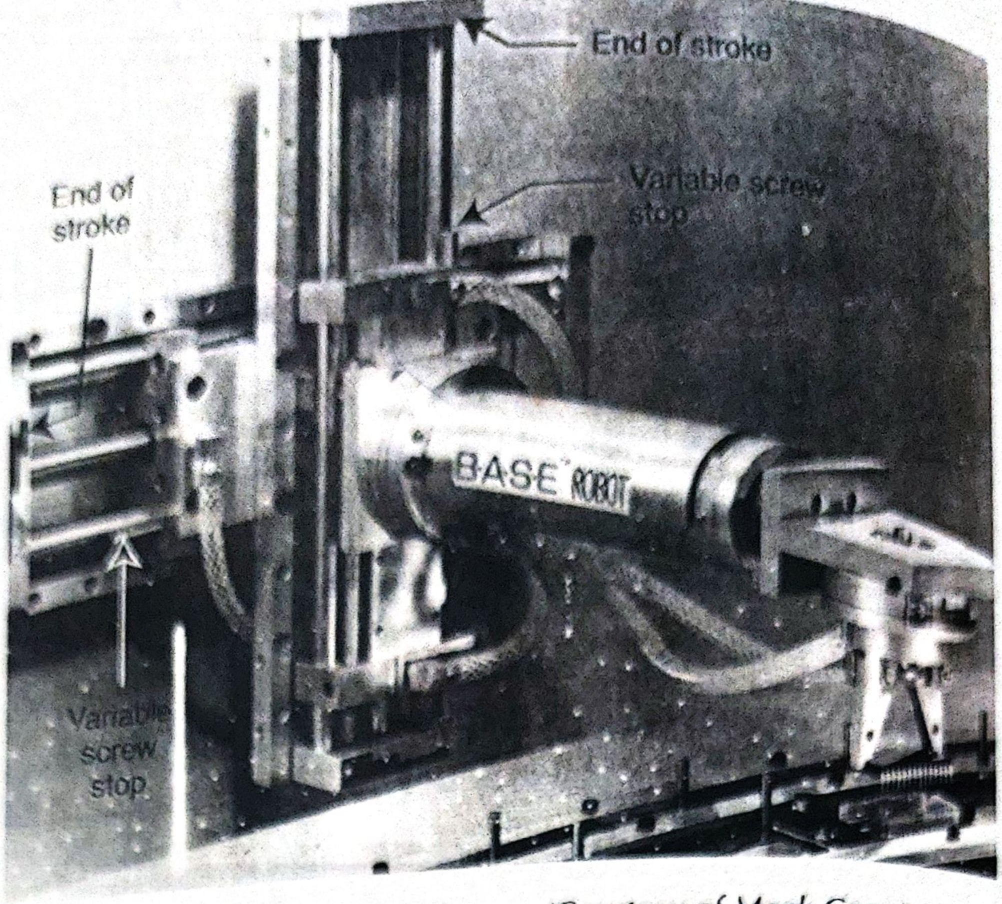

Figure 2.3.18 Robot with variable hard stops *(Courtesy of Mack Corp.)*

$$sps = \frac{6\ (rpm)}{(step\ angle)} \qquad \text{(Equation 2.3.9)}$$

Stepper motors are available to run as fast as 5,000 sps with an output torque of 6.25 inch-lbs. A stepper motor is often used to extend a robot arm for gripper positioning. In this case, the motor's rotary motion is converted to linear motion by means of a gear drive or a belt and pulley system. Because the stepper motor has a low torque output, considerable mechanical advantage must be gained from the gear or pulley system in order to move the arm and its tooling effectively. Figure 2.3.19 shows such a stepper motor with a translator control.

The advantages of nonservo control are:

- Low cost
- Ease of operation
- High repeatability within 0.010 in. for small units
- High speed
- Control simplicity

The disadvantages of nonservo control are:

- Lack of speed control and therefore less accuracy.
- Time lost through mechanical changes.
- Position stops of robot require accurate placement.

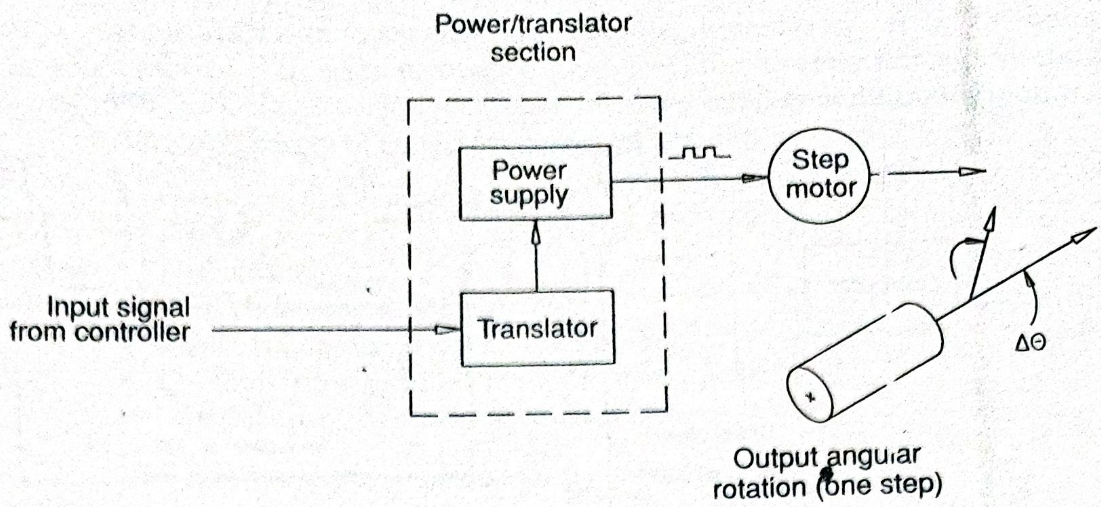

Figure 2.3.19 Stepper motor with translator control

Over half the robots currently in use fall into the nonservo (open loop) classification. Primary application areas served include material handling and machine tending.

Servo (closed loop). The servo robot is a more sophisticated system. The signal from the controller is dependent upon the output of the system. A **servomechanism** is a control system used to detect and correct errors. The system automatically measures the position of each joint and compares this to where it should be. It then utilizes feedback to drive the system to its proper position. Because the system has a self-correcting capability, the desired position of the end effector is stored in the controller memory. This difference allows robots under closed loop control to be programmed to stop at any point in their work envelope. Figure 2.3.20 illustrates a typical **servo system**.

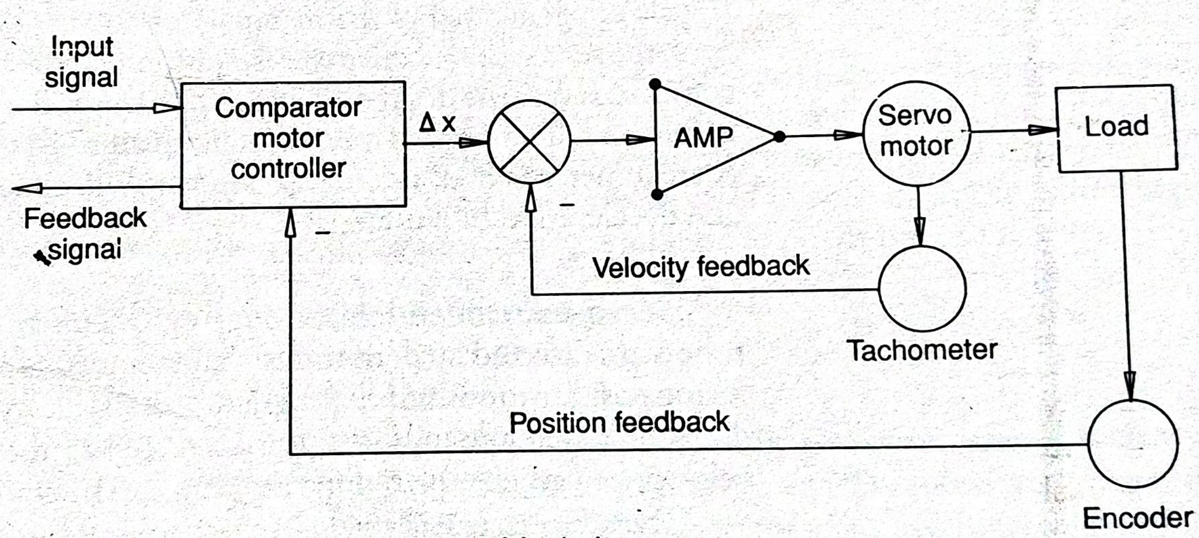

Figure 2.3.20 Typical servo system block diagram

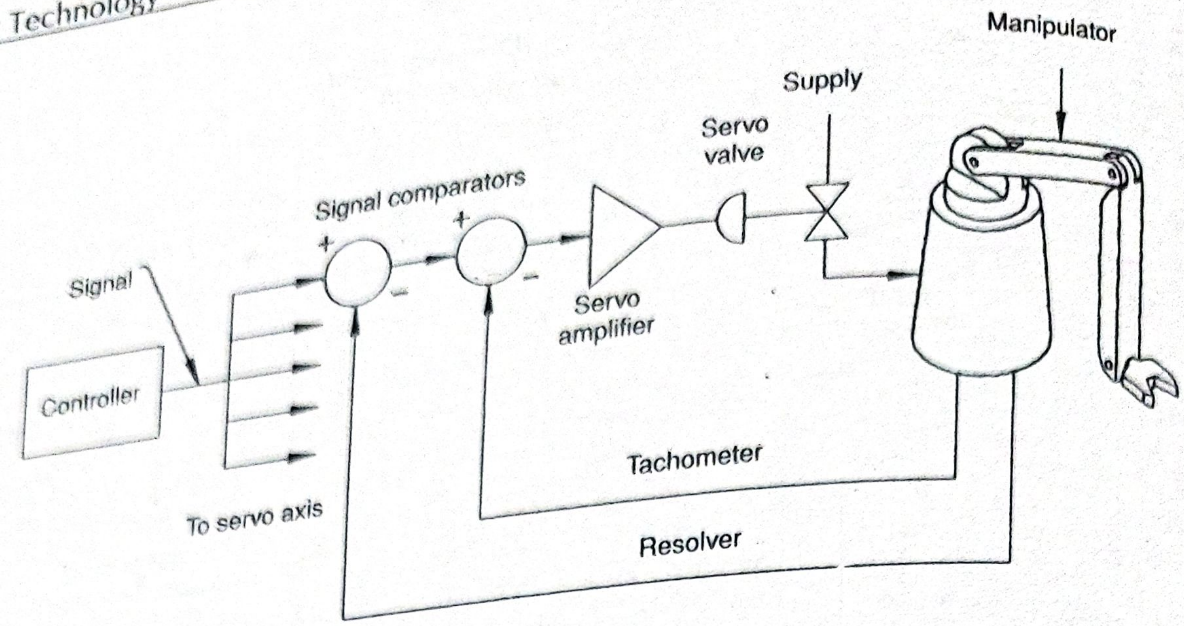

Figure 2.3.21 Actual servo robotic system (closed loop)

Figure 2.3.21 is used to explain the operating principle of the **servo robot**. The diagram is a simplified version of a six-axis robot with a hydraulic power supply.

When the cycle is initiated, the controller addresses the first desired location and interprets the actual locations of the various axes. The desired location signal generated by the controller is compared with the feedback signals from the resolver. The difference in the signals, known as the error signal, is amplified and applied to the servo valve. The valve opens proportionally to the level of the command signal generated by the amplifier. The open valve admits fluid to the actuator on the manipulator. The actuator then moves the manipulator. New signals are generated as the manipulator moves. When the error signal reaches zero, the servo control valve closes, shutting off the flow of fluid. The manipulator comes to rest at the desired position. The controller then addresses the next point in memory. The process is repeated until all steps of the program are completed. A tachometer is used in conjunction with the controller to control acceleration and deceleration of movements.

Servo-controlled (closed loop with controlled path). Servo-controlled robots are directed by a controller that memorizes a sequence of arm and end-effector positions to follow a programmed trajectory or contoured surface. Hundreds or thousands of points can be stored in the computer memory, and the velocity and acceleration along the path can be controlled.

Transducers, called **encoders,** are constructed into the robot arm to convert position data into electrical signals that provide position feedback for each joint.

These feedback signals are compared with the desired position data to direct the robot motion. Velocity data may be computed from the encoder signals and used as an additional feedback signal to assure servo stability and smooth motion.

The advantages of closed loop control are:

- Higher positional accuracy
- Higher speeds
- Higher torque
- Flexible program control
- Ease of changing programmed points
- Capability for complex manufacturing tasks
- Multiple program storage and executions

The disadvantages of closed loop control are:

- Large capital investment
- Sophisticated programming
- User training
- High-skill maintenance

The nonservo robot is further classified as a nonintelligent robot and the servo robot as either intelligent or highly intelligent. The difference between an intelligent and a highly intelligent robot is its level of awareness of its enrichment. (Control systems are discussed in detail in Chapter 8.)

2.4 ROBOT ANATOMY

Robot anatomy is concerned with the physical construction and characteristics of the body, arm, and wrist, which are components of the robot manipulator. Most robots today are mounted on a base. The body is attached to the base and the arm assembly to the body. At the end of the arm is the wrist, which consists of a number of components that allow it to be oriented in a variety of positions. Movements between the various components of the body, arm, and wrist are provided by a series of joints. These joint movements usually involve either rotation or sliding motions (which are described in detail in Chapter 3).

Attached to the robot's wrist is the end effector (or end-of-arm-tooling) that performs the work. The end effector is not considered a part of the robot's anatomy. (The end effector will be discussed in much greater detail in Chapter 5.) The body and arm joints of the manipulator are used to position the end effector, and the wrist joints of the manipulator are all used to orient the end effector.

Robot Configurations

Industrial robots are available in a wide range of shapes, sizes, speeds, load capacities, and other capabilities. The motion characteristics of robots vary, depending upon their mechanical design. The vast majority of today's commercially available robots possess five distinct design configurations:

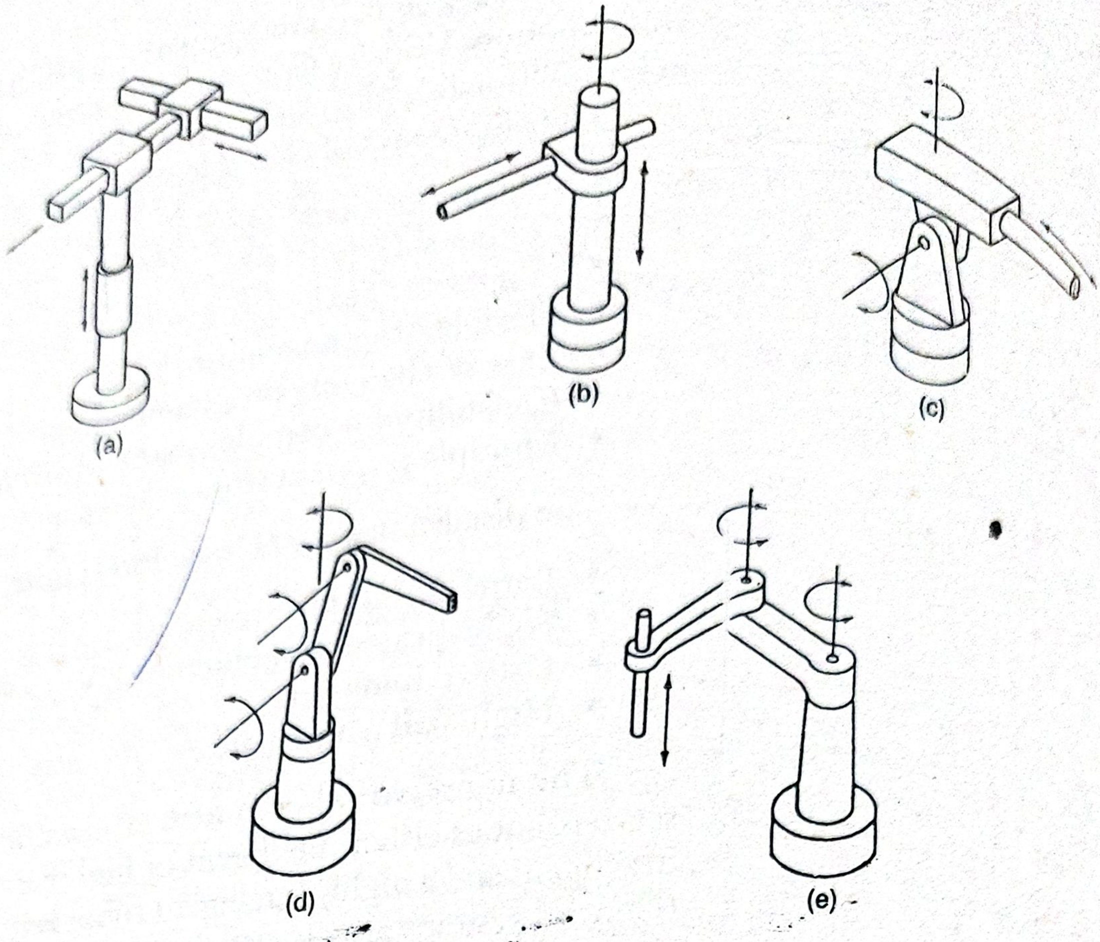

Figure 2.4.1 Five common anatomies of commercial industrial robots: (a) Rectangular, (b) Cylindrical, (c) Spherical, (d) Jointed-arm, and (e) SCARA, or Selectively Compliant Assembly Robot Arm

- Rectangular (or Cartesian)
- Cylindrical (or Post-type)
- Spherical (or Polar)
- Jointed-arm (Articulated or **revolute)**
- SCARA (Selective Compliance Assembly Robot Arm)

The five configurations are illustrated in Figure 2.4.1.

The rectangular configuration, illustrated in (a), uses three perpendicular slides to construct the x, y, and z axes. By moving the three slides relative to one another, the robot is capable of operating within a rectangular work envelope.

The cylindrical configuration, illustrated in (b), uses a vertical column and a slide that can be moved up and 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 retrieving a cylindrical work envelope.

The spherical configuration, illustrated in (c), uses a telescoping arm that can be raised or lowered about a horizontal pivot point. The pivot point is mounted on a rotating base and gives the robot its vertical movement. These various joints provide the robot with the ability to move its arm within a spherical envelope.

The jointed-arm configuration, illustrated in (d), consists of two straight components whose shoulder and elbow joints rotate about horizontal axes corresponding to the human forearm and upper arm. A wrist is attached to the end of the forearm to provide additional joints. Its work envelope is of irregular shape. When it is viewed from the top, it is circular; when viewed from the side, it is circular with an inner scalloped surface due to the limits of the joints.

The SCARA configuration, illustrated in (e), is a special version of the jointed-arm robot whose shoulder and elbow joints rotate about vertical axes instead of horizontal. Its work envelope is cylindrical and much larger than all other configurations, which provides a substantial rigidity in the vertical direction for many essential tasks.

Robots may be attached permanently to the floor of a manufacturing plant, may move along overhead rails (a **gantry** robot), or may be equipped with wheels to move along the factory floor (a mobile robot).

2.5 ROBOT GENERATIONS

For years, people have predicted that robots are about to experience a market growth rate similar to that of the electronic computer. The new generation of computers currently under development should greatly increase the power of artificial intelligence programs. These programs, when applied to robotics, should greatly increase the new robots' abilities.

The trends in sensors are also moving toward miniaturization for compatibility with logic systems and less emphasis on electromechanical systems. New developments include sensor fusion and **smart sensors**, which are capable of microcomputer-based calibration, computation, and decision making.

Expert systems, which are computer programs, utilize artificial intelligence and a knowledge base acquired from expert data to solve problems and make decisions. They are also being used to simplify maintenance and diagnostics for robots. These systems are being used to program **robotic** workcells and to route products dynamically between work cells and other manufacturing systems.

In 1984, the growth rates of the work force and the population throughout the world began to slow down. We are now approaching the time when the size of the work force will actually decline. When this happens, it will become much more difficult to find workers to fill various less-attractive jobs—jobs that robots are ready and waiting to fill. It is now estimated by the RIA that the U.S. robotics industry should see a 25–35 percent growth rate each year.

Voice-activated robots are now being used experimentally to help the physically disabled. They will soon be generally available for helping disabled people in a multitude of ways.

New types of robot actuators will also appear. These might rely on shape-memory alloy wire or other types of artificial muscles.

The fully automated factory has been under development in Japan for some time and should be completed within the near future. Such factories will use robots in areas that require flexibility.

The Japanese government is also working on the fifth generation of electronic computers, in which thousands of microcomputers will work in parallel. It is hoped that this design will greatly increase the intelligence capacity of artificial intelligence programs. Companies in the United States are working on fifth-generation computers as well. Such computer designs will also lead to more-intelligent robots.

The five generations of robot controllers after the high-tech inception in 1960 are described as follows:

1. *First Generation:* Repeating robots. These were generally pneumatically powered "pick and place" robots, with mechanical sequences defining stop points. Revolving drums with cam-and-follower control provided the programming. To reprogram the robot, a new precision cam was installed. It is estimated that more than 90 percent of the early robots belong to this category.
2. *Second Generation:* Hardwired (patch board) controllers provided the first programmable units. In "pick and place" robots, signals were derived from limit switches, proximity switches, and similar devices. These controllers were also applicable to servo control. The electrical system consisted of a bank of relays and the reprogramming for any new job that required rewiring. These controls are still used in simpler pick-and-place robots, and will probably always play a role in robotics as the most economical solution for situations involving only simple motion requirements.
3. *Third Generation:* **Programmable logic controllers (PLC)**, introduced into industry over thirteen years ago, provided a microprocessor-based robotic controller that is easy to reprogram. The controller primarily serves to direct the sequence of robot motions, stop points, gripper actions, and velocity.
4. *Fourth Generation:* When control beyond a PLC is required, a microcomputer may control the entire system, including other programmable machinery in a robot workcell. Whereas PLCs are limited in their programming, minicomputers may utilize a special robot programming language or standard language (such as BASIC, C, or C++) for more-advanced **off-line programming** or **CAD/CAM** and **CIM** interface. Minicomputer-type robots based on artificial intelligence became commercially available at the end of 1980. These controllers now allow integration with vision or tactile sensors.
5. *Fifth Generation:* Robot controllers will involve complete artificial intelligence (AI), miniaturized sensors, and decision-making capabilities. Some rudimentary efforts have already been made in this direction, as previously explained, with some AI algorithms (such as for bin picking and search routines for gripper positioning) now available. An artificial biological robot might provide the impetus for sixth and higher generation robots. A visualization of these overlapping generations of robots is shown in Figure 2.5.1.

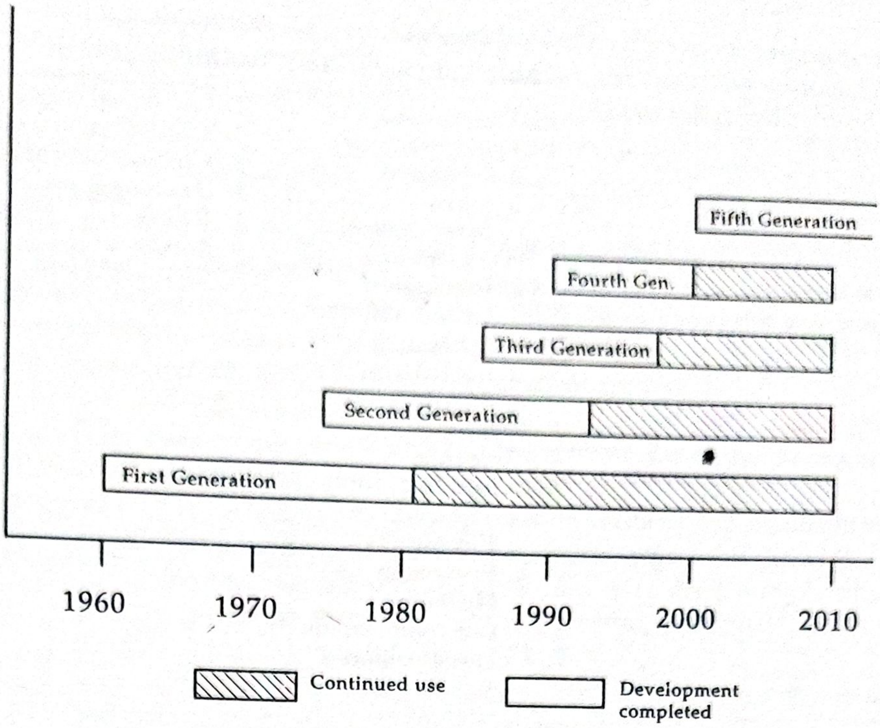

Figure 2.5.1 Robot generations

2.6 ROBOT SELECTION

As with human workers, robots have individual characteristics, features, and capabilities. Therefore, it is imperative that robots be matched properly by capabilities to task requirements. An objective approach to robot selection provides fewer restrictions in system design by allowing for the optimum system design to be achieved, regardless of the specific robot needed. The system design, when accomplished, establishes the requirements for the robot within the workplace. The ideal approach then is not to choose a robot first, but to wait until all task requirements have been defined before the final choice of robot is made.

Process Knowledge

In designing systems, we can observe the manual operations for guidance in the concepts for an automated approach. The point here is *not* necessarily to attempt to duplicate all that the human worker does, but rather to analyze the work elements in light of human capabilities and how they will need to be restructured for a robot. In task restructuring, we can exploit the capabilities of the robot.

To arrive at the proper conclusion concerning application development, system design, and task restructuring, it is necessary to start with process knowledge. With a thorough knowledge of the part and the manner in which it is processed, attention can focus on improved efficiency within the process that may be achieved

Table 2.1 Criteria for Robot Selection

Technical Issues	Nontechnical issues
1. Type	1. Cost & benefit consideration
a. Nonservo	2. Commonality of equipment
b. Servo	3. Training & maintenance requirements
c. Servo-controlled	4. Reliability
2. Work envelope	5. Service
a. Rectangular	6. "Systems" Help
b. Cylindrical	7. Safety
c. Spherical	
d. Jointed-arm	
e. SCARA	
3. Payload	
4. Cycle time	
5. Repeatability	
6. Drive	
a. Electric	
b. Pneumatic	
c. Hydraulic	
d. Any combination	
7. Unique capabilities	

through part design modifications. Alternatively, the efficiency improvements may come from reversing or combining processes, implementation of better production planning and scheduling, better material flow by grouping successive operations together, grouping families of parts to be manufactured in flexible manufacturing cells, and utilizing other group technology approaches.

Special attention should be given to end-effector concepts as the system elements are designed during stages of application development. Keeping in mind the end-effector workplace, it is appropriate to rank tooling design high on the list of critical system elements.

Determining the proper robot type and options necessary for the task can best be made by following the consideration of all the aforementioned issues. Thinking in generic terms about the robot best suited for a task based on such technical issues as work envelope, control system, power supply, payload, velocity, accuracy, and repeatability, and such nontechnical issues as cost, reliability, vendor support, and experience, robot selection is simplified, as shown in Table 2.1.

(To evaluate the potential of a robot selection in detail, see Chapter 12.)

Safety

Safety is of such importance that it is not mentioned as a phase of process knowledge because human workers and robots interface issues need to be addressed in all design, manufacture, and implementation phases of a robot project. Properly designed systems do not allow a human worker and a robot to share the same work space unless the greatest amount of care has been taken to ensure protection of the human worker through proper presence/position-detection sensors. Physical barriers are the safest of all possible approaches. (Robot safety is discussed extensively in Chapter 11.)

2.7 SUMMARY

Robot technology is an applied science that is referred to as a combination of machine tool fundamentals and computer applications. To describe this technology, we must define the variety of technical features about the way a robot is constructed and works and the factors that influence its selection.

The basic components of an industrial robot are:

1. The manipulator, which provides motions similar to the human arm and hand and physically performs the work
2. The end effector, which is equipped with various types of attachments to meet special handling requirements to actually perform the work
3. The power supply, which is the prime mover to drive the robot by independent actuators and controls using electric, pneumatic, or hydraulic sources
4. The control system, which is the brain of the robot and stores data to initiate and terminate movements of the manipulator

The control systems used in the United States to position the tooling are classified into three major categories: nonservo, servo, and servo-controlled.

Robot anatomy is concerned with the physical construction and operation of the manipulator and has five basic configurations: rectangular, cylindrical, spherical, jointed-arm, and SCARA.

So far, there have been five generations of robot controllers, and we are merging now to sixth, seventh, and even higher generations. Robots with increasing intelligence, sensory capability, dexterity, and sophisticated control systems have become the dominant factor in modern manufacturing.

The three factors that influence the selection of robots in manufacturing are:

1. Dynamic properties and performance
2. Economics
3. Safety

2.8 REVIEW QUESTIONS

2.1 What are the general characteristics of an industrial robot?
2.2 What are the basic components of an industrial robot?
2.3 What is the primary function of a manipulator?
2.4 What is mounted on the end of a manipulator?
2.5 What kind of power sources are used for industrial robots?
2.6 What controls the motion of the robot's manipulator and how is it accomplished?

2.7 What are the number of joints or movable axes present in a manipulator called?

2.8 What are the three orientation axes in the wrist called?

2.9 What is the area that represents the maximum extent of the robot's manipulator called?

2.10 What is the measure of how well the controller can drive the robot's arm back to a taught point called?

2.11 What is the maximum rate at which the robot can move the TCP to a specified location called?

2.12 List six end-effector attachments.

2.13 What methods of path motion are used in industrial robots?

2.14 What are feedback devices and how are they operated?

2.15 What are the five design configurations of industrial robots?

2.16 List the three factors that influence the selection of robots in manufacturing.

2.9 PROBLEMS

2.1 An air cylinder is to be used to actuate the linear arm joint for a polar configuration robot. The piston diameter is 2.0 in., the air pressure is 100 psi, and the airflow rate is 0.273 feet^3/min. Determine the force generated by the piston and the velocity during the forward stroke.

2.2 A double-acting hydraulic cylinder is operated at 1000 psi pressure. The cylinder has a 6-in. bore and a 12-in. stroke. The piston rod is 1.5 in. in diameter. Find the "push" and "pull" force exerted by the piston rod.

2.3 A pump supplies oil at 20 gpm to a 2-in. diameter double-acting hydraulic cylinder. If the load is 1000 lbs (extending and retracting) and the rod diameter is 1 in., find:

a. The hydraulic pressure during the extending stroke
b. The piston velocity during the extending stroke
c. The cylinder horsepower during the extending stroke
d. The hydraulic pressure during the retraction stroke
e. The piston velocity during the retraction stroke
f. The cylinder horsepower during the retraction stroke

2.4 A stepper motor runs at 1500 rpm with a step angle of 1.8°. Determine the motor's speed in steps/sec.

2.5 A stepper motor runs at 2500 sps with a step angle of 1.8°. Determine the motor's speed in rpm.

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