CHAPTER 3

Robot Classification

3.0 OBJECTIVES

After studying this chapter, the reader should:

1. Be aware of robot classification
2. Be acquainted with the manipulator arm geometry
3. Understand the degrees of freedom of a robotic system
4. Recognize the types of power sources used in current robots
5. Be familiar with types of motion
6. Know a robot's path control
7. Understand the intelligence level of robots

3.1 CLASSIFICATION

Industrial robots can be classified into six categories according to their characteristics:

1. Arm geometry: rectangular; cyclindrical; spherical; jointed-arm (vertical); joined-arm (horizontal)
2. Degrees of freedom: robot arm; robot wrist
3. Power source: electrical; pneumatic; hydraulic; any combination
4. Types of motion: slew motion; joint-interpolation; straight-line interpolation; circular interpolation
5. Path control: limited-sequence; point-to-point; continuous path; controlled-path
6. Intelligence level: low-technology (nonservo); high-technology (servo)

3.2 ARM GEOMETRY

The robot manipulator may be classified according to the type of axis movement needed to complete a task. Because we live in a three-dimensional world, the general robot must be able to reach a point in space within three axes by moving forward and backward, to the left and right, and up and down. This can be accomplished in several ways. The simplest way is by identifying those movements as robot arm geometry and describing them in the coordinate system as follows.

Rectangular-Coordinated

A rectangular- or **cartesian**-coordinated robot manipulator has three linear axes of motion or coordinates. The first coordinate, x, might represent left and right motion; the second, y, may describe forward and backward motion; the third, z, generally is used to depict up-and-down motion. The disadvantage of this design

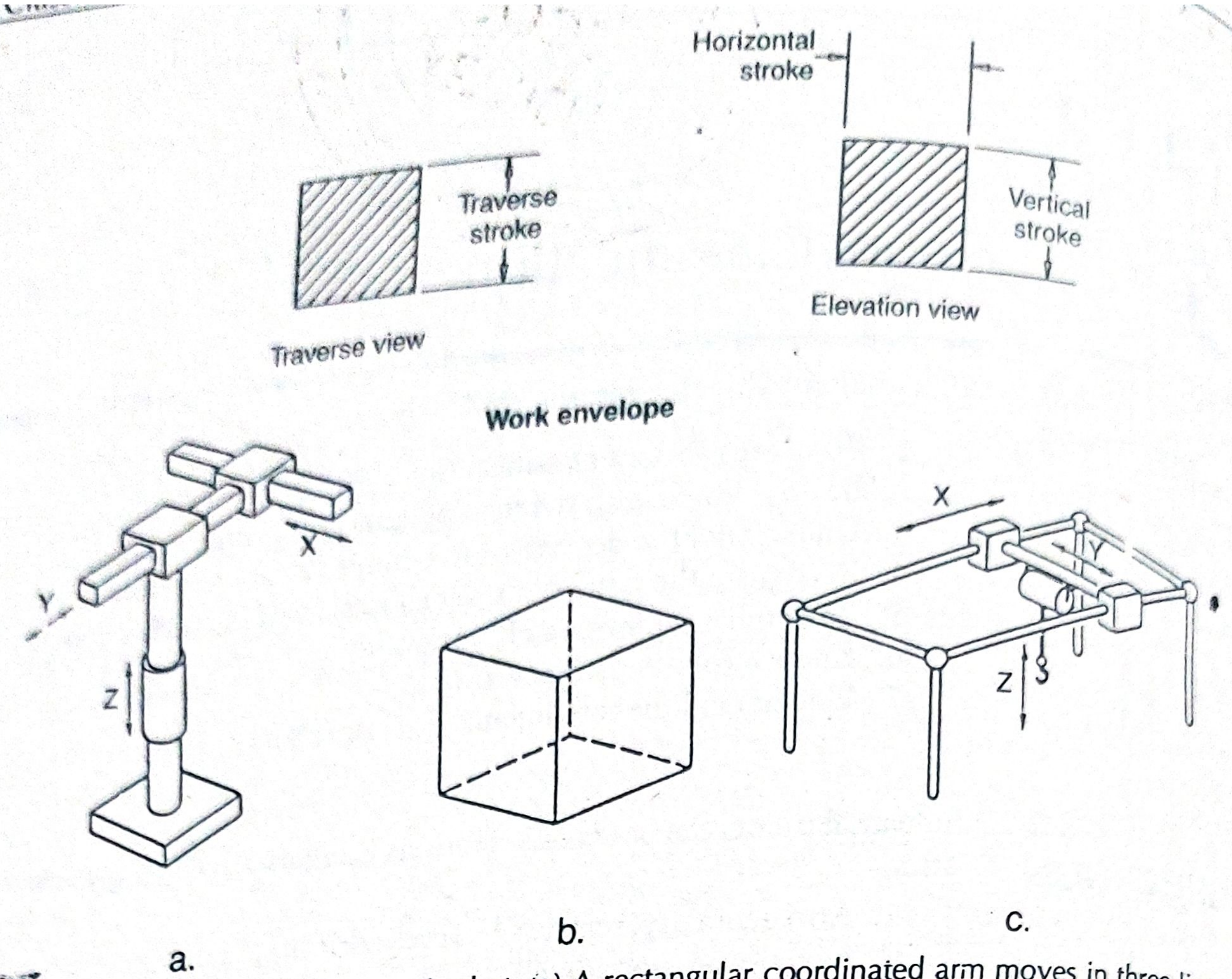


Figure 3.2.1 Rectangular or Cartesian-coordinated robot: (a) A rectangular coordinated arm moves in three linear axes. (b) The box-shaped work envelope within which a rectangular manipulator operates. (c) Overhead crane movements are similar to those of a rectangular-coordinated arm.

is that the motion of each axis is limited to one direction and makes it independent of the other two. However, equal increments of motion may be achieved in all axes by using identical actuators.

The work envelope of a rectangular robot is a cube or rectangle, so that any work performed by the robot must only involve motions inside this space. The work envelope of a robot is the outline of the work volume region. When a robot is mounted from above in a bridgelike frame, it is referred to as a gantry robot, otherwise called traverse-type. Figure 3.2.1 shows (a) a typical rectangular-coordinated robot, (b) its work envelope, and (c) its work area similar to an overhead crane, referred to as a gantry robot. An actual rectangular-coordinated robot is shown in Figure 3.2.2.

The power for movement in the x, y, and z directions is provided by linear actuators in small robots or by ball-screw-drives in large systems. Rectangular-coordinated robots have the following advantages:

- They can obtain large work envelopes because traveling along the x axis, the volume region can be increased easily.

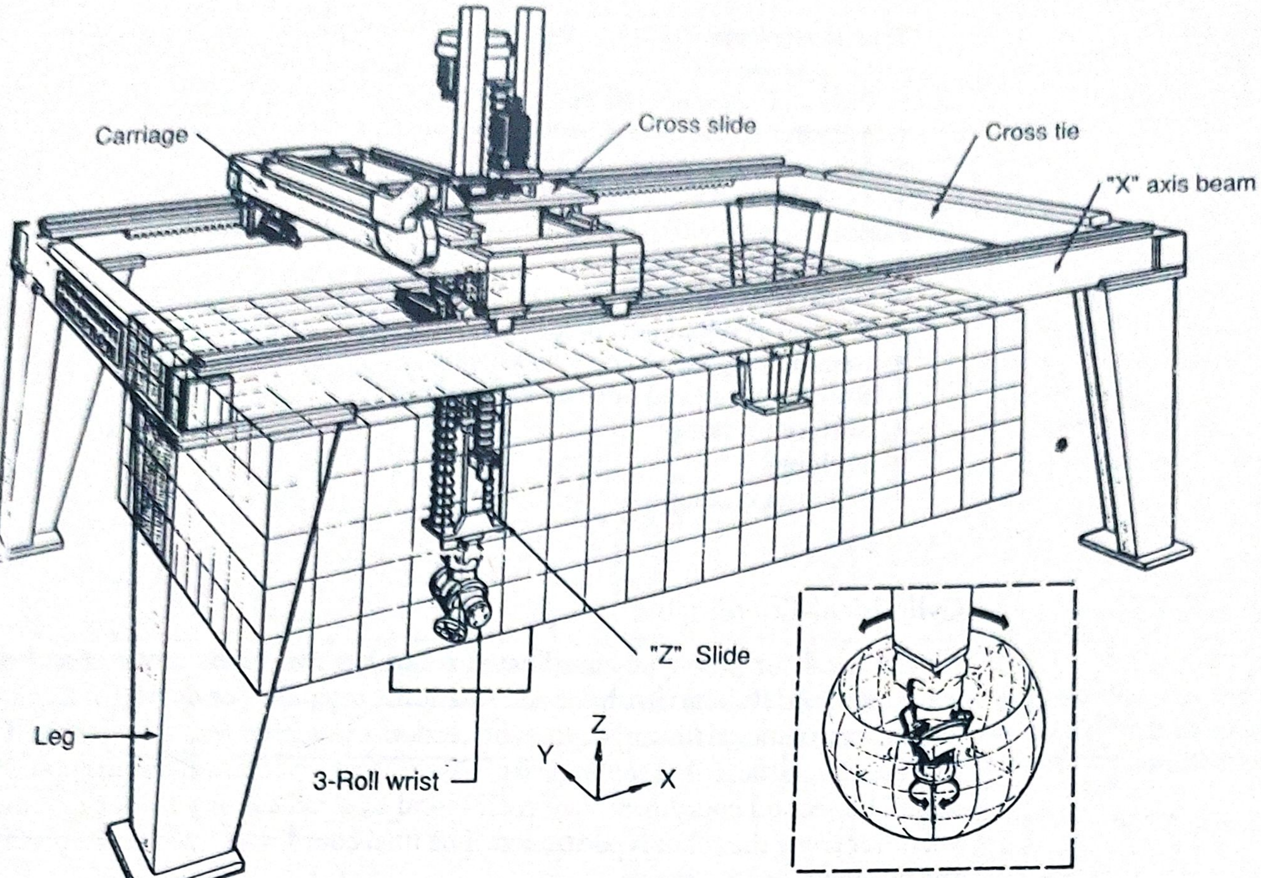


Figure 3.2.2 An actual rectangular gantry robot model T^3 886, manufactured by Cincinnati Milacron. This unit can lift loads up to198 pounds and has six electrically actuated servo-controlled axes. *(Source: Cincinnati Milacron)*

- Their linear movement allows for simpler controls.
- They have a high degree of mechanical rigidity, accuracy, and repeatability due to their structure.
- They can carry heavy loads because the weight-lifting capacity does not vary at different locations within the work envelope.

Rectangular-coordinated robots have the following disadvantages:

- They makes maintenance more difficult for some models with overhead drive mechanisms and control equipment.
- Access to the volume region by overhead crane or other material-handling equipment may be impaired by the robot-supporting structure.
- Their movement is limited to one direction at a time.

Typical applications for rectangular robots include:

- Pick-and-place operations
- Adhesive applications (mostly long and straight)
- Advanced munitions handling
- Assembly and subassembly (mostly straight)
- Automated loading CNC lathe and milling operations
- Inspection
- General machining operations
- Nuclear material handling
- Remotely operated decontamination
- Robotic X-ray and neutron radiography
- Surface finishing
- Welding
- Waterjet cutting

Cylindrical-Coordinated

A cylindrical- or post-type-coordinated robot has two linear motions and one rotary motion. Robots that have one rotational capability or degree of freedom and two translational (linear) degrees of freedom can achieve variable motion. The first coordinate describes the angle θ of base rotation, perhaps about the up-down axis. The second coordinate may correspond to a radical or y in-out motion at whatever angle the robot is positioned. The final coordinate again corresponds to the up-down or z position.

The **cylindrical-coordinated** robot shown in Figure 3.2.3 can reach any point in a cylindrical volume of space, although a central portion of the space must be devoted to the robot and limits to the full rotation may also be imposed.

Its rotational ability gives the advantage of moving rapidly to the point in the z plane of rotation. An actual cylindrical-coordinated robot is shown in Figure 3.2.4, where its smallest possible increment of change, which is called resolution, is not usually equal in its three axes of motion. The resolution of the base rotation is expressed in terms of an angular measurement, and the resolution of the linear axis is expressed in terms of linear increments.

A cylindrical-coordinated robot generally results in a larger work envelope than a rectangular robot manipulator. These robots are ideally suited for pick-and-place operations.

Some advantages of the cylindrical-coordinated robots are:

- Their vertical structure conserves floor space.
- Their deep horizontal reach is useful for far-reaching operations.
- Their capacity is capable of carrying large payloads.

Some disadvantages of cylindrical-coordinated robots are:

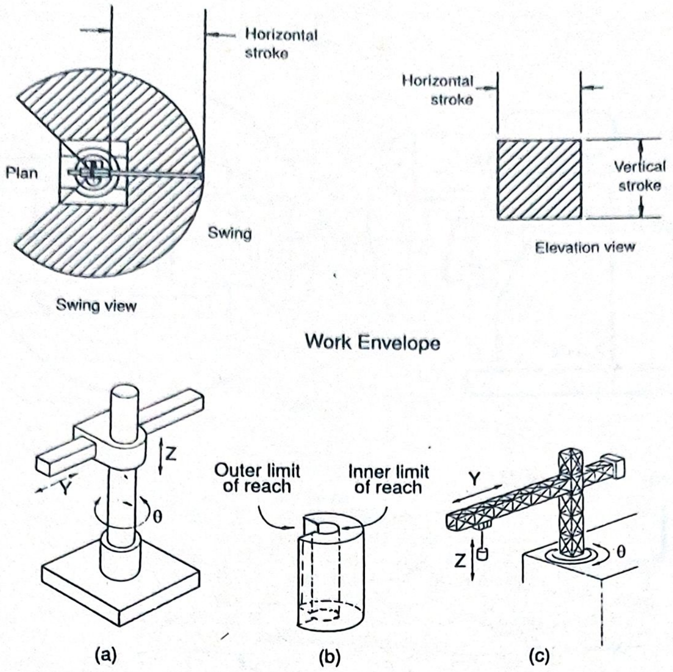
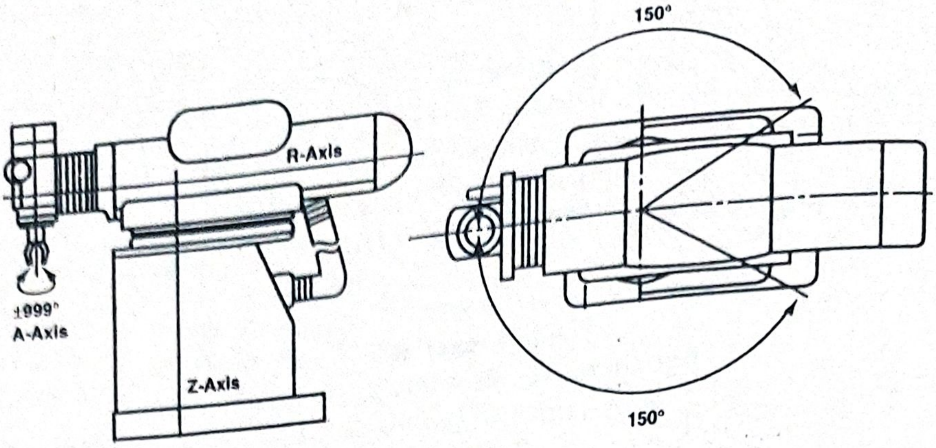


Figure 3.2.3 Cylindrical-coordinated robot: (a) A cylindrical-coordinated arm rotates about its base, moves in and out, and up and down. (b) The space between the two cylinders shown is the work envelope occupied by a cylindrical-coordinated manipulator. (c) The movements of a construction crane on top of a tall building are similar to those of a cylindrical-coordinated manipulator.

- Their overall mechanical rigidity is lower than that of the rectilinear robots because their rotary axis must overcome the inertia.
- Their repeatability and accuracy are also lower in the direction of rotary movement.
- Their configuration requires a more sophisticated control system than the rectangular robots.

Typical applications for cylindrical robots include:

- Assembly
- Coating applications
- Conveyor pallet transfer
- Die casting
- General material handling
- Foundry and forging applications
- Inspection molding
- Investment casting
- Machine loading and unloading
- Meat packing
- Pick-and-place operations



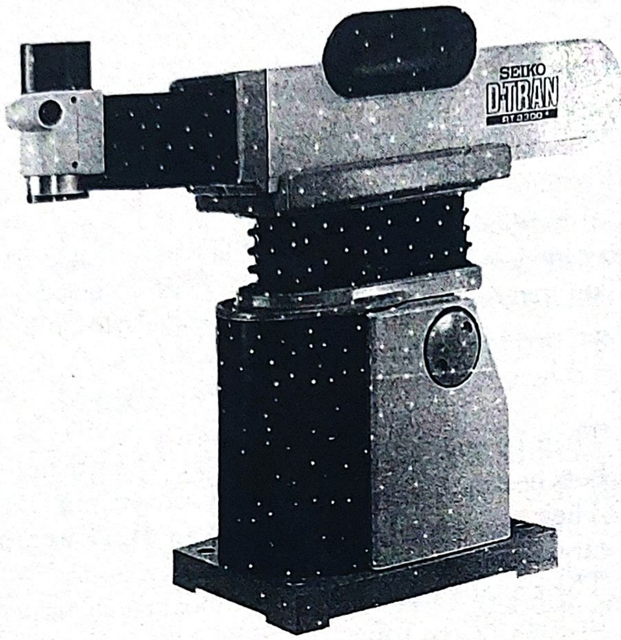


Figure 3.2.4 A high-speed cylindrical robot model RT3300, manufactured by Seiko Instruments. This robot is a four-axis multitasking unit with AC servo-controlled motors and can handle loads up to twenty-seven pounds. *(Courtesy of Seiko Instruments USA, Inc.)*

Spherical-Coordinated

A spherical- or polar-coordinated robot has one linear motion and two rotary motions. The work volume or envelope is shaped like a section of a sphere with upper and lower limits imposed by the angular rotations of the arm. A central core of the work volume is omitted to accommodate the robot base. A pie-shaped section may also be omitted to accommodate the rearward motion of the arm or to provide a safe operating position for the operator.

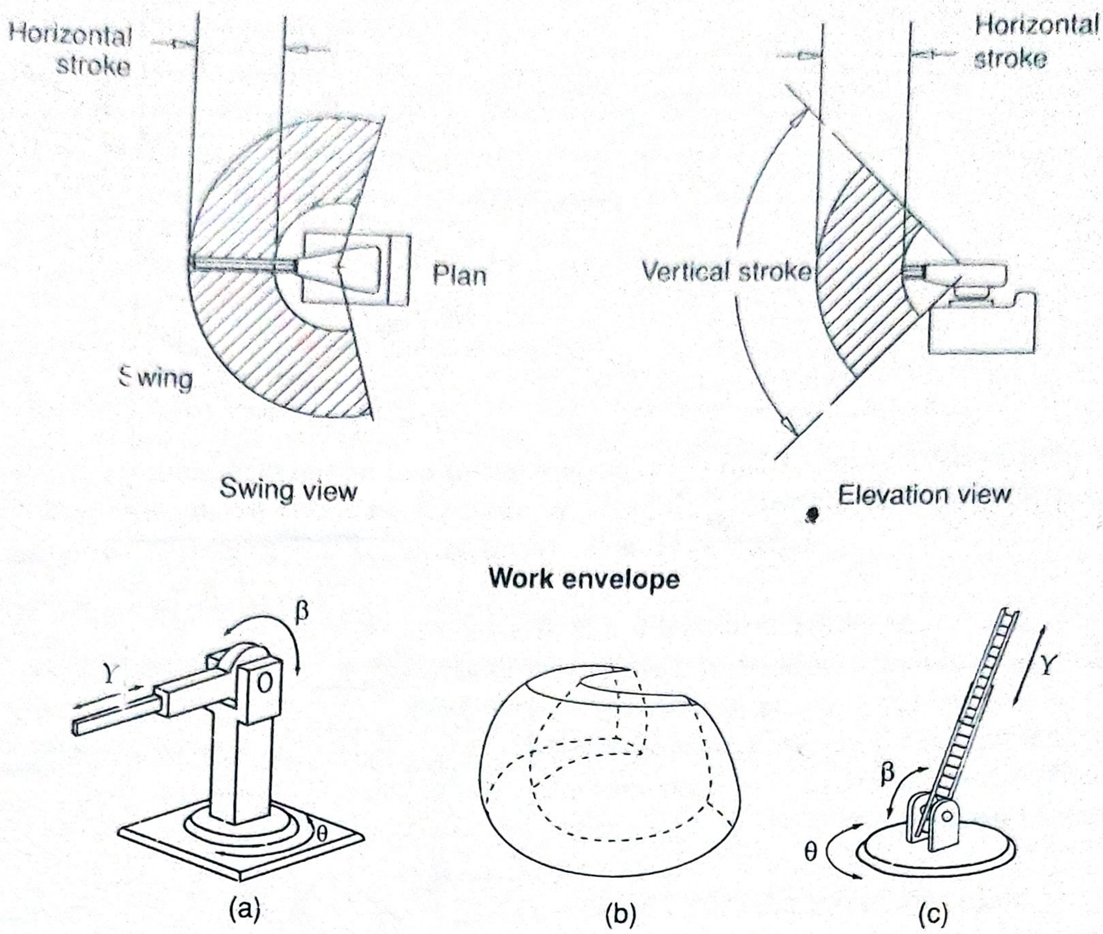
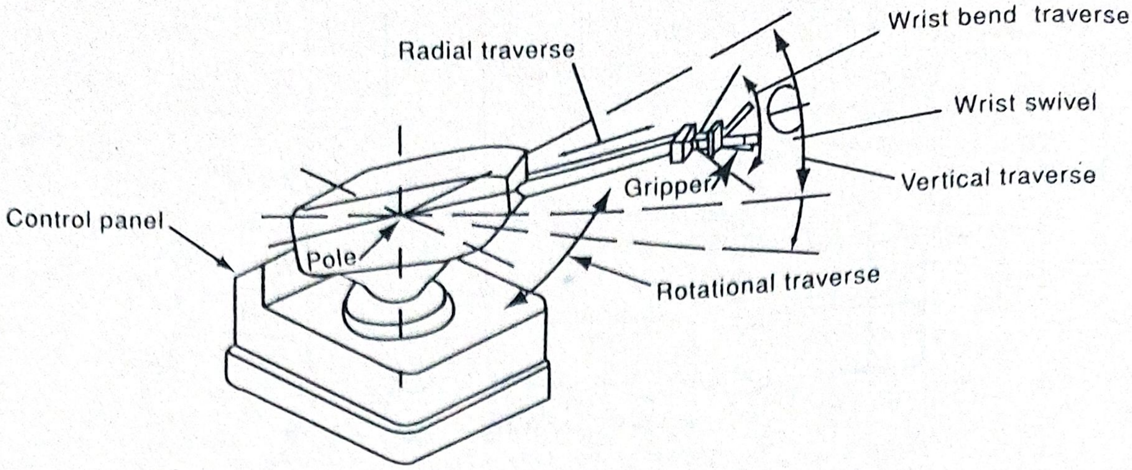


Figure 3.2.5 Spherical- or polar-coordinated robot: (a) A polar- or spherical-coordinated manipulator rotates about its base and shoulder and moves linearly in and out. (b) The work envelope of a polar-coordinated manipulator is the space between the two hemispheres. (c) A ladder on a hook-and-ladder truck has movements similar to those of a polar-coordinated manipulator.

The **spherical-coordinated** robot, shown in Figure 3.2.5, reaches any point in space through one linear and two angular motions. The first motion corresponds to a base rotation about a vertical axis. The second motion corresponds to an elbow rotation. The third motion corresponds to a radial, or in-out, translation. The two rotations can point the robot in any direction and permit the third motion to go directly to a specified point. The points that can be reached by the spherical-coordinated robot include the volume of a globe or sphere. An actual spherical-coordinated robot is shown in Figure 3.2.6. A spherical-coordinated robot generally provides a larger work envelope than the rectilinear or cylindrical robot. The design is simple and gives good weight-lifting capabilities. This configuration is suited for applications where a small amount of vertical movement is adequate, such as loading and unloading a punch press.



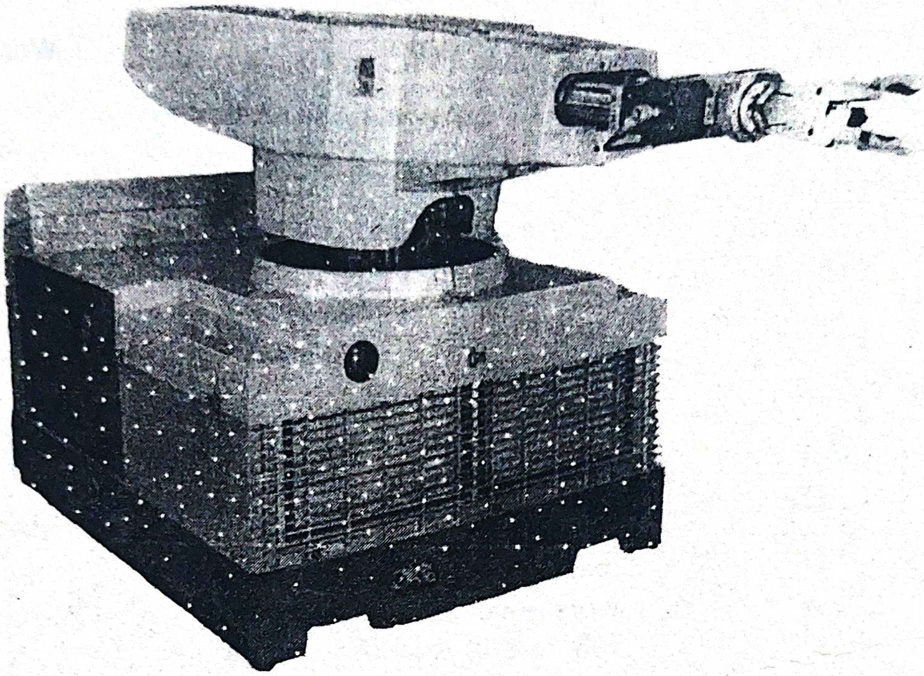


Figure 3.2.6 An actual spherical-coordinated robot, series 2000, manufactured by Unimation Inc., with six servo axes and a payload capacity of three hundred pounds. It is used for die casting, injection molding, forging, machine tool loading, heat treating, glass handling, dip coating, press loading, and material transfer.

The advantages and disadvantages listed for cylindrical-coordinated robots can also be applied to spherical, with the following exceptions: Cylindrical is more vertical in structure, whereas spherical yields a low and long machine size to provide the horizontal reach; also, their vertical movement is limited.

Typical applications for spherical robots include:

- Die casting
- Dip coating
- Forging

- Glass handling
- Heat treating
- Injection molding
- Machine tool loading
- Material transfer
- Parts cleaning
- Press loading
- Stacking and unsticking

Jointed-Arm-Coordinated

A jointed-arm or revolute (often referred to as **anthropomorphic** or human-like) coordinated robot performs in an irregularly shaped work envelope and comes in two basic configurations: vertical and horizontal.

Vertical. The vertical jointed-arm robot has three rotary motions to reach any point in space. This design is similar to the human arm, which has two links, the shoulder and the elbow, and positions the wrist by rotating the base about the z axis. The first rotation, therefore, is about the base; the second rotation is about the shoulder in a horizontal axis; and the final motion is a rotation of the elbow, which may be about a horizontal axis, but the axis may be at any position in space determined by the base and shoulder rotations.

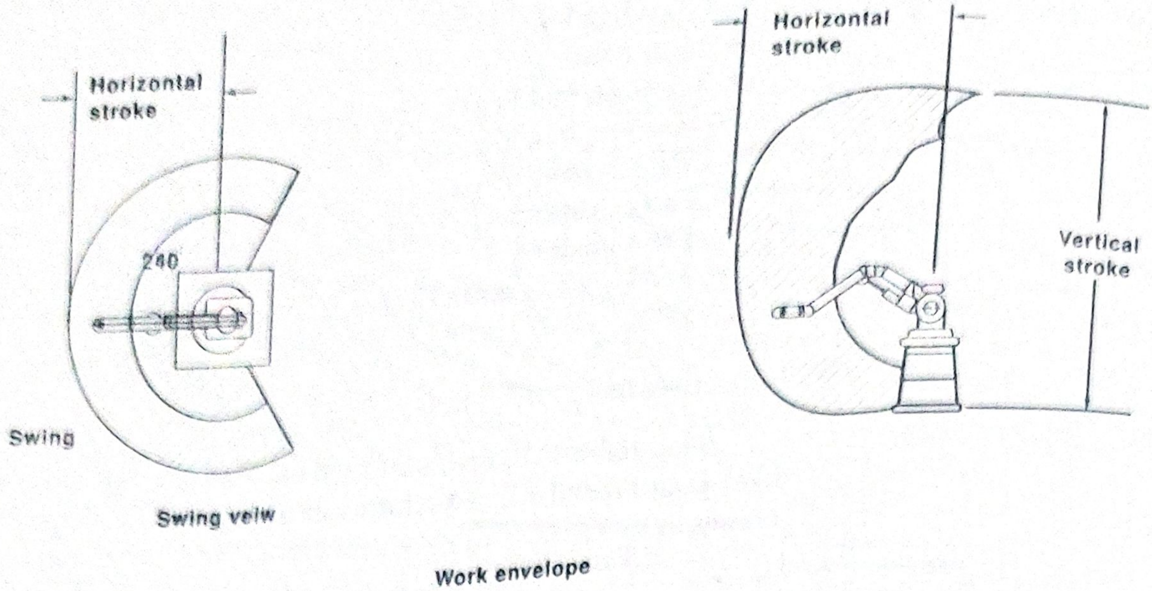
The work envelope is circular when viewed from the top of the robot. When looked at from the side, the envelope has a circular outer surface with an inner scalloped surface due to the limits of the joints. The vertical jointed-arm robot, typically called tear drop, is shown in Figure 3.2.7.

This type of robot can move at high speeds in various directions and has a greater variety of angles of approach to a given point; therefore, it is very useful for painting and welding applications. An actual anthropomorphic robot is shown in Figure 3.2.8.

Horizontal. The horizontal jointed-arm robot generally reaches any point in space through one linear (vertical) motion and two rotary motions. Also called the SCARA (Selective Compliance Assembly Robot Arm), this robot has two horizontally jointed-arm segments fixed to a rigid vertical member (base) and one vertical linear motion axis. The first rotary motion corresponds to the shoulder about its vertical axis. The second rotary motion corresponds to the elbow also about its vertical axis, and the third (linear) motion corresponds about the vertical up-down z axis.

The horizontal jointed-arm robot (SCARA) is shown in Figure 3.2.9. One particularly attractive feature of this robot is that it is extremely useful in assembly operations where insertions of objects into holes are required. The SCARA robot was developed at Yamanashi University in Japan in 1978 for parts assembly work.

The jointed-arm robot has several advantages. It is by far the most versatile configuration and provides a larger work envelope than the rectangular-, cylin-



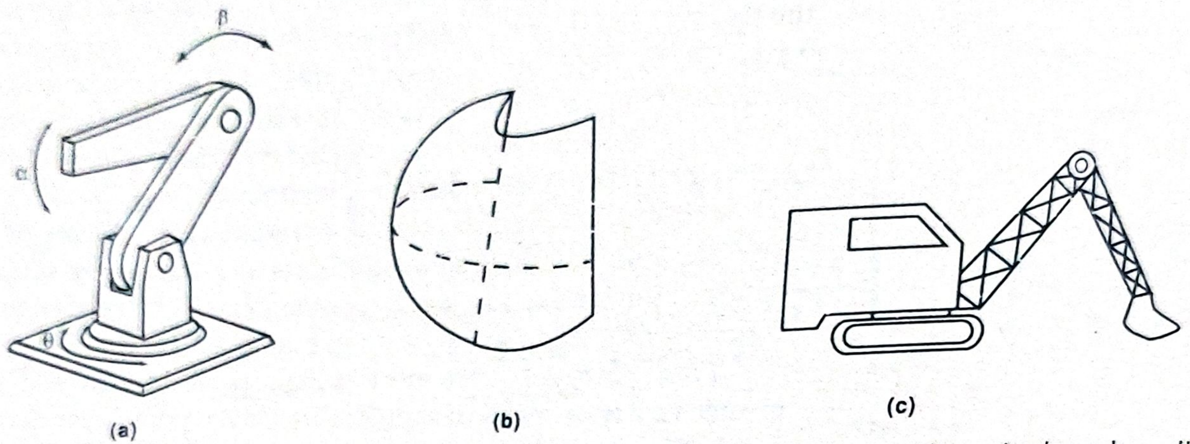


Figure 3.2.7 A jointed-arm or articulated-coordinated robot: (a) A jointed-arm-coordinated manipulator has all three axes rotational. (b) The area between the sphere and the column (representing the base support) is the work envelope for the jointed-arm manipulator. The jointed-arm manipulator can reach above and below an obstacle. (c) A power shovel has movements similar to those of a jointed-arm manipulator.

drical- or spherical-coordinated robots. It occupies minimum floor space and achieves deep horizontal reach. The high positioning mobility at the end-of-arm-tooling allows the arm to reach into enclosures and around obstructions. An actual SCARA robot is shown in Figure 3.2.10.

The drawback of this type of robot is that it requires a very sophisticated controller because the programming is more complex. Also, different locations in the work envelope can affect accuracy, load-carrying capacity, dynamics, and repeatability of movement. This configuration can also become less stable when the arm approaches its maximum reach, but this can be overcome by the addition of feedback controls.

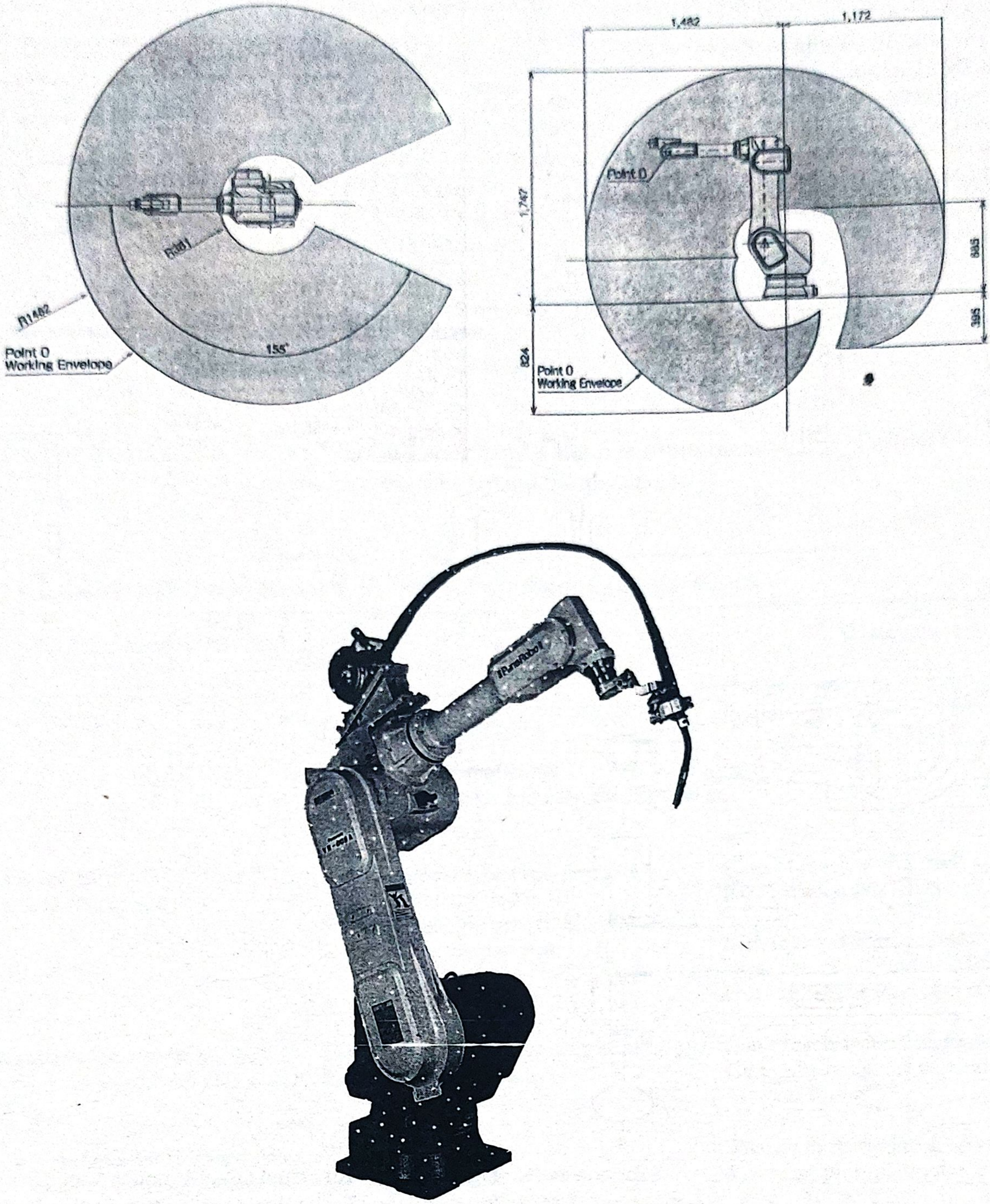
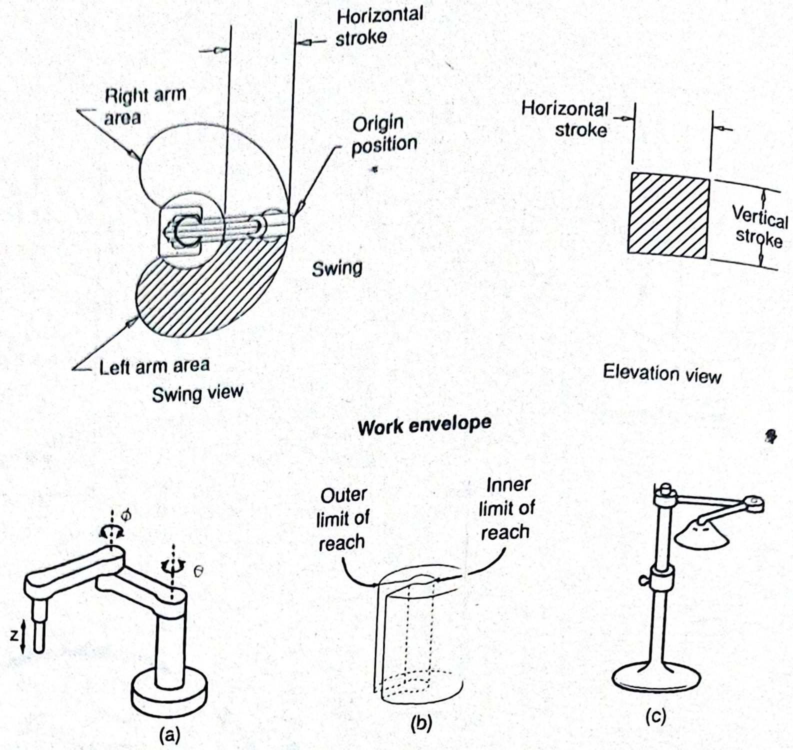


Figure 3.2.8 An actual vertical jointed-arm or articulated-coordinated robot model VR-008A manufactured by Matsushita Industrial Equipment Co., Ltd., with six rotational axes and exceptional wide working envelope for flexible, quick, smooth, and vast variety of welding operations *(Courtesy of Panasonic Factory Automation, Division of Matsushita Corp.)*

Figure 3.2.9 A horizontal or SCARA robot: (a) A SCARA robot rotates in two axes in the horizontal plane and moves linearly up and down. (b) The work envelope for the SCARA manipulator is the space between two cylinders, which can reach around obstacles. (c) A folding lamp has movements similar to those of a SCARA manipulator.



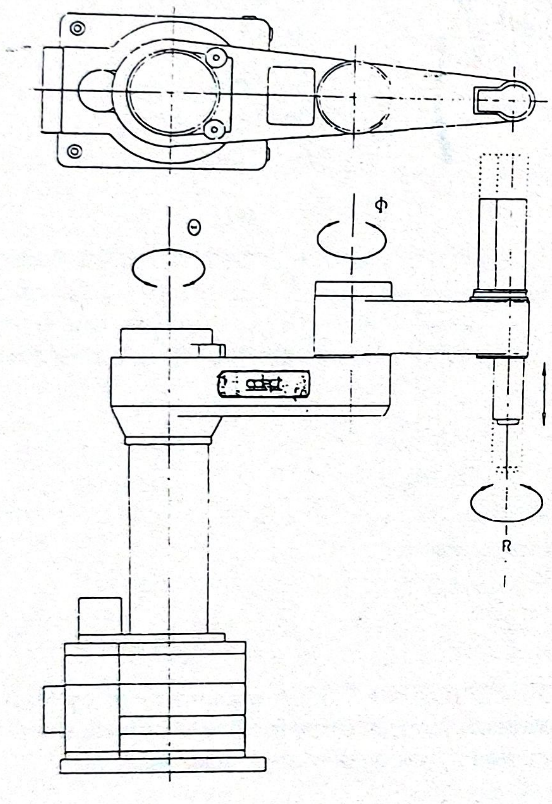


Figure 3.2.10 An actual SCARA model AdeptOne robot manufactured by Adept Technology, Inc., with a playload of 20 lb, resolution of ±0.0005 in. and repeatability of ±0.001 in. This is an electrically powered manipulator robot with maximum velocity of an end effector of 30 ft/s. It is used in accurate assembly (insertion, sealing, fitting), loading/unloading, molding inserts, palletizing, inspection, gauging, and fine-part soldering. *(Source: Adept Technology Inc.)*

Typical applications for articulated robots include:

- Automatic assembly
- Die casting
- In-process inspection
- Machine loading and unloading
- Machine vision
- Material cutting
- Material removal
- Multiple-point light machining operations
- Paint and adhesive applications
- Palletizing
- Thermal coating
- Welding

Table 3.1 summarizes the five robot manipulator configurations with their respective advantages and disadvantages.

Table 3.1 Summary of the Five Basic Robot Manipulator Configurations

Configuration	Advantages	Disadvantages
Rectilinear coordinates (x, y, z-base travel, reach, and height)	Three linear axes Easy to visualize Rigid structure Easy to program off-line Linear axes make for easy mechanical stops	Can only reach in front of itself Requires large floor space for size of work envelope Axes hard to seal
Cylindrical coordinates (θ, y, z-base rotation, reach, and height)	Two linear axes, one rotating axis Can reach all around itself Reach and height axes rigid Rotation axis easy to seal	Cannot reach above itself Base rotation axis is less rigid than a linear axis Linear axis is hard to seal Won't reach around obstacles Horizontal motion is circular
Spherical coordinates (vertical) (θ, y, β-base rotation, elevation angle, reach angle)	One linear axis, two rotating axes Long horizontal reach	Can't reach around obstacles Generally has short vertical reach
Revolute (or jointed-arm) coordinates (vertical) (θ, β, α-base rotation, elevation angle, reach angle)	Three rotating axes Can reach above or below obstacles Largest work area for least floor space	Two or four ways to reach a point Most complex manipulator
SCARA coordinates (horizontal) (θ, Φ, z-base rotation, reach angle, height)	One linear axis, two rotating axes Height axis is rigid Large work area for floor space Can reach around obstacles	Two ways to reach a point Difficult to program off-line Highly complex arm

3.3 DEGREES OF FREEDOM

The degrees of freedom or grip of a robotic system can be compared to the way in which the human body moves. For each degree of freedom, a joint is required. The degrees of freedom located in the arm define the configuration. Each of the five basic motion configurations discussed previously utilizes three degrees of freedom in the arm. For applications that require more flexibility, additional degrees of freedom are used in the wrist of the robot. Three degrees of freedom located in the wrist give the end effector all the flexibility. A total of six degrees of freedom is needed to locate a robot's hand at any point in its work space. Although six degrees of freedom are needed for maximum flexibility, most robots employ only three to five degrees of freedom. The more degrees of freedom, the greater the complexity of motions encountered.

In comparison, the movement of the human hand is controlled by thirty-five muscles. Fifteen of these muscles are located in the forearm. The arrangement of the muscles in the hand provides great strength to the fingers and thumb for grasping objects. Each finger can act alone or together with the thumb. This enables the hand to do many intricate and delicate tasks. Some of the grips of the human hand for moving objects are difficult for robotic systems to duplicate.

The human hand has twenty-seven bones: the eight bones of the carpus, or wrist, arranged in two rows of four; the five bones of the metacarpus, or palm, one to each digit; and the fourteen digital bones, or phalanges, two in the thumb and three in each finger. The carpal bones fit into a shallow socket formed by the bones of the forearm. There are twenty-two degrees of freedom (joints) in the hand, with seven in the wrist. From Figure 3.3.1, it can be seen that the hand is a very complex multipurpose tool. Hands can be used to perform various repetitive tasks.

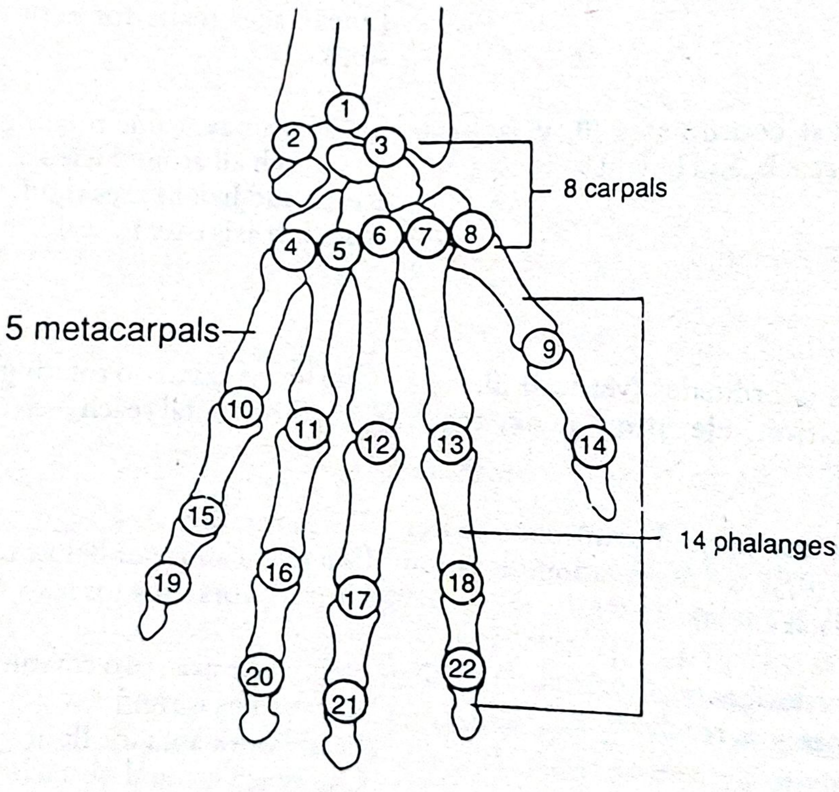


Figure 3.3.1 Degrees of freedom of the human hand

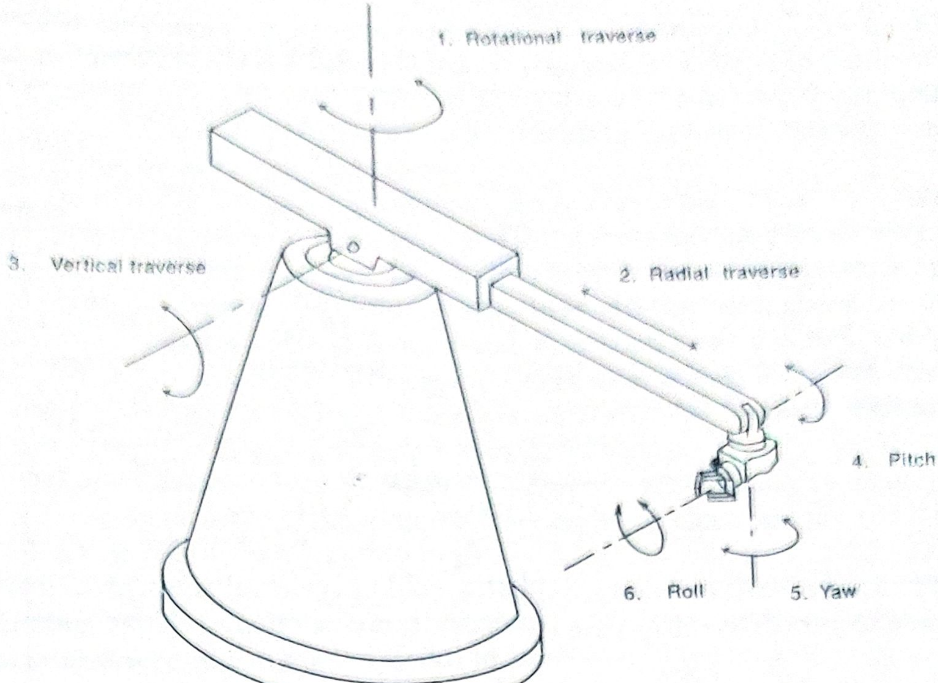


Figure 3.3.2 Six major degrees of freedom of a robotic system

The bones and joint arrangement give the human hand dexterity not found in robotic systems. The movements of a robotic system seem awkward and clumsy, because the robot is usually accomplishing these movements with only six degrees of freedom.

The three degrees of freedom located in the arm of a robotic system are (1) the rotational traverse, (2) the radial traverse, and (3) the vertical traverse. The rotational traverse is the movement of the arm assembly about a rotary axis, such as the left-and-right swivel of the robot's arm about a base. The radial traverse is the extension and retraction of the arm or the in-and-out motion relative to the base. The vertical traverse provides the up-and-down motion of the arm of the robotic system.

The three degrees of freedom located in the wrist, which bear the names of aeronautical terms, are (4) pitch, (5) yaw, and (6) roll, as previously discussed.

The pitch or bend is the up-and-down movement of the wrist. The yaw is the right-and-left movement of the wrist. The roll or swivel is the rotation of the hand. Figure 3.3.2 illustrates the six basic degrees of freedom of a robotic system.

3.4 POWER SOURCES

A 1990 survey of manufacturers of robots in the United States, Europe, and Japan, based upon nearly two hundred suppliers and not including a number of small and very specialized robot manufacturers, indicated that models available were de-

Table 3.2 Load-Carrying Capacit / of Robots

Load Capacity		Percentage of Robots
Pounds	Kilogram:	Models offered
300–2,300	136–1,04:	11
100–299	45–136	16
50–99	23–45	15
20–49	9–22	21
10–19	5–9	17
less than 10	less than !	20

signed to handle loads ranging from about 1 ,ound (0.5 kilogram) upward to about 2,300 pounds (1,043 kilograms).

Applications listed in the survey for robots included die casting, forging, plastic molding, machine tools, investment castings, a general and miscellaneous category, spray painting, welding, and mac iining. It is well established that the use of robots in light manufacturing and inspecting operations, such as are found in the electronics industry, has increased markedly during the past few years. In terms of models available, the breakdown was approximately that shown in Table 3.2.

A recent survey indicated that, in terms of total robots made, electric drives account for about one half of the robot drives used; pneumatic drives, about one third of the total; and hydraulic drives, about one sixth of the total. Some authorities believe that these ratios will hold rather steady; others profess a solid trend toward electric drives. Electric servo units lately have been advanced in power and durability.

Electric Power Source

All robot systems use electricity as the primary source of energy. Electricity turns the pumps that provide hydraulic and pneumatic pressure. It also powers the robot controller and all the electronic components and peripheral devices.

In all electric robots, the drive actuators, as well as the controller, are electrically powered. Most electric robots use **servomotors** for axes motion, but a few open loop robot systems utilize stepper motors. The majority of robots presently are equipped with DC servomotors, but eventually will be changed to AC servomotors because of their higher reliability, compactness, and high performance. Most new model robots appear to be with an AC servomotor and an encoder, which simplifies wiring, reduces maintenance, and increases performance. Therefore, AC servomotors are gaining confidence and importance in the robot industry. Electric motors provide the greatest variety of choices for powering manipulators, especially in the low- and moderate-load ranges, and for low-speed high-load operations.

Motors generally operate at speeds that far exceed those desirable for manipulator joints; therefore, speed reducers are required. The ability to accelerate and decelerate the working load quickly is a very desirable attribute. Also required is the ability to operate at variable speeds. An example of an electrically powered robot is shown in Figure 3.4.1.

Because electric robots do not require a hydraulic power unit, they conserve floor space and decrease factory noise. Direct drive models provide very quick response. No energy conversion is required because the electric power is applied directly to the drive actuators on the axes. In an electric manipulator, the motors generally provide rotational motion and, therefore, must use rack-and-pinion gears or ball-screw drives to change to linear movements, for direct drives are connected to the joints through some kind of mechanical coupling, such as a lead screw, pulley block, spur gears, or harmonic drive.

Permanent magnet DC motors have proved a good choice for medium- and small-size manipulators in the past. The brushless, electronically commutated versions have very long lives.

Printed-circuit motors have high torque relative to their rotor inertia and, therefore, fast response times. These motors are capable of driving at low speeds without the need of speed reducers.

The disadvantages of electric drives are that the payload capability is limited to three hundred pounds or less, and the operation in explosive environments poses problems.

Pneumatic Power Source

Pneumatic drives are generally found in relatively low-cost manipulators with low load-carrying capacity. When used with non-servo controllers, they usually require mechanical stops to ensure accurate positioning. Pneumatic drives have been used for many years for powering simple stop-to-stop motions. Most often used configurations are a linear single or a double-acting piston actuator. Rotary actuators also are used. In converting linear actuation to rotary motion, a drive pulley connected to the actuator by a cable may be used, thus avoiding the nonlinearities of joint motion inherent in linkwork conversion of linear to rotary motion.

An advantage of the pneumatic actuator is its inherently light weight, particularly when operating pressures are moderate. This advantage, coupled with readily available compressed air supplies, makes pneumatics a good choice for moderate to low load applications that do not require great precision. Because of the light weight, pneumatics are often used to power end effectors even when other power sources are used for the manipulator's joints.

The principal disadvantages of pneumatic actuators include their inherent low efficiencies, especially at reduced loads; their low stiffness (even at the high end of practical operating pressure); and problems of controlling them with high accuracy. An example of a pneumatically powered robot can be seen in Figure 2.3.16. Also, a simple pneumatic circuit is shown in Figure 3.4.2.

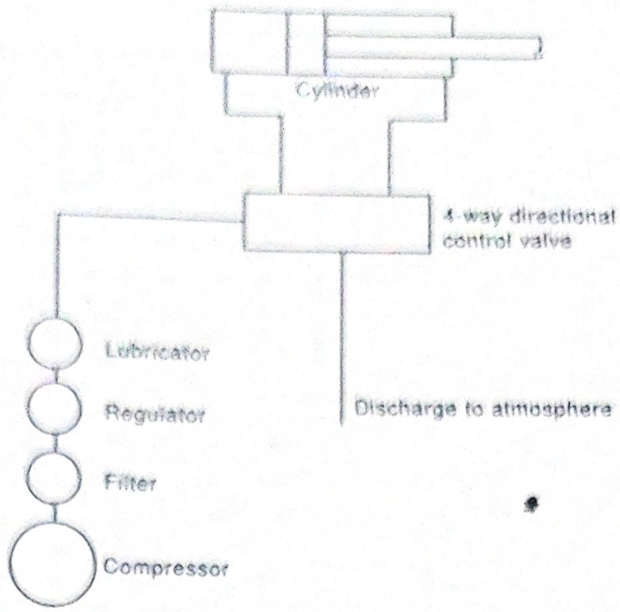


Figure 3.4.2 Simple pneumatic circuit

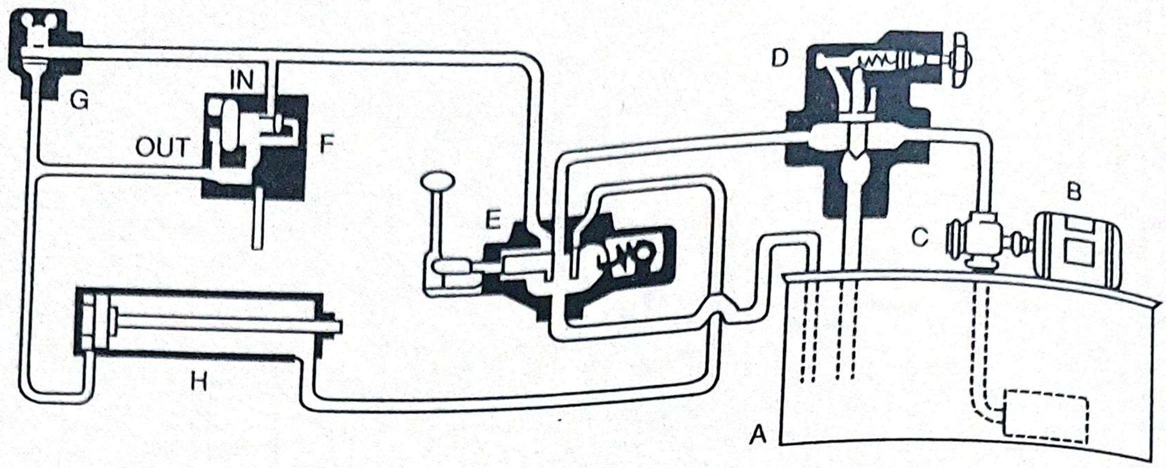
Hydraulic Power Source

Hydraulic drives are either linear piston actuators or a rotary vane configuration. If the vane type is used as a direct drive, the range of joint rotation is limited to less than 360 degrees because of the internal stops on double-acting vane actuators. Hydraulic actuators provide a large amount of power for a given actuator.

The high power-to-weight ratio makes the hydraulic actuator an attractive choice for moving moderate to high loads at reasonable speeds and moderate noise levels.

Hydraulic motors usually provide a more efficient way of using energy to achieve a better performance, but they are more expensive and generally less accurate.

A major disadvantage of hydraulic systems is their requirement for an energy storage system, including pumps and accumulators. Hydraulic systems also are susceptible to leakage, which may reduce efficiency or require frequent cleaning and maintenance. The working fluid must always be kept clean and filter-free of particles. Fluid must be kept at a constant warm temperature (100°F–110°F). Also, air entrapment and cavitation effects can sometimes cause difficulties. One of the chief concerns with hydraulic power is the environmental issue. Oil that is contaminated is costly to remove, and any leakage is considered an environmental contamination problem. During the 1996 National Robotics Safety Convention in Detroit, some facts about this issue were presented by the three big auto companies. They feel that electric servomotor power is the solution to avoid the hazards of oil contamination.



List of Components

A — Reservoir
B — Electric Motor
C — Pump
D — Maximum Pressure (Relief) Valve
E — Directional Valve
F — Flow Control Valve
G — Right-Angle Check Valve
H — Cylinder

Figure 3.4.3 A hydraulic power supply system with linear actuator (cylinder). *(Courtesy of Vickers, Inc.)*

In paint spraying and other applications, where the environment may present an explosion hazard, the robot must be either explosion-proof or intrinsically safe. In such cases, the hydraulically driven robot has obvious advantages over its electric counterpart.

Hydraulic power lends itself to some robot applications because energy can be easily stored in an accumulator and released when a burst of robot activity is called for. A typical hydraulic power system with linear hydraulic actuator (cylinder) is shown in Figure 3.4.3, and two actual different-sized power units are shown in Figure 3.4.4. Also, a simple (single-line) hydraulic circuit is shown in Figure 3.4.5. Virtually all hydraulic circuits are essentially the same regardless of the application. There are six basic components required in a hydraulic circuit (refer to Figure 3.4.3):

1. A tank (reservoir) to hold the liquid, which is usually hydraulic oil.
2. A pump to force the liquid through the system.
3. An electric motor or other power source to drive the pump.
4. Valves to control liquid direction, pressure, and flow rate.
5. An actuator to convert the energy of the liquid into mechanical force or torque to do useful work. Actuators can be either cylinders to provide linear motion, such as shown in Figure 3.4.3, or motor (hydraulic) to provide rotary motion.
6. Piping, which carries the liquid from one location to another.

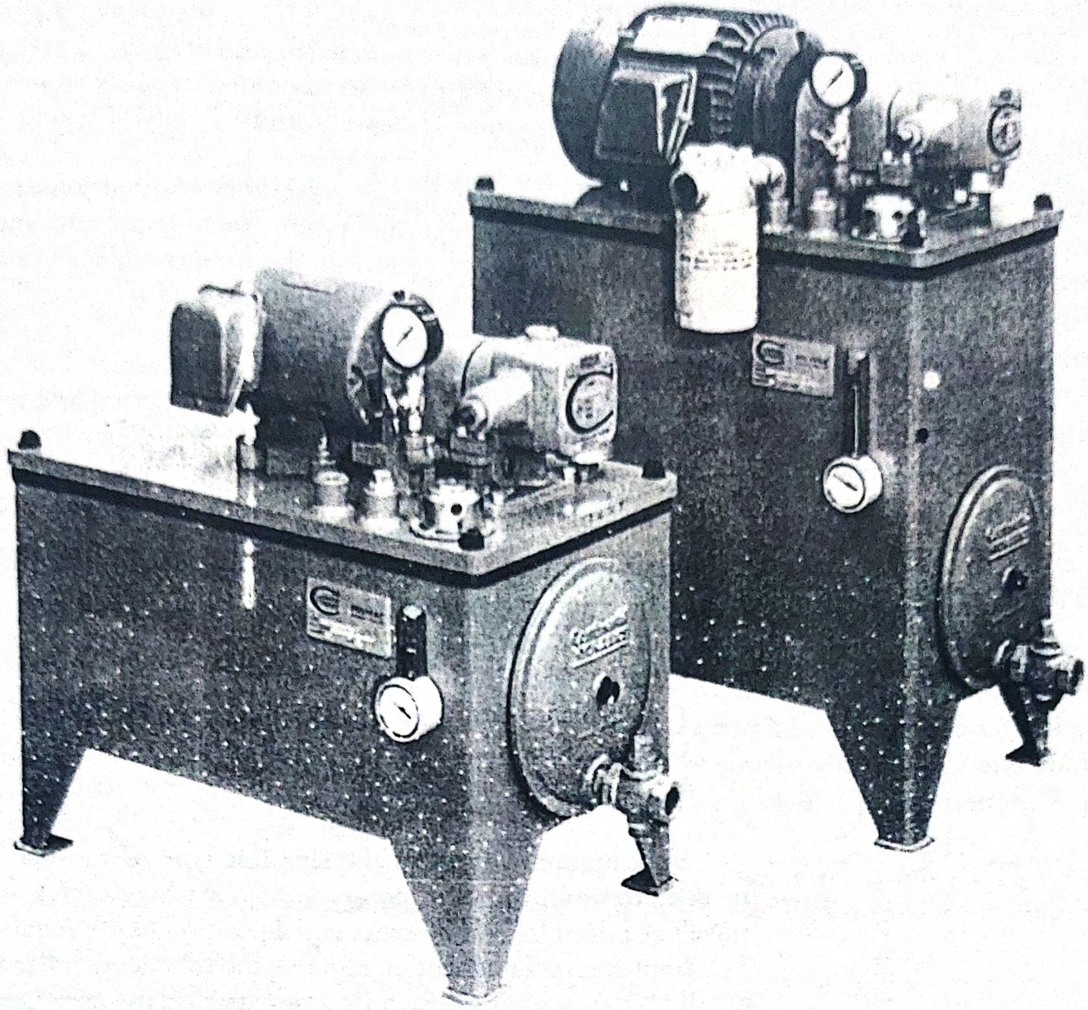


Figure 3.4.4 (above) Two actual different-sized, complete, hydraulic power units *(Courtesy of Continental Hydraulics)*

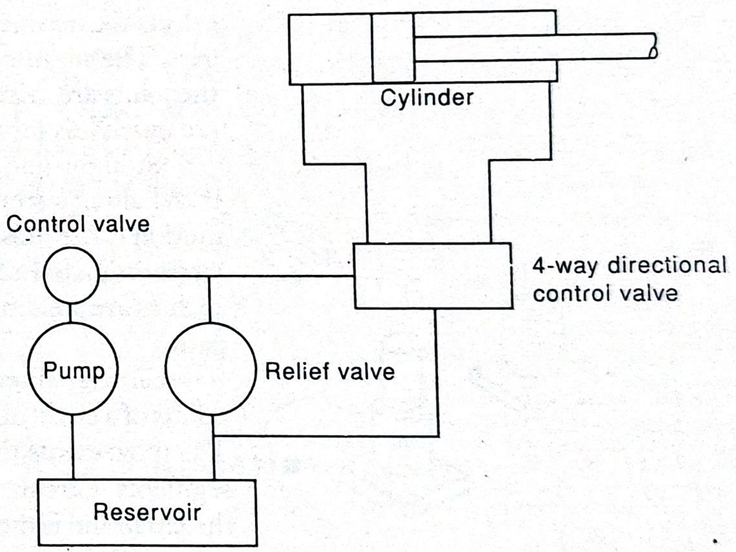


Figure 3.4.5 (right) Simple hydraulic circuit

Electromechanical Power Source

Electromechanical power sources are used in about 20 percent of the robots available today. Typical forms are servomotors, stepping motors, pulse motors, linear solenoids and rotational solenoids, and a variety of synchronous and timing belt drives.

The primary use of AC servomotors in robot joint movements is for fast, accurate positioning, high stall torque, small frame size, and light weight. Pneumatically driven robots, because of the compressibility of air, normally are found in light-service, limited-sequence, and pick-and-place applications. Hydraulic robots usually employ hydraulic servo valves and analog resolvers for control and feedback. Digital encoders and well-designed feedback control systems can provide hydraulically actuated robots with an accuracy and repeatability generally associated with electrically driven robots.

3.5 TYPES OF MOTION

A robot manipulator can make four types of motion in traveling from one point to another in the workplace:

1. Slew motion
2. Joint-interpolated motion
3. Straight-line interpolation motion
4. Circular interpolation motion

Slew motions represent the simplest type of motion. The robot is commanded to travel from one point to another where each axis of the manipulator travels at a default speed from its initial position to the required final destination.

Joint-interpolated motion requires the robot controller to calculate the time it will take each joint to reach its destination at the commanded speed. Then it selects the maximum time among these values and uses it as the time for the other axes. The advantage of joint-interpolated motion compared to slew motion is that the joints are driven at lower velocities, and therefore the maintenance problems are much less for the robot.

Straight-line interpolation motion requires the end of the end effector to travel along a straight path determined in rectangular coordinates. This type of motion is the most demanding for a controller to execute, except for a rectangular-coordinated robot. Straight-line interpolation is very useful in applications such as arc welding, inserting pins into holes, or laying material along a straight path.

Circular interpolation motion requires the robot controller to define the points of a circle in the workplace based on a minimum of three specified positions. The movements that are made by the robot actually consist of short straight-line segments. Circular interpolation, therefore, produces a linear approximation of the circle and is more readily available using a programming language rather than manual or **teach pendant** techniques.

3.6 PATH CONTROL

Commercially available industrial robots can be classified into four categories, according to their path control system:

1. Limited-sequence
2. Point-to-point
3. Controlled-path
4. Continuous-path

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 together with a sequencer to coordinate and time the actuation of the joints. 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. Therefore, their control system is intended for simple motion cycles, such as pick-and-place applications where each axis is normally limited to two end points. However, some pick-and-place robots also include one or two intermediate stops; therefore, they can be called stop-to-stop or sometimes bang-bang.

Pick-and-place robots were named by the job they normally perform in industry. They pick up parts or materials from one location and place them in another location. A pick-and-place robot can be used to unload a conveyor or a transfer line. It also can be used for simple press loading and unloading applications. Limited-sequence robots use pick-and-place motion. A pick-and-place robot is shown in Figure 3.6.1.

Pick-and-place robots are the simplest of all robots. This is not to say that because they are simple they lack value. Pick-and-place robots are an excellent

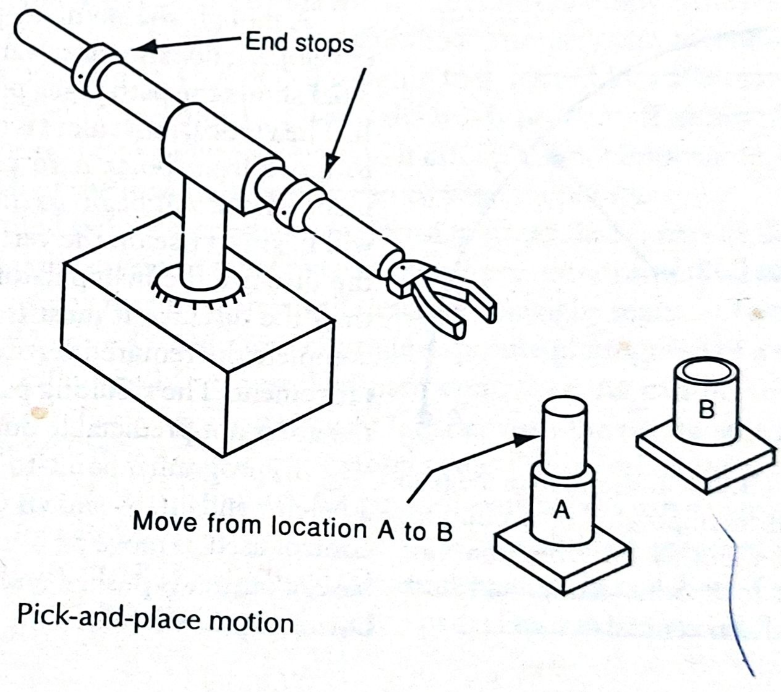


Figure 3.6.1 Pick-and-place motion

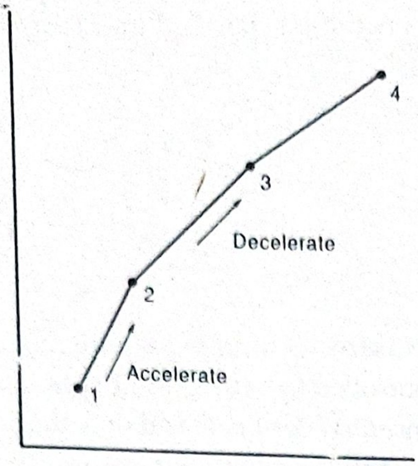


Figure 3.6.2 Point-to-point motion

choice for simple jobs. They have the lowest level of control but are the least expensive of the four types. There is no reason to buy more capacity than is necessary to do a job.

Pick-and-place robots also have the advantage of being the easiest to maintain. They can normally be served by the plant electrical or machine repair personnel. In general, a limited-sequence robot will operate longer between failures, and when it does fail, the repairs will normally be simple and fast. These types of robots are normally pneumatically actuated.

Point-to-point robots are the most common of the four classifications and can move from one specified point to another but cannot stop at arbitrary points not previously designated. Point-to-point robots driven by servos are often controlled by potentiometers set to stop the robot arm at a specified point. Point-to-point robots can be programmed (taught) to move from any point within the work envelope to any other point within the work envelope. This versatility greatly expands their potential applications. Therefore, these robots can be used in simple machine loading and unloading applications as well as more-complex applications, such as spot welding (resistance welding), assembly, grinding, inspection, palletizing, and depalletizing.

Point-to-point motion involves the movement of the robotic system through a number of discrete points, as shown in Figure 3.6.2. The programmer uses a combination of the robot axes to position the end effector at a desired point. These positions or points are recorded and stored in memory. During the playback mode, the robot steps through the points recorded in memory.

The point-to-point robot can move more than one of its axes at a time. For example, the spherical-coordinated robot can rotate about its base when at the same time it is reaching other axes. In a more complex application, it is possible to have the robot moving all of its major axes and all of its minor axes at the same time.

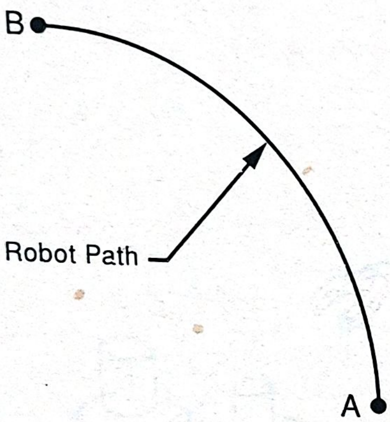


Figure 3.6.3 Illustration of the path of the manipulator of a point-to-point robot as it moves from one point to another (combined horizontal and vertical movement)

Although the point-to-point robot can move to any point within its work envelope, it does not necessarily move in a straight line between two points. Figure 3.6.3 shows the path that a point-to-point robot might take between points A and B. The vertical movement is much shorter than the horizontal movement required to move from point A to point B. When directed by the control, the robot's manipulator will begin to move from point A toward point B. The manipulator will begin to rise on the vertical axis and then reach the horizontal axis. Because the distance the manipulator must travel along the vertical axis is much shorter than the distance it must travel along the horizontal axis, the manipulator will complete the required vertical movement long before it completes the horizontal movement. The resulting path will be some form of an arc, but the exact shape of the arc is not predictable during the programming of the robot.

To program a point-to-point robot, the programmer must push buttons on a teach pendant, as shown in Figure 3.6.4. The teach pendant is much like the control used to move an overhead crane in a factory. To rotate the robot about its base, a button is pushed and the robot turns. To extend the manipulator, another button is pushed. When the robot has been led to the desired point, the program-

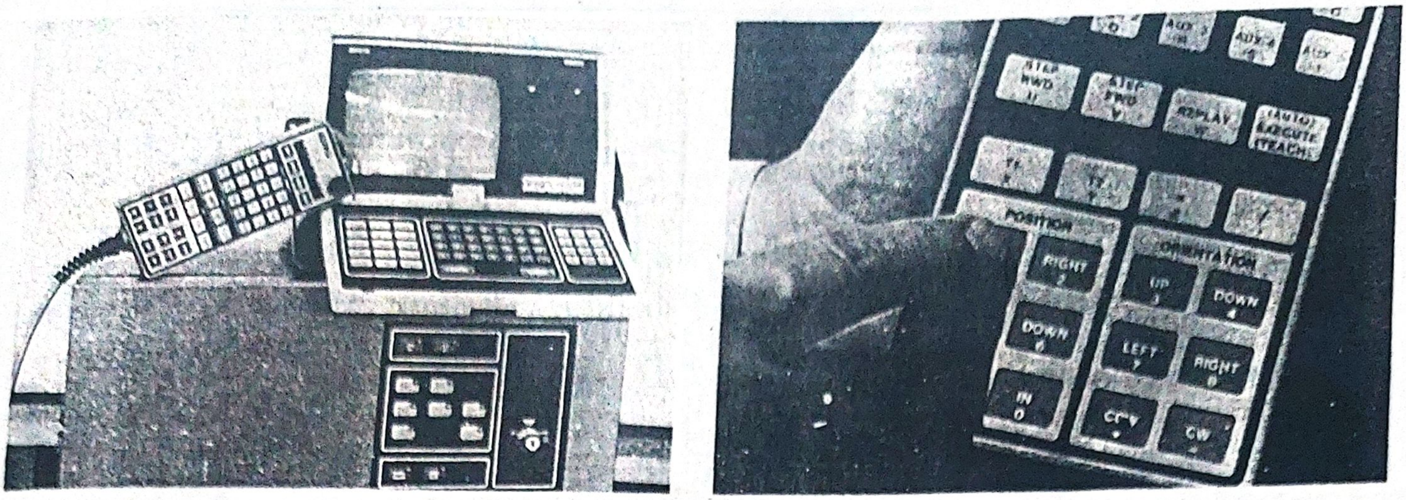


Figure 3.6.4 Teach pendant used for programming a point-to-point robot. *(Source: Cincinnati Milacron)*

mer pushes a button to record that point in the robot's memory. The programmer then moves the manipulator to the next desired point by pushing the appropriate buttons. The path the programmer takes to get the manipulator to the next point is not remembered by the robot. When the manipulator is finally brought to the desired point, the button to record the point is again pushed, and the second point is recorded into the robot's memory. When the program is played back, the robot will move from the first point in its memory to the second point, then to the third point, and so forth, until it has moved to all the points it has been taught. After the last point has been reached by the robot, the controller moves the manipulator back to the first point in the memory and the entire program is repeated. With some robots, the arm may be pulled roughly to a desired location manually, but the final location is fine-tuned by using the teach pendant. The simple control method of the point-to-point robot makes it difficult, if not impossible, to predict the exact path of the manipulator between two taught points.

Controlled path is a specialized control method that is part of the general category of a point-to-point robot but with more-precise control. The controlled-path robot ensures that the robot will describe the right segment between two taught points. Figure 3.6.5 shows a multiple-exposure photograph of a robot that is under the influence of a controlled-path controller. As can be seen in this illustration, the robot moves in a straight line between the two taught points.

Controlled-path is a calculated method and is desired when the manipulator must move in a perfect path motion. Controlled-path robots can generate straight lines, circles, interpolated curves, and other paths with high accuracy. Paths can be specified in geometric or algebraic terms in some of these robots. Good accuracy can be obtained at any point along the path. Only the start and finish coor-

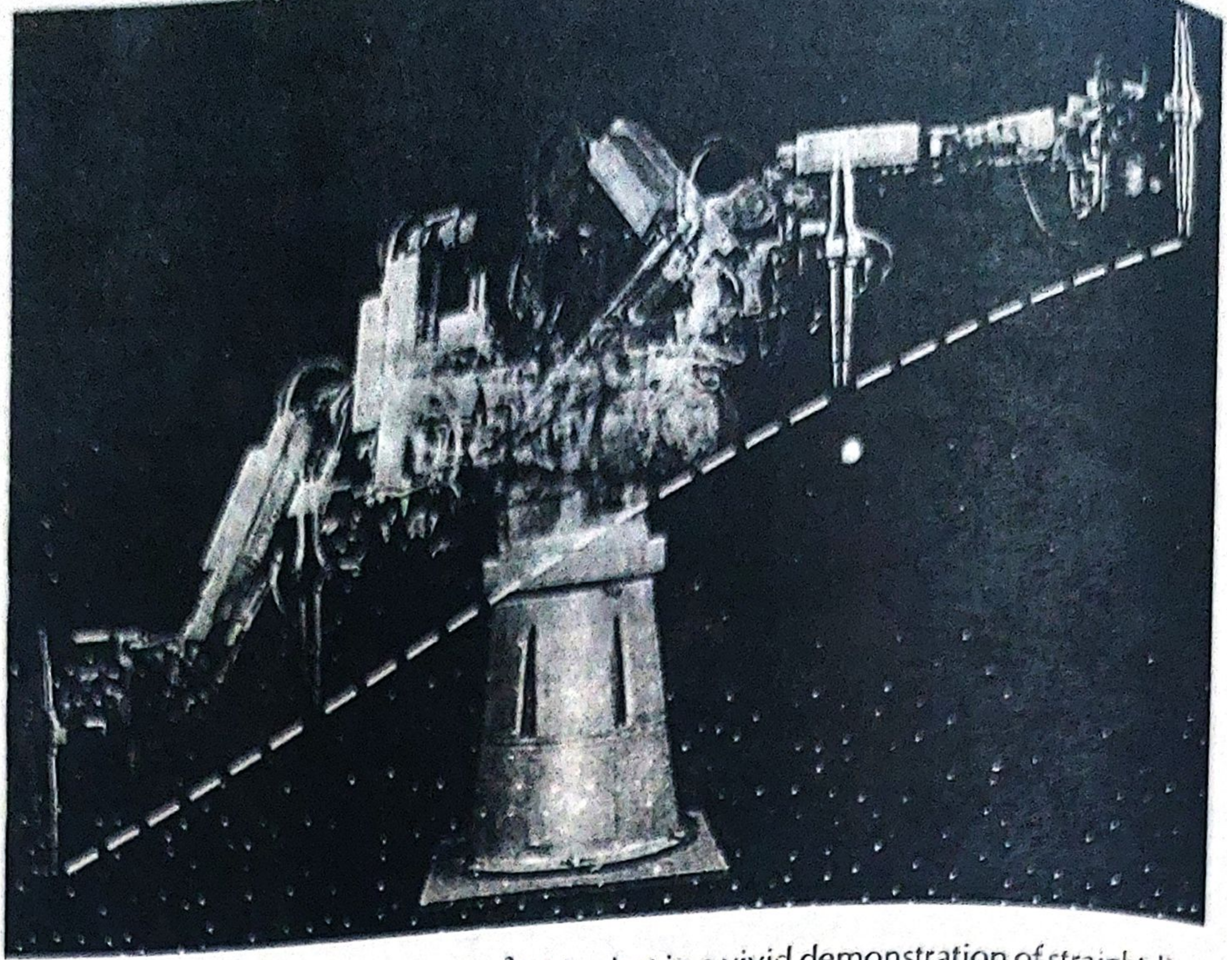


Figure 3.6.5 A Cincinnati Milacron T^3 566 robot in a vivid demonstration of straight-line, controlled-path motion. The dotted line shows the path of the robot manipulator. *(Source: Cincinnati Milacron)*

dinates and the path definition are required for control. Although assembly operations can be accomplished simply by point-to-point control, programming with a controlled-path robot can perform such operations more easily. For example, if the robot is to put a shaft into a bearing, any deviation from a straight line could cause the shaft to score the bearing or could bend the shaft. Using a controlled-path robot will ensure that the robot will slip the shaft into the bearing in a straight line. On the other hand, if you desire to use the point-to-point robot in a straight-line operation, it is necessary to program the robot with many points along the path. The more points programmed, the straighter the path on the point-to-point robot will be.

Other applications that are simplified through the use of a controlled-path robot are arc welding, drilling, polishing, and assembly.

The method for programming the controlled-path robot is identical to that for programming the point-to-point robot except that the points must be calculated.

The difference between the execution of a point-to-point controlled-path and a point-to-point noncontrolled-path program is illustrated in Figure 3.6.6. The figure shows two programmed points for a two-axis (x and y) robot.

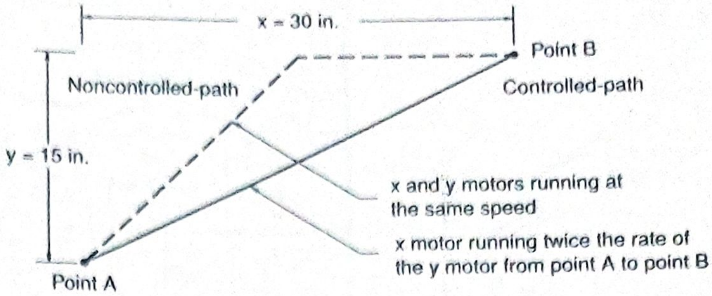


Figure 3.6.6 Comparison of controlled-path and noncontrolled-path operation

Notice that all the axis drivers on a noncontrolled-path robot move at the same time, whereas the axis drivers on a controlled-path robot move at a speed proportional to the length of the axis that is produced by a controlled-path controller.

For the controlled-path the x-axis motor runs at twice the speed of the y-axis motor, and therefore both finish their moves simultaneously at point B, which is a complete straight-line motion.

Continuous-path motion is an extension of the point-to-point method. The difference is that continuous path involves the utilization of more points and its path can be an arc, a circle, or a straight line. A continuous-path program can have several thousand points. Because more points are used, the distances between points are extremely close, as shown in Figure 3.6.7.

Because of the large number of points, the robot is capable of producing smooth movements that give the appearance of continuous or contour movements. Continuous-path motion is more concerned with control of the path movement than with end-point positioning. Programming of the path of motion is accomplished by an operator physically moving the end effector of the robot through its path of motion. While the operator is moving the robot through its motion, the positions of the various axes are recorded on some constant time frame. Programs are generally recorded on magnetic tape or a magnetic disk.

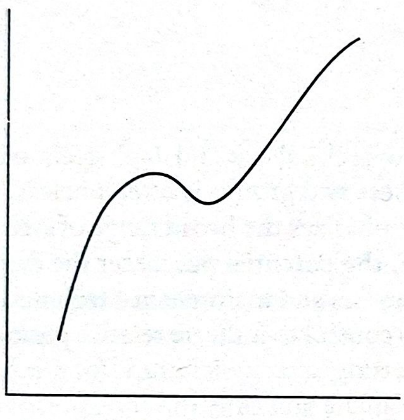


Figure 3.6.7 Continuous path motion

The continuous-path robot is programmed differently than the point-to-point robot and the controlled-path robot. Rather than leading the robot to the point desired by pushing buttons on a teach pendant, the manipulator of a continuous-path robot is programmed by grabbing hold of the robot's arm and actually leading the arm through the path that we wish the robot to remember. The robot remembers not only the exact path through which the programmer moves the manipulator but also the speed at which the programmer moves the manipulator.

If the programmer should move the arm too slowly, the speed can be adjusted at the control console. Changing the speed does not affect the path of the robot's arm.

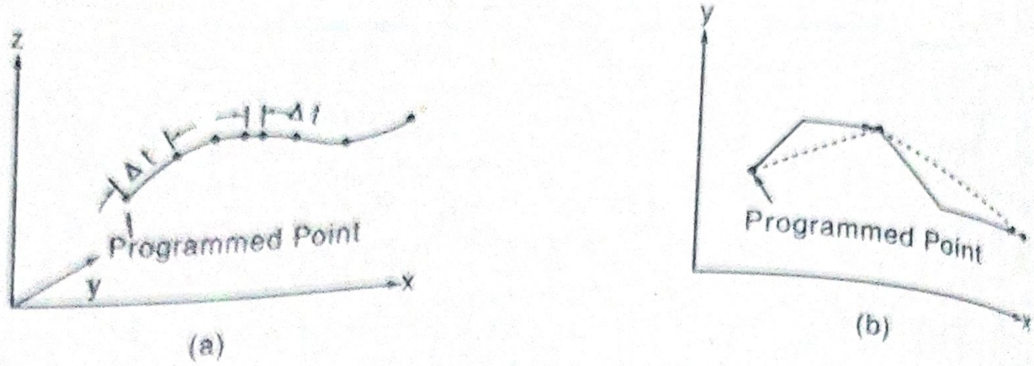


Figure 3.6.8 (a) In continuous path, real-time programming points are automatically programmed. (b) In point-to-point, the path generated is not easily predicted.

The continuous-path robot is really a form of the point-to-point robot. As the robot is taught the desired program, the control examines the location of the manipulator hundreds of times per second and stores each point in memory for playback at a later time. It is like programming thousands of individual points into the memory of a standard point-to-point robot. The continuous-path robot is often used for spray painting, arc welding, or any other operation that requires constant control of the robot's path.

The major difference between the continuous path control and the standard point-to-point control is the control's ability to remember thousands of programmed points in the continuous path, whereas the point-to-point control is limited to several hundred points of memory. Figure 3.6.8 illustrates the difference between the two methods.

Off-line programming is another method that has become very popular today. It's a simple software-driven program that is done either on a computer or by the use of a programmable controller. (Details about off-line programming will be discussed in Chapter 9.)

3.7 INTELLIGENCE LEVEL

Robot systems are usually classified as low-technology and high-technology groups. Although the distinction between these two groups is often unclear, the classification serves two purposes. First, it emphasizes the broad range of systems and features available. Second, it indicates to the potential purchaser the degree of training that will be required for new operators and maintenance technicians.

Low-technology 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, together with a sequencer, to coordinate and time the actuation of the joints. Their control system is intended for simple motion cycles, such as pick-and-place applications where each axis is normally limited to two end points. Figure 3.6.1 illustrates such an application; however, some pick-and-place robots

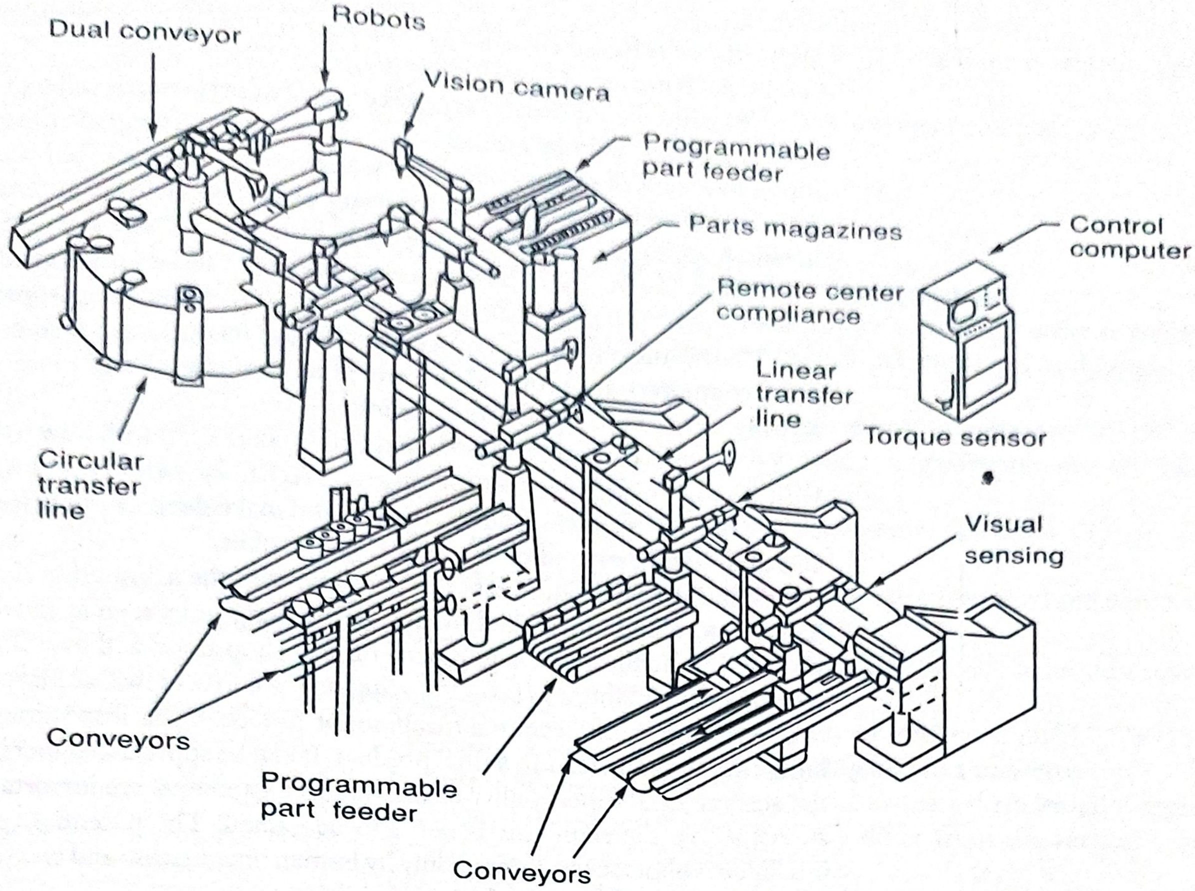


Figure 3.7.1 Automated assembly operations using high-technology robots

also include one or two intermediate stops; therefore, they can be called stop-to-stop or sometimes bang-bang.

High-technology robots are servo-controlled systems; they accept more-sophisticated sensors and complex programming languages. Figure 3.7.1 illustrates such a system. There are two types available in this category: numerically controlled and intelligent control.

The numerically controlled robot is programmed and operates much like a **numerical control (NC)** machine (see Chapter 8) in which the mechanical sections are controlled and programmed by coded alphanumerical data. The robot is servo controlled by digital data, and its sequence of movements can be changed with relative ease. The two basic types of controls are point-to-point and continuous-path.

Point-to-point robots are easy to program and have a higher load-carrying capacity and a much larger work envelope. Continuous-path robots have greater repeatability than point-to-point, but lower load-carrying capacity. Some advanced robots have a complex system of path control, which enables them to have high-speed movements with great accuracy.

The intelligent control robot is capable of performing some of the functions and tasks carried out by human beings. It can detect changes in the work environment by means of sensory perception. Also, an **intelligent robot** is equipped with a variety of sensors and sensor apparatus providing visual (computer vision) and tactile (touching) capabilities to respond instantly to variable situations.

Much like humans, the robot observes and evaluates the immediate environment by perception and pattern recognition. It then makes appropriate decisions for the next movement and proceeds. Because its operation is so complex, powerful computers are required to control its movements and more-sophisticated sensing devices to respond to its actions.

Extensive research has been and still is concerned with how to equip robots with seeing "eyes" and tactile "fingers." **Artificial intelligence (AI)** that will enable robots to respond, adapt, reason, and make decisions to react to change is also an inherent capability of the intelligent robot.

Significant developments still continue with the assumption that robots will behave more and more like humans, performing tasks such as moving among a variety of machines and equipment on the shop floor and avoiding collisions; recognizing, picking, and properly gripping the correct raw material or workpiece; transporting a workpiece to a machine for processing or inspection; and assembling the components into a final product. It can be appreciated that in such tasks, the accuracy and repeatability of the robot's movements are important considerations, as are the economic benefits to be gained. The potential application of intelligent robots seems limited only by human imagination and creativity. (Chapter 10 discusses advanced robots in detail.)

3.8 SUMMARY

This chapter introduced the general concepts of robot classification. It provided an overview of all types of robot arm geometry and styles, considering degrees of freedom, power sources, control systems, and path control.

The arm geometry, which is also described in the previous chapter, is currently available in five basic configurations: rectangular, cylindrical, spherical, jointed-arm, and SCARA. For each configuration, the chapter described the geometry of its work envelope, the advantages and disadvantages of its axes, and its typical applications. Table 3.1 summarizes the five basic configurations.

The three degrees of freedom located in the arm of a robot system are the rotational traverse, the radial traverse, and the vertical traverse. The three degrees of freedom located in the wrist are pitch, yaw, and roll.

The four power sources used in current robots are electric, hydraulic, pneumatic, and electromechanical.

There are four types of motion that a robot manipulator can make in traveling from one point to another in the workplace: slew motion, joint-interpolated motion, straight-line interpolation motion and circular interpolation motion.

There are four types of path controls for robots: limited-sequence, point-to-point, controlled-path, and continuous path.

Robot systems are usually classified as low-technology and high-technology groups.

3.9 REVIEW QUESTIONS

3.1 Name the five styles of manipulators.
3.2 Describe the axes of the five styles of manipulators.
3.3 Compare the five styles of manipulators according to the advantages and disadvantages of each configuration, work envelope, and typical applications.
3.4 Describe the four types of power sources used in current robots and compare their advantages and disadvantages according to economics, reliability, and load-carrying ability.
3.5 Discuss the roles that the major and minor axes of a robot play in positioning a part in space.
3.6 Discuss the major differences between servo-controlled and nonservo-controlled robots.
3.7 Describe the six degrees of freedom that are needed to locate a robot's arm at any point in its work space.
3.8 What is the main difference between an intelligent and highly intelligent robot and what are its advantages compared to a nonservo type?
3.9 Name the four types of path control and compare them with this application.
3.10 How does the SCARA arm geometry differ from the vertical articulated arm?
3.11 Give three typical applications for each of the four-path controls.
3.12 Why is the SCARA arm more ideal for assembly applications?

3.10 PROBLEMS

3.1 Sketch the work envelopes of the robot configurations for each of the five types of manipulators.
3.2 In Problem 3.1, compare the work envelopes and explain which configuration gives the largest work envelope and why.
3.3 Which style of manipulator has the largest reach for the amount of floor space it occupies? Sketch and discuss your answer.
3.4 Compare the five basic robot configurations according to the work envelope, typical applications, and power sources.
3.5 What is meant by the degrees of freedom of a robot system and how do they compare to the human hand?
3.6 Sketch the degrees of freedom located in a SCARA robot's arm and a cylindrical robot's arm.
3.7 What are the four patterns of motion of industrial robotics systems? Discuss and sketch each pattern.
3.8 What are some factors to consider in the selection of a control unit for an industrial robot? Give an example.