# 6

# Robot Technology

**Contents**

## 6.1 Introduction to Robot Technology

A robot is an automatically controlled material handling unit that is widely used in the manufacturing industry. It is generally used for high-volume production and better quality.

Implementation of robot technology with the integration of automatic systems can contribute to increasing of productivity of the company and enhances the profitability of the company.

The word 'robot' first appeared in 1921 in the Czech playwright Karel Capek's play 'Rossum's Universal Robots. The word is linked to Czech words Robota (meaning work) and Robotnik (meaning-slave). Computer Aided Manufactures International of USA describes the meaning of robot as a device that performs functions ordinarily ascribed to human beings or operates with what appears to human intelligence.

Another definition from Robot Institute of America is a programmable multi-function manipulator designed to move and manipulate material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of specified tasks.

ISO defines a robot as an automatically controlled, reprogrammable, multipurpose, manipulative machine with several reprogrammable axes, which are either fixed in a place or mobile for use in industrial automation applications.

There are several successful examples of robot applications such as:

- Robots perform more than 98% of the spot welding on Ford's Taurus and Sable cars in the U.S.A.
- A robot drills 660 holes in the vertical tail fins of an F-16 fighter in 3 hours at General Dynamics compared to 24 man-hours when the job was done manually.
- Robots insert disk drives into personal computers and snap keys onto electronic typewriter keyboards.

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.

With 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.

Robots fill the gap between the specialized and limited capabilities normally associated with fixed automation and the extreme flexibility of human labor.

## 6.2 Robot Physical Configurations

Commercially available industrial robots have one of the following configurations:

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

5 SCARA Robot

### 6.2.1 Cartesian Coordinates

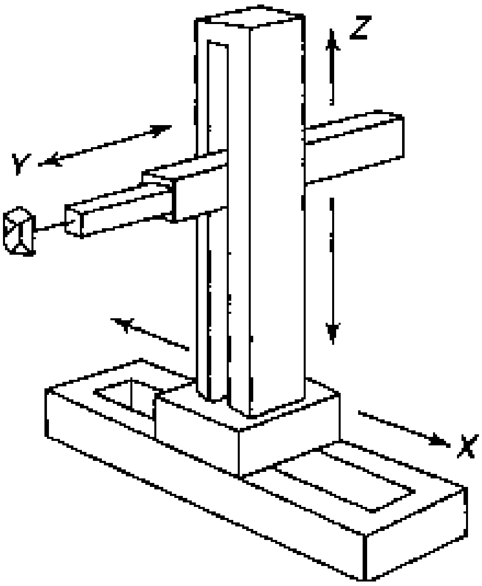



*Fig.6.1 - Typical Motions of a Cartesian or Rectilinear Robot*

Positioning may be done by linear motion along three principal axes: left and right, in and out, and up and down. These axes are known respectively, as the cartesian axes X, Y, and Z.

*Fig.6.1* shows a typical manipulator arm for a Cartesian coordinates robot. The work area or work envelope serviced by the Cartesian-coordinates robot's arm is a big box-shaped area.

Programming motion for Cartesian-coordinates robot consists of specifying to the controller the X, Y, and Z values of the desired point to be reached. The robot then moves along each axis to the desired point. This is one of the simplest types of robots.

### 6.2.2 Cylindrical Coordinates

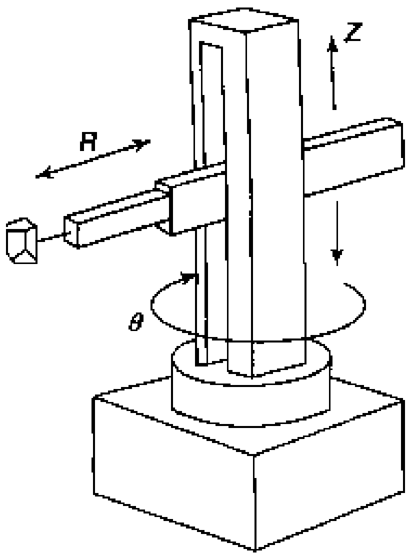



*Fig.6.2 - Typical Motions of a Cylindrical Robot*

In this type of robot, there is a rotary motion at the base followed by the two linear motions. The axes for the cylindrical coordinates are θ, the base rotational axis; R (reach) the in-and-out axis; and Z, the up-and-down axis.

The work area is the space between two concentric cylinders of the same height. The inner cylinder represents the reach of the arm with the arm fully retracted, and the outer cylinder represents the reach of the arm with the arm fully extended.

### 6.2.3 Spherical or Polar Coordinates

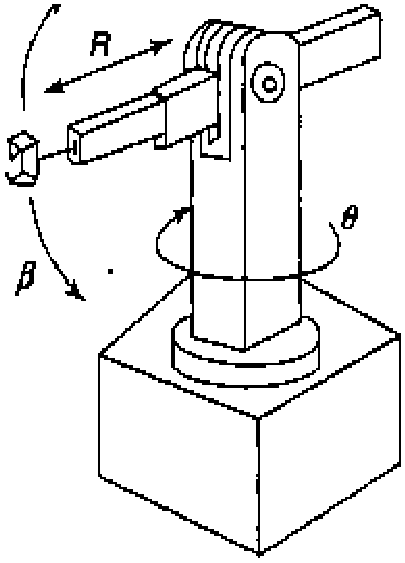



*Fig.6.3 - Typical Motions of a Spherical Robot*

This type of robot uses mostly rotational axes. The axes for the spherical coordinates are θ, the rotational axis; R, the reach axis; and β, the bend-up-and-down axis.

The work area serviced by a polar-coordinates robot is the space between two concentric hemispheres. The reach of the arm defines the inner hemisphere when it is fully retracted along the R axis. The reach of the arm defines the outer hemisphere when it is fully straightened along the R axis.

### 6.2.4 Jointed Arm Configuration

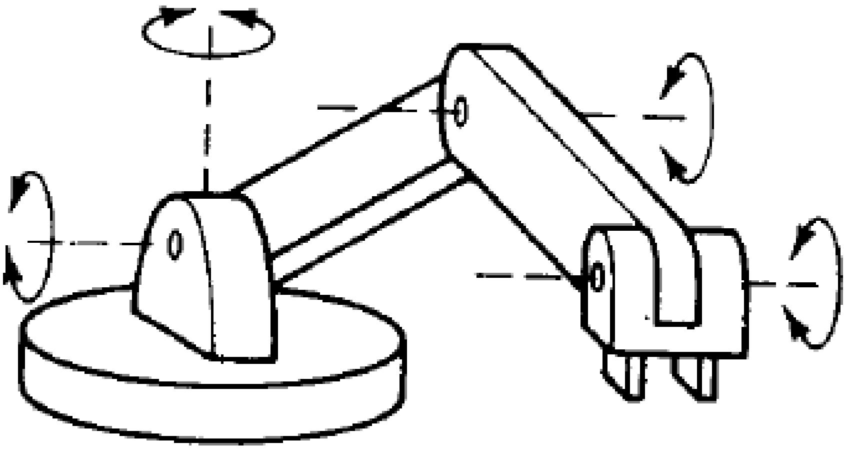


*Fig.6.4 - Typical Motions of a Cylindrical Robot*

The jointed arm configuration is similar in appearance to the human arm. The arm consists of several straight members connected by joints that are analogous to the human shoulder, elbow, and wrist. The robot arm is mounted to a base that can be rotated to provide the robot with the capacity to work within a quasi-spherical space.

### 6.2.5 SCARA Robot

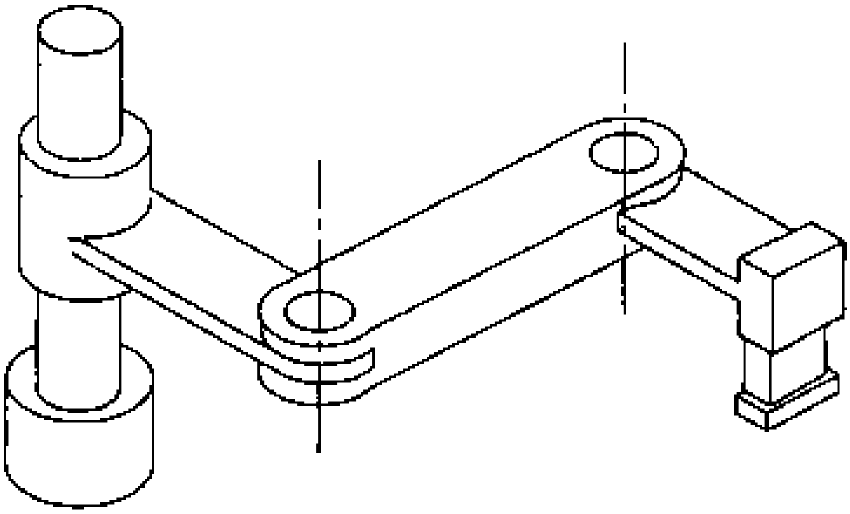


*Fig.6.5 - SCARA Robot*

Selective Compliance Assembly Robot Arm (SCARA) is a type of robot that is commonly used for assembly applications.

The arm picks up a piece-part vertically from a horizontal table and moves it in a horizontal plane to a point just above another place on the table. Then it lowers the part to the table at the proper point to accomplish the assembly, perhaps including a rotation operation to insert the part into the assembly.

## 6.3 Robot Components

A robot, as a system, consists of the following elements, which are integrated to form a whole:

**Manipulator, or Rover:** This is the main body of the robot and consists of the links, joints, and other structural elements of the robot. Without other elements, the manipulator alone is not a robot.

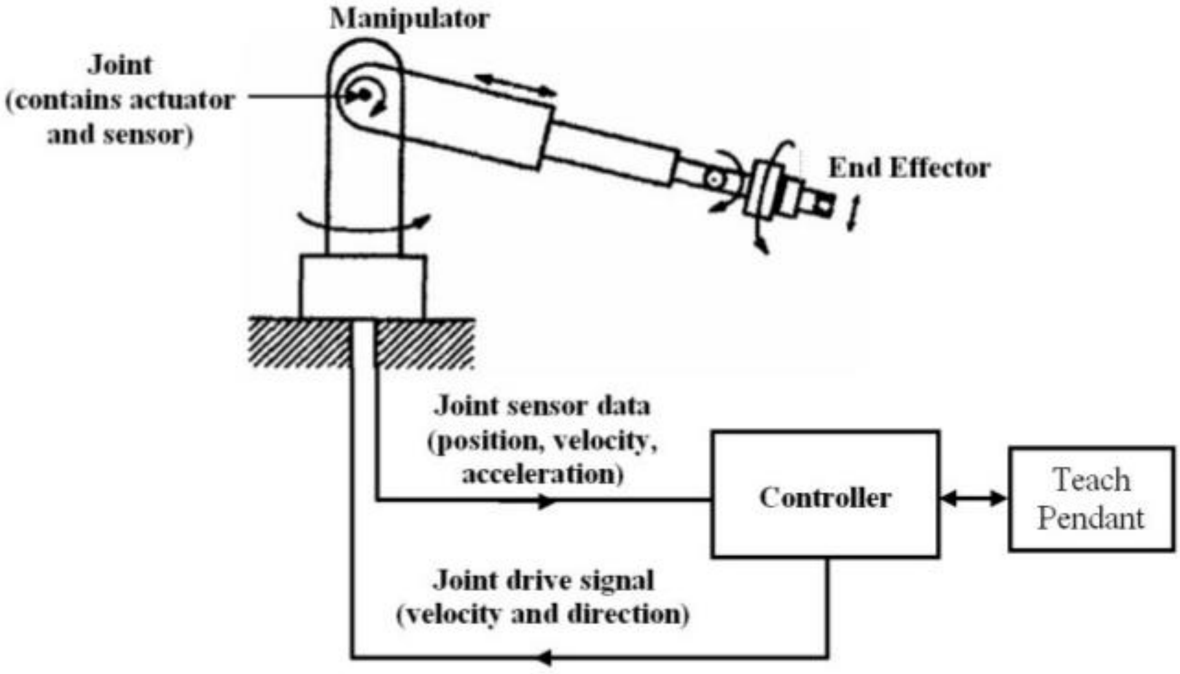



*Fig.6.6 Robot Components*

**End effector**: This is the part that is connected to the last joint (hand) of a manipulator, which generally handles objects, makes a connection to other machines, or performs the required tasks. Robot manufacturers generally do not design or sell end effectors.

- In most cases, all they supply is a simple gripper. Generally, the hand of a robot has provisions for connecting specialty end effectors that are specifically designed for a purpose. This is the job of a company's engineers or outside consultants to design and install the end effector on the robot and to make it work for the given situation.
- A welding torch, a paint spray gun, a glue-laying device, and a parts handler are but a few of the possibilities. In most cases, the action of the end effector is either controlled by the robot's controller, or the controller communicates with the end effector's controlling device (such as a PLC).

**Actuators**: Actuators are the "muscles" of the manipulators. Common types of actuators are servomotors, stepper motors, pneumatic cylinders, and hydraulic cylinders. Actuators are controlled by the controller.

**Sensors**: Sensors are used to collect information about the internal state of the robot or to communicate with the outside environment.

- As in humans, the robot controller needs to know where each link of the robot is to know the robot's configuration. Even in absolute darkness, you still know where your arms and legs are! This is because feedback sensors in your central nervous system embedded in your muscle tendons send information to your brain.
- The brain uses this information to determine the length of your muscles, and thus, the state of your arms, legs, etc. The same is true for robots; sensors integrated into the robot send information about each joint or link to the controller, which determines the configuration of the robot.
- Robots are often equipped with external sensory devices such as a vision system, touch, and tactile sensors, speech synthesizers, etc., which enable the robot to communicate with the outside world.

**Controller**: The controller is rather similar to your cerebellum, and although it does not have the power of your brain, it still controls your motions.

- The controller receives its data from the computer, controls the motions of the actuators, and coordinates the motions with the sensory feedback information.
- Suppose that for the robot to pick up apart from a bin, its first joint must be at 36°. If the joint is not already at this magnitude, the controller will send a signal to the actuator (a current to an electric motor, air to a pneumatic cylinder, or a signal to a hydraulic servo valve), causing it to move. It will then measure the change in the joint angle through the feedback sensor attached to the joint (a potentiometer, an encoder, etc.). When the joint reaches the desired value, the signal is stopped.
- In more sophisticated robots, the velocity and the force exerted by the robot are also controlled by the controller.

**Processor**: The processor is the brain of the robot.

- It calculates the motions of the robot's joints, determines how much and how fast each joint must move to achieve the desired location and speeds, and oversees the coordinated actions of the controller and the sensors.
- The processor is generally a computer, which works like all other computers, but is dedicated to a single purpose. It requires an operating system, programs, peripheral equipment such as monitors, and has many of the same limitations and capabilities of a PC processor.

**Software**: There are perhaps three groups of software that are used in a robot.

- One is the operating system, which operates the computer.
- The second is the robotic software, which calculates the necessary motions of each joint based on the kinematic equations of the robot. This information is sent to the controller. This software may be at many different levels, from machine language to sophisticated languages used by modern robots.
- The third group is the collection of routines and application programs that are developed to use the peripheral devices of the robots, such as vision routines, or to perform specific tasks.

It is important to note that in many systems, the controller and the processor are placed in the same unit. Although these two units are in the same box, and even if they are integrated into the same circuit, they have two separate functions.

## 6.4 Robot Characteristics

The following definitions are used to characterize robot specifications:

**Payload**: Payload is the weight a robot can carry and remain within its other specifications.

- For example, a robot's maximum load capacity may be much larger than its specified payload, but at the maximum level, it may become less accurate, may not follow its intended path accurately, or may have excessive deflections. The payload of robots compared with their weight is usually very small.
- For example, the Fanuc Robotics LR Mate™ robot has a mechanical weight of 86 lbs and a payload of 6.6 lbs, and the M-16i™ robot has a mechanical weight of 694 lbs and a payload of 36 lbs.

**Reach**: Reach is the maximum distance a robot can reach within its work envelope.

- Many points within the work envelope of the robot may be reached with any desired orientation (called dexterous).
- However, for other points, close to the limit of the robot's reach capability, orientation cannot be specified as desired (called nondexterous point). Reach is a function of the robot's joint lengths and its configuration.

**Precision (validity)**: Precision is defined as how accurately a specified point can be reached. This is a function of the resolution of the actuators, as well as its feedback devices. Most industrial robots can have a precision of 0.001 inches or better.

**Repeatability (variability)**: Repeatability is how accurately the same position can be reached if the motion is repeated many times.

- Suppose that a robot is driven to the same point 100 times. Since many factors may affect the accuracy of the position, the robot may not reach the same point every time but will be within a certain radius from the desired point. The radius of a circle that is formed by this repeated motion is called repeatability.
- Repeatability is much more important than precision. If a robot is not precise, it will generally show a consistent error, which can be predicted and thus corrected through programming. As an example, suppose that a robot is consistently off 0.06 inches to the right. In that case, all desired points can be specified at 0.06 inches to the left, and thus the error can be eliminated. However, if the error is random, it cannot be predicted and thus cannot be eliminated.
- Repeatability defines the extent of this random error. Repeatability is usually specified for a certain number of runs. More tests yield larger (bad for manufacturers) and more realistic (good for the users) results. Manufacturers must specify repeatability in conjunction with the number of tests, the applied payload during the tests, and the orientation of the arm.

- For example, the repeatability of an arm in a vertical direction will be different from when the arm is tested in a horizontal configuration. Most industrial robots have repeatability in the 0.001-inch range.

## 6.5 Basic Robot Motions

Whatever the configuration, the purpose of the robot is to perform a useful task. To accomplish the task, an end effector, or hand, is attached to the end of the robot's arm.

It is this end effector which adapts the general-purpose robot to a particular task. To do the task, the robot arm must be capable of moving the end effector through a sequence of motions and/or positions.

### 6.5.1 Six Degrees of Freedom

There are six basic motions, or degrees of freedom, which provide the robot with the capability to move the end effector through the required sequence of motions. There are six degrees of freedom are intended to emulate the versatility of movement possessed by the human arm. Not all robots are equipped with the ability to move in all six degrees.

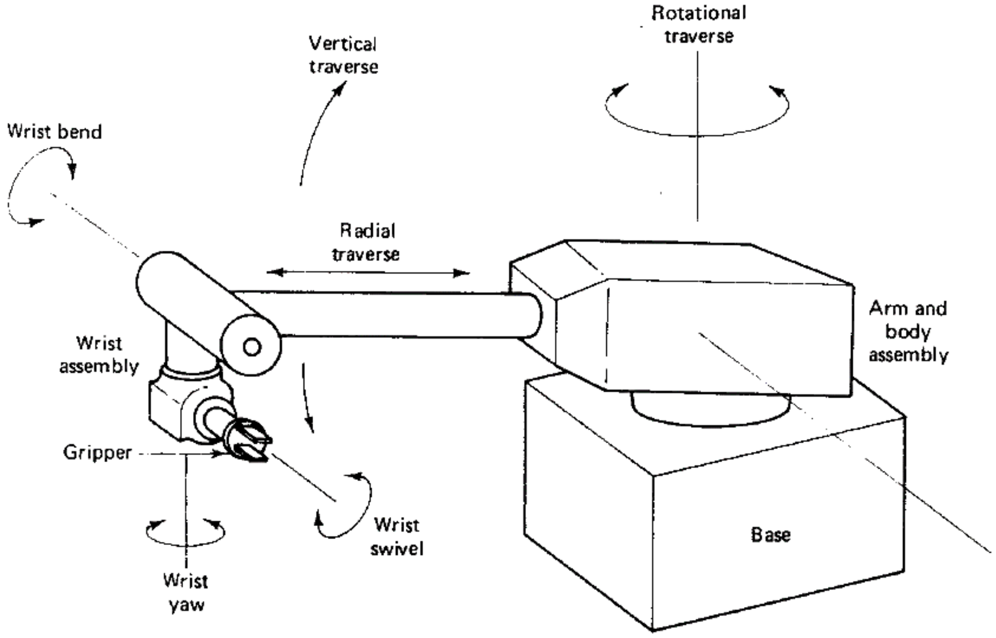



*Fig.6.7 - Typical six degrees of freedom in robot motion*

The six basic motions consist of three-arm body motions and three wrist motions, as illustrated in *Fig.6.7* polar type robot. These motions are described below.

1. **Vertical transverse**: Up-and-down motions of the arm, caused by pivoting the entire arm about a horizontal axis or moving the arm along a vertical slide
2. **Radial transverse**: Extension and retraction of the arm (in-and-out movement)
3. **Rotational transverse**: Rotation about the vertical axis (right or left swivel of the robot arm)
4. **Wrist swivel**: Rotation of the wrist
5. **Wrist bend**: Up-or-down movement of the wrist, which also involves a rotational movement
6. **Wrist yaw**: Right-or-left swivel of the wrist

Additional axes of motion are possible, for example, by putting the robot on a track or slide. The slide would be mounted on the floor or in an overhead track system, thus providing a conventional six-axis robot with the seventh degree of freedom. The gripper device is not normally considered to be an additional axis of motion.

### 6.5.2 Motion Systems

Similar to NC machine tool systems, the motion systems of industrial robots can be classified as either point-to-point (PTP) or contouring (also called continuous path).

In **point-to-point,** the robot's movement is controlled from one point location in space to another. Each point is programmed into the robot's control memory and then played back during the work cycle. No particular attention is given to the path followed by the robot in its move from one point to the next. Point-to-point robots would be quite capable of performing certain kinds of productive operations, such as machine loading and unloading, pick-and-place activities, and spot welding.

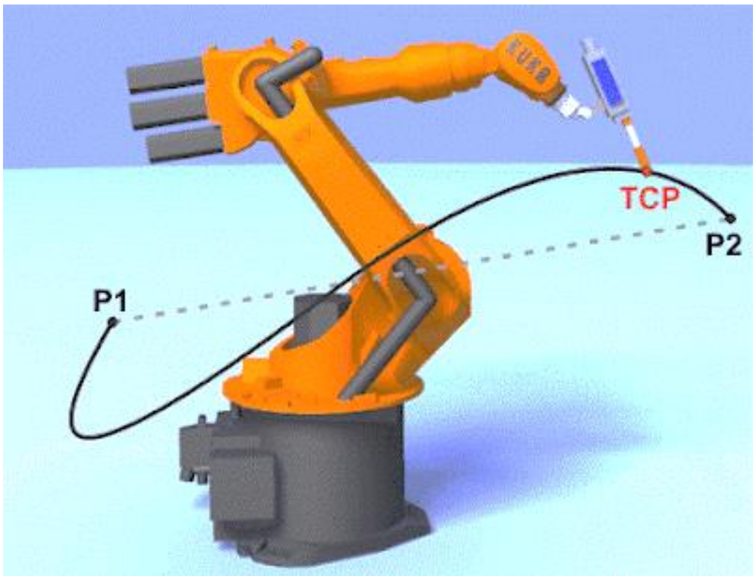



*Fig.6.8 - Point-to-point (PTP) path system*

**Contouring** robots can follow a closely spaced locus of a point which describes a smooth compound curve. The memory and control requirements are greater for contouring robots than for PPT because the complete path taken by the robot must be remembered rather than merely the endpoints of the motion sequence. However, in certain industrial operations, continuous control of the work cycle path is essential to the use of robots in the operation. Examples of these operations are paint spraying, continuous welding processes, and grasping objects moving along a conveyor.

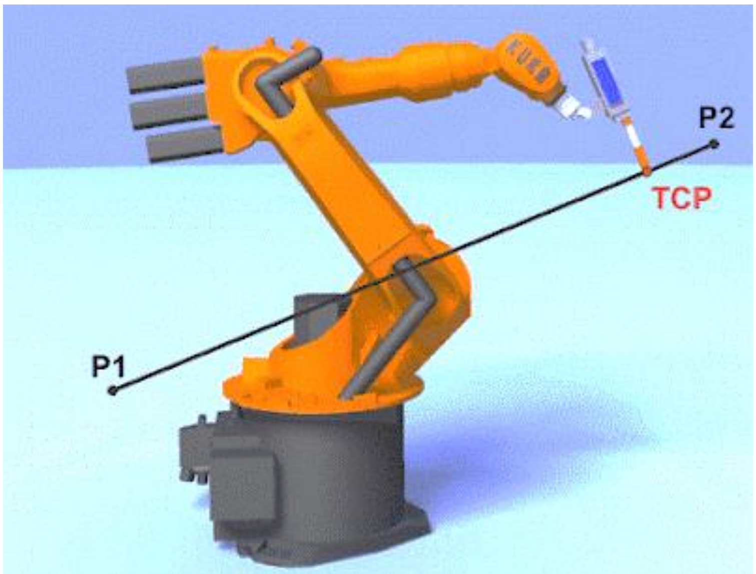



*Fig.6.9 - Contouring path system*

### 6.5.3 Other Technical Features

There are numerous other technical features of an industrial robot that determine its efficiency and effectiveness at performing a given task.

The following are some of the most important among these technical features:

**Work volume:**

The term "work volume" refers to space within which the robot can operate. To be technically precise, the work volume is the spatial region within which the end of the robot's wrist can be manipulated. Robot manufacturers have adopted the policy of defining the work volume in terms of the wrist end, with no hand or tool attached.

The work volume of an industrial robot is determined by its physical configuration, size, and limits of its arm and joint manipulations.

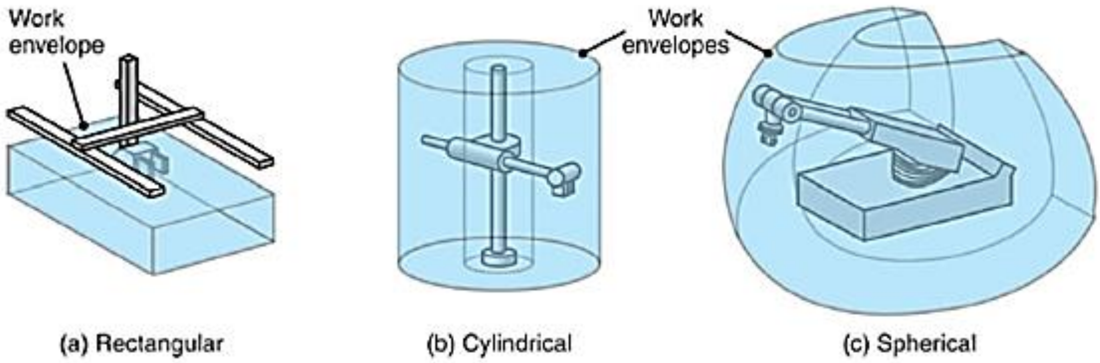



*Fig.6.10 – Work Volume*

The work volume of a Cartesian coordinate robot will be rectangular. The work volume of a cylindrical coordinate robot will be cylindrical. A polar coordinate configuration will generate a working volume which is a partial sphere. The work volume of a jointed arm robot will be somewhat irregular, the outer reaches generally resembling a partial sphere.

Robot manufacturers usually show a diagram of the particular model's work volume in their marketing literature, providing a top view and side view with dimensions of the robot's motion envelope.

**The precision of movement:**

The precision with which the robot can move the end of its wrist is a critical consideration in most applications. In robotics, the precision of movement is a complex issue, and we will describe it as consisting of three attributes: Spatial resolution, Accuracy, and Repeatability.

These attributes are generally interpreted in terms of the wrist end with no end effector attached and with the arm fully extended.

- **Spatial resolution**: The term "spatial resolution" refers to the smallest increment of motion at the wrist end that can be controlled by the robot. This is determined largely by the robot's control resolution, which depends on its position control system and/or its feedback measurement system. In addition, mechanical inaccuracies in the robot's joints would tend to degrade its ability to position its arm.
  The spatial resolution is the sum of the control resolution plus these mechanical inaccuracies. The factors determining control resolution are the range of movement of the arm and the bit storage capacity in the control memory for that movement.

The arm movement must be divided into its basic motions or degrees of freedom, and the resolution of the degree of freedom is figured separately. Then the total control resolution is the vector sum of each component.

- **Accuracy**: The accuracy of the robot refers to its capability to position its wrist end (or a tool attached to the wrist) at a given target point within its work volume. Accuracy is closely related to spatial resolution since the robot's ability to reach a particular point in space depends on its ability to divide its joint movement into small increments.
  According to this relation, the accuracy of the robot would be one-half the distance between two adjacent resolution points. The robot's accuracy is also affected by mechanical inaccuracies, such as the deflection of its components, gear inaccuracies, and so forth.
- **Repeatability**: This refers to the robot's ability to position its wrist end (or tool) back to a point in space. Repeatability is different from accuracy.
  The robot will initially be programmed to move the wrist end to the target point T. Because it is limited by its accuracy, the robot was only capable of achieving point A. The distance between points A and T is the accuracy. Later, the robot is instructed to return to this previously programmed point A. However, because it is limited by its repeatability, it is only capable of moving to point R. The distance between points R and A is a measure of the robot's repeatability.
  As the robot is instructed to return to the same position in subsequent work cycles, it will not always return to point R, but instead will form a cluster of positions about point A. Repeatability errors form a random variable. In general, repeatability will be better (less) than accuracy.
  Mechanical inaccuracies in the robot's arm and wrist components are principal sources of repeatability errors.

**Speed of movement:**

The speed with which the robot can manipulate the end effector ranges up to a maximum of about 1.6 m/s. almost all robots have an adjustment to set the speed to the desired level for the task performed. This speed should be determined by such factors as the weight of the object being moved, the distance moved, and the precision with which the object must be positioned during the work cycle.

Heavy-object cannot be moved as fast as light objects because of inertia problems. Also, objects must be moved more slowly when high positional accuracy is required.

**Weight-carrying capacity:**

The weight-carrying capacity of commercially available robots covers a wide range. At the upper end of the range, there are robots capable of lifting over 1000 lb. The Versatran FC model has a maximum load-carrying capacity rated at 2000 lb. At the lower end of the range, the ultimate PUMA Model 260 has a load capacity of only 2.6 lb. What complicates the issue for the low-weight-capacity robots is that the rated capacity includes the weight of the end effector. For example, if the gripper for the PUMA 260 weighs 1 lb, the net capacity of the robot is only 1.6 lb.

**Type of drive system:**

There are three basic drive systems used in commercially available robots: Hydraulic, Electric motor, and Pneumatic.

**Hydraulic** drive systems are usually associated with large robots, and this drive system adds to the floor space required by the robot. Advantages which this type of system gives to the robot are mechanical simplicity, high strength, and high speed.

Robots driven by **electric** motors (dc stepping motors or servo motors) do not possess the physical strength or speed of hydraulic units, but their accuracy and repeatability are generally better. Less floor space is required due to the absence of the hydraulic power unit.

**Pneumatically** driven robots are typically smaller and technologically less sophisticated than the other two types. Pick-and-place tasks and other simple, high-cycle-rate operations are examples of the kinds of applications usually reserved for these robots.

## 6.6 Actuators

Actuators are the muscles of robots. If you imagine that the links and the joints are the skeletons of the robot, the actuators act as muscles, which move or rotate the links to change the configuration of robots. The actuator must have enough power to accelerate and decelerate the links and to carry the loads, yet be light, economical, accurate, responsive, reliable, and easy to maintain.

There are many types of actuators available, and, undoubtedly, there will be more varieties available in the future. The following types are noteworthy:

- Electric motors
    - Servomotors
    - Stepper motors
    - Direct-drive electric motors
- Hydraulic actuators
- Pneumatic actuators
- Shape memory metal actuators
- Magnetostrictive actuators


*Fig.6.11 - Actuators*

Electric motors — especially servomotors — are the most commonly used robotic actuators.

Hydraulic systems were very popular for large robots in the past and are still around in many places, but are not used in new robots as often anymore.

Pneumatic cylinders are used in robots that have 1/2 degree of freedom, on-off type joints, as well as for insertion purposes.

Direct drive electric motors, the shape memory metal type-actuators, and others like them are mostly in the research and development stage and may become more useful shortly.

## 6.7 End Effectors

In the terminology of robotics, an end effector can be defined as a device that is attached to the robot's wrist to perform a specific task. The task might be work part handling, spot welding, spray painting, or any of a great variety of other functions.

The possibilities are limited only by the imagination and ingenuity of the applications engineers who design robot systems. Economic considerations might also impose a few limitations. The end effector is the special-purpose tooling that enables the robot to perform a particular job.

*Fig.6.12 - End effectors*

It is usually custom engineered for that job, either by the company that owns the robot or by the company that sold the robot. Most robot manufacturers have engineering groups that design and fabricate end effectors or provide advice to their customers on end-effector design.

For purposes of organization, we will divide the various types of end effectors into two categories: grippers and tools. The following two sections discuss these two categories.

### 6.7.1 Tools as End Effectors

In many applications, the robot is required to manipulate a tool rather than a work part. In a limited number of these applications, the end effector is a gripper that is designed to grasp and handle the tool.

The reason for using a gripper in these applications is that there may be more than one tool to be used by the robot in the work cycle. The use of a gripper permits the tools to be exchanged during the cycle, and thus facilitates this multitool handling function.

In most of the robot applications in which a tool is manipulated, the tool is attached directly to the robot wrist. In these cases, the tool is the end effector. Some examples of tools used as end effectors in robot applications include:

- Spot-welding tools
- Arc-welding torch
- Spray-painting nozzle
- Rotating spindles for operations such as drilling, routing, wire brushing, and grinding
- Heating torches
- Water jet cutting tool

## 6.8 Grippers

Grippers are end effectors used to grasp and hold objects. The objects generally work parts that are to be moved by the robot. These part-handling applications include machine loading and unloading, picking parts from a conveyor, and arranging parts onto a pallet.

In addition to work parts, other objects handled by robot grippers include cartons, bottles, raw materials, and tools. We tend to think of grippers as mechanical grasping devices, but there are alternative ways of holding objects involving the use of magnets, suction cups, or other means.

### 6.8.1 Mechanical Grippers

A mechanical gripper is an end effector that uses mechanical fingers actuated by a mechanism to grasp an object. The fingers, sometimes called jaws, are the appendages of the gripper that make contact with the object.

The fingers are either attached to the mechanism or are an integral part of the mechanism. If the fingers are of the attachable type, then they can be detached and replaced. The use of replaceable fingers allows for wear and interchangeability.

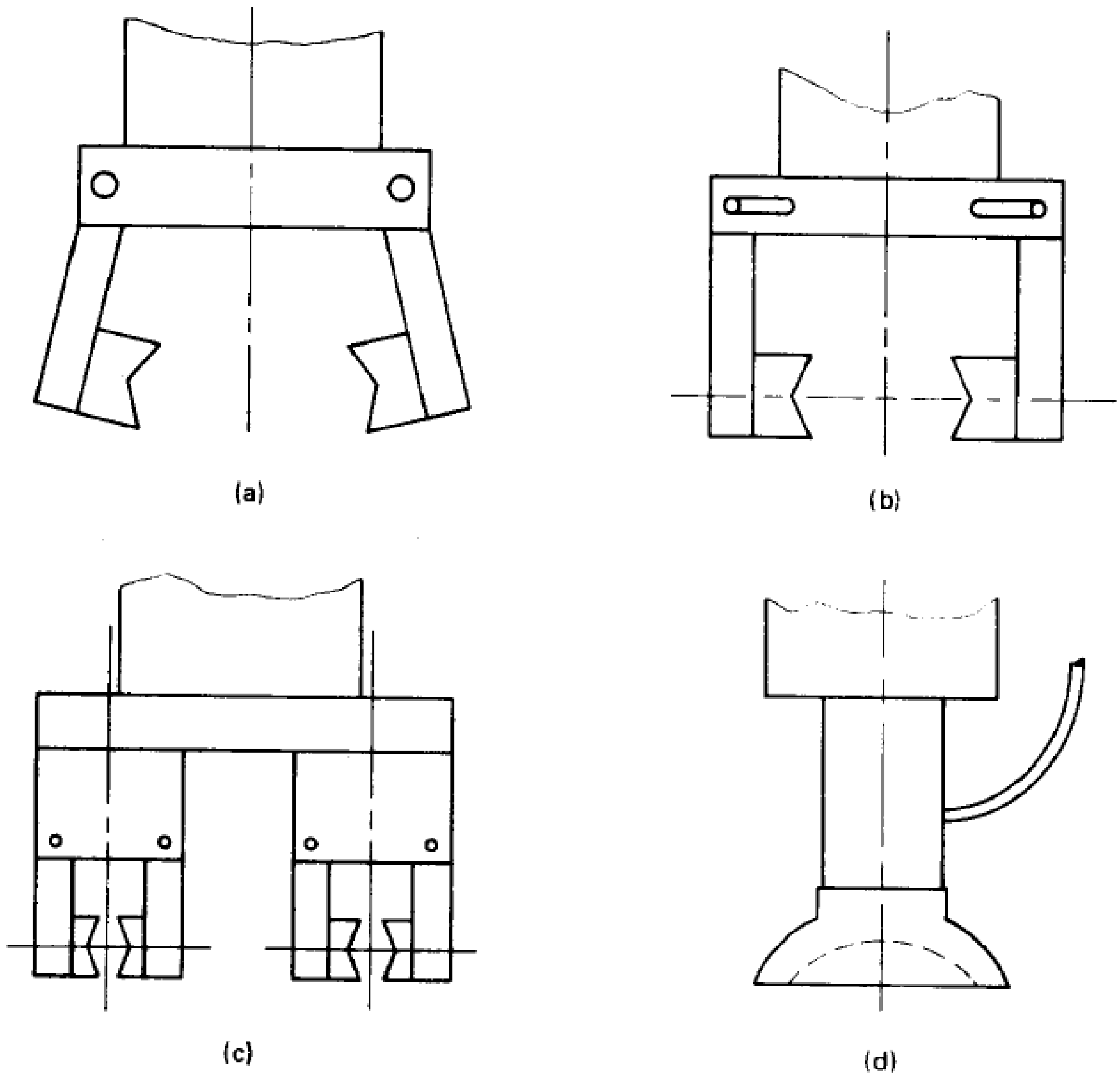



*Fig.6.13 - Sample gripper designs: (a) pivot action grippe; (b) slide action gripper;(c) double gripper-pivot action mechanism; (d) vacuum-operated hand*

### 6.8.2 Vacuum cups

Vacuum cups, also called suction cups, can be used as gripper devices for handling certain types of objects. The usual requirements on the objects to be handled are that they are flat, smooth, and clean, conditions necessary to form a satisfactory vacuum between the object and the suction cup.

The suction cups of the robot gripper are typically made of an elastic material such as rubber or soft plastic. An exception would be when the object to be handled is composed of a soft material. In this case, the suction cup would be made of a hard substance.

### 6.8.3 Magnetic Grippers

Magnetic grippers can be a very feasible means of handling ferrous materials. The stainless steel plate would not be an appropriate application for a magnetic gripper because 18-8 stainless steel is not attracted by a magnet. Other steels, however, including certain types of stainless steel, would be suitable candidates for this means of handling, especially when the materials are handled in sheet or plate form.

In general, magnetic grippers offer the following advantages in robotic handling applications:

- Pickup times are very fast.
- Variations in part size can be tolerated. The gripper does not have to be designed for one particular work part.
- They can handle metal parts with holes (not possible with vacuum grippers).
- They require only one surface for gripping.

Disadvantages with magnetic grippers include the residual magnetism remaining in the workpiece which may cause a problem in subsequent handling, and the possible side slippage and other errors which limit the precision of this means of handling.

### 6.8.4 Adhesive Gripper

Gripper designs in which an adhesive substance performs the grasping action can be used to handle fabrics and other lightweight materials. The requirements on the items to be handled are that they must be gripped on one side only and that other forms of grasping such as a vacuum or magnet are not appropriate.

One of the potential limitations of an adhesive gripper is that the adhesive substance loses its tackiness on repeated Usage. Consequently, its reliability as a gripping device is diminished with each successive operation cycle.

To overcome this limitation, the adhesive material is loaded in the form of a continuous ribbon into a feeding mechanism that is attached to the robot wrist. The feeding mechanism operates like a typewriter ribbon mechanism.

## 6.9 Transducers

A transducer is a device that converts one type of physical variable (e.g., force, pressure, temperature, velocity, flow rate, etc.) into another form. A common conversion is to electrical voltage, and the reason for making the conversion is that the converted signal is more convenient to use and evaluate.

A sensor is a transducer that is used to measure a physical variable of interest. Some of the common sensors and transducers include strain gauges (used to measure force and pressure), thermocouples (temperatures), speedometers (velocity), and Pitot tubes (flow rates).

Any sensor or transducer requires calibration to be useful as a measuring device. Calibration is the procedure by which the relationship between the measured variable and the converted output signal is established.

Transducers and sensors can be classified into two basic types depending on the form of the converted signal. The two types are:

1. Analog transducers
2. Digital transducers

Analog transducers provide a continuous analog signal such as electrical voltage or current. This signal can then be interpreted as the value of the physical variable that is being measured.

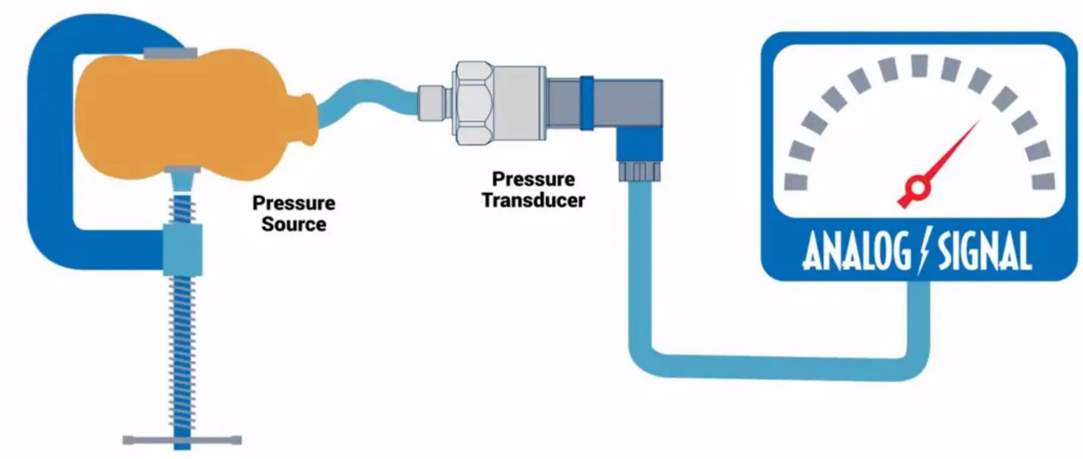



*Fig.6.14 – A Pressure Transducer*

Digital transducers produce a digital output signal, either in the form of a set of parallel status bits or a series of pulses that can be counted. In either form, the digital signal represents the value of the measured variable.

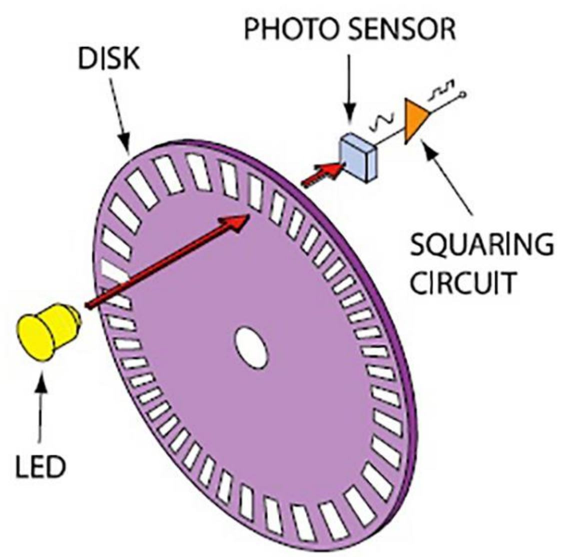



*Fig.6.15 – A Shaft Encoder – Digital Transducer*

Digital transducers are becoming more popular because of the ease with which they can be read as separate measuring instruments. In addition, they offer the advantage in automation and process control that they are generally more compatible with the digital computer than analog-based sensors.

### 6.9.1 Intelligent Robots

Intelligent robots constitute a growing class of industrial robot that possesses the capability not only to playback a programmed motion cycle but to also interact with its environment in a way that seems intelligent. Invariably, the controller unit consists of a digital computer or similar device (e.g., programmable controller).

Intelligent robots can alter their programmed cycle in response to conditions that occur in the workplace. They can make logical decisions based on sensor data received from the operation. The robots in this class can communicate during the work cycle with humans or computer-based systems.

Intelligent robots are usually programmed using an English-like and symbolic language, not unlike a computer programming language.

Indeed, the kinds of applications that are performed by intelligent robots rely on the use of a high-level language to accomplish the complex and sophisticated activities that can be accomplished by these robots. Typical applications for intelligent robots are assembly tasks and arc-welding operations.

### 6.9.2 Work Cell Control

Industrial robots usually work with other things: processing equipment, work parts, conveyors, tools, and perhaps, human operators. A means must be provided for coordinating all of the activities which are going on within the robot workstation.

Some of the activities occur sequentially, while others take place simultaneously. To make certain that the various activities are coordinated and occur in the proper sequence, a device called the work cell controller is used (another name for this is the workstation controller). The work cell controller usually resides within the robot and has overall responsibility for regulating the activities of the work cell components.

### 6.9.3 Interlocks

An interlock is the feature of work cell control that prevents the work cycle sequence from continuing until a certain condition or set of conditions has been satisfied. In a robotic work cell, there are two types: outgoing and incoming.

The **outgoing interlock** is a signal sent from the workstation controller to some external machine or device that will cause it to operate or not operate. For example, this would be used to prevent a machine from initiating its process until it was commanded to proceed by the work cell controller.

An **incoming interlock** is a signal from some external machine or device to the work controller which determines whether or not the programmed work cycle sequence will proceed. For example, this would be used to prevent the work cycle program from continuing until the machine signaled that it had completed its processing of the workpiece.

The use of interlocks provides an important benefit in the control of the work' cycle because it prevents actions from happening when they shouldn't, and it causes actions to occur when they should. Interlocks are needed to help coordinate the activities of the various independent components in the work cell and to help avert damage of one component by another.

In the planning of interlocks in the robotic work cell, the application engineer must consider both the normal sequence of activities that will occur during the work cycle and the potential malfunctions that might occur.

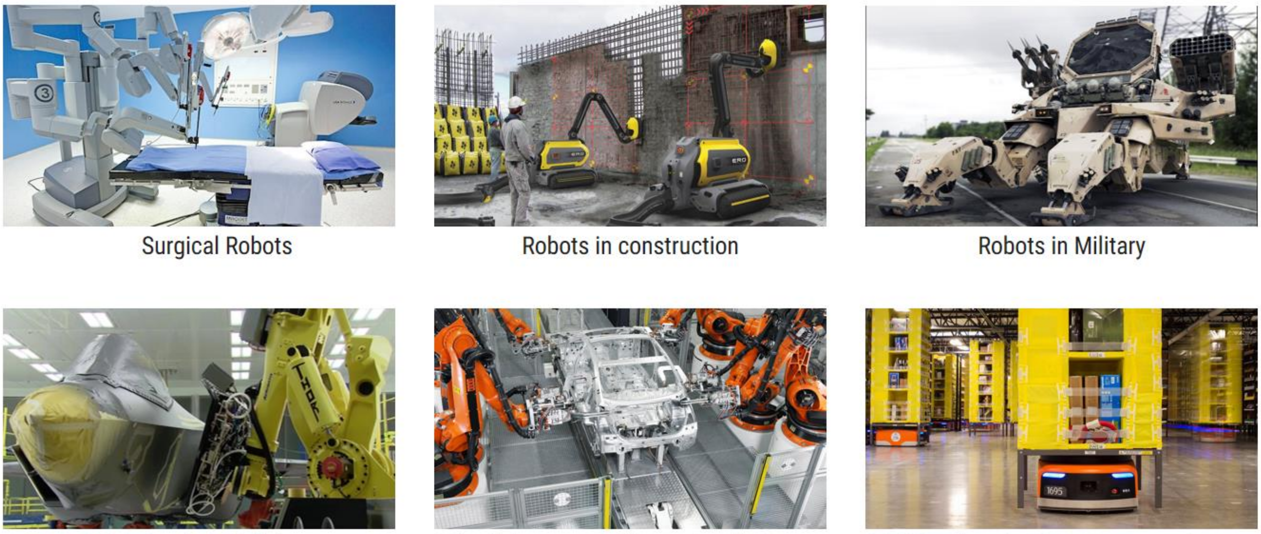
Then these normal activities are linked together through limit switches, pressure switches, photoelectric devices, and other system components. Malfunctions that can be anticipated are prevented using similar devices.

## 6.10 Robot Applications

Robots are best suited to work in environments where humans cannot perform the tasks. Robots have already been used in many industries and for many purposes. They can often perform better than humans and at lower costs.

For example, a welding robot can probably weld better than a human welder, because the robot can move more uniformly and more consistently. In addition, robots do not need protective goggles, protective clothing, ventilation, and many other necessities that their human counterparts do. As a result, robots can be more productive and better suited for the job.

A robot exploring the ocean bottom would require far less attention than a human diver. Also, the robot can stay underwater for long periods and can go to very large depths and still survive the pressure; it also does not require oxygen.



Surgical Robots | Robots in construction | Robots in Military

660 holes in F-16 fighter | 98% of the spot welding on Ford's Taurus by Robots | 30,000 robots in 10 Amazon warehouses

*Fig.6.16 - Robot Applications*

The following is a list of some applications where robots are useful. The list is not complete by any stretch of the imagination. There are many other uses as well, and other applications find their way into the industry and the society all the time:

- **Machine loading**, where robots supply parts to or remove parts from other machines. In this type of work, the robot may not even perform any operation on the part but is only a means of handling parts within a set of operations.
- **Pick and place operations**, where the robot picks up parts and places them elsewhere. This may include palletizing, placing cartridges, a simple assembly where two parts are put together (such as placing tablets into a bottle), placing parts in an oven, and removing the treated part from the oven.
- **Welding**, where the robot, along with proper setups and a welding end effector, is used to weld parts together. This is one of the most common applications of robots in the auto industry. Due to the robots' consistent movements, the welds are very uniform and accurate. Welding robots are usually large and powerful.
- **Painting** is another very common application of robots, especially in the automobile industry. Since maintaining a ventilated, but clean, room suitable for humans is difficult, and compared with those performed by humans, robotic operations are more consistent, painting robots are very well suited for their job.

- **Inspection** of parts, circuit boards, and other similar products is also a very common application for robots. In general, some other device is integrated into the system for inspection. This may be a vision system, an X-ray device, an ultrasonic detector, or other similar devices.
    - In one application, a robot equipped with an ultrasound crack detector was given the computer-aided design (CAD) data about the shape of an airplane fuselage and wings and was used to follow the airplane's body contours and check each joint, weld, or rivet.
    - In a similar application, a robot was used to search for and find the location of each rivet, detect and mark the rivets with fatigue cracks, drill them out, and move on. The technicians would insert and install new rivets. Robots have also been extensively used for circuit board and chip inspection.
- **Sampling** with robots is used in many industries, including in agriculture. Sampling can be similar to pick and place and inspection, except that it is performed only on a certain number of products.
- **Assembly operations** are among the most difficult for the robot to do. Usually, assembling components into a product involves many operations. For example, the parts must be located and identified, carried in a particular order with many obstacles around the setup, fitted together, and then assembled. Many of the fitting and assembling tasks are complicated as well and may require pushing, turning, bending, wiggling, pressings, and snapping the tabs to connect the parts.
- **Manufacturing** by robots may include many different operations, such as material removal, drilling, deburring, laying glue, cutting, etc. It also includes the insertion of parts, such as electronic components into circuit boards, installation of boards into electronic devices such as VCRs, and other similar operations.
- **Surveillance** by robots has been tried but was not too successful. However, the use of vision systems for surveillance has been very extensive, both in security industry and in traffic control. For example, in one part of the highway system in Southern California, one lane of traffic has been leased out to private industry, which maintains the road and provides services but also charges users. Surveillance cameras are used to detect the license plates of the cars that use the road, which is subsequently charged a toll for road use.
- **Medical applications** are also becoming increasingly common. For example, the Robodoc was designed to assist a surgeon in total-joint replacement operations. Since many of the functions that are performed during this procedure, such as cutting off the head of the bone, drilling a hole in the bone's body, reaming the hole for precise dimension, and installation of the manufactured implant joint, can be performed by a robot with better precision than by a human, the mechanical parts of the operation are assigned to the robot. Similarly, many other robots have been used to assist surgeons during microsurgery, including operations on heart valves in Paris.
- **Assisting disabled individuals** has also been tried with interesting results. There is much that can be done to help the disabled in their daily lives. In one study, a small table-top robot was programmed to communicate with a disabled person and to perform simple tasks such as placing a food plate into the microwave oven, removing the plate from the oven, and placing the plate in front of the disabled person to eat. Many other tasks were also programmed for the robot to perform.
- **Hazardous environments** are well suited for robotics use. Because of their inherent danger in these environments, humans must be well protected against the dangers. However, robots can access, traverse, maintain, and explore these areas without the same level of concern. Servicing a radioactive environment, for instance, can be done much easier with a robot than with a human.
- **Underwater, space, and remote locations** can also be serviced or explored by robots. Although no human has yet been sent to Mars, there have been several rovers that have already landed and explored it.

## 6.11 Advantages and Disadvantages of Robots

- Robotics and automation can, in many situations, increase productivity, safety, efficiency, quality, and consistency of products.
- Robots can work in hazardous environments without the need for life support, comfort, or safety concerns.
- Robots need no environmental comfort, such as lighting, air conditioning, ventilation, and noise protection.
- Robots work continuously without experiencing fatigue or boredom, do not get mad, do not have hangovers, and need no medical insurance or vacation.
- Robots have repeatable precision at all times unless something happens to them or unless they wear out.
- Robots can be much more accurate than humans. Typical linear accuracies are a few thousands of an inch. New wafer-handling robots have microinch accuracies.
- Robots and their accessories and sensors can have capabilities beyond that of humans.
- Robots can process multiple stimuli or tasks simultaneously. Humans can only process one active stimulus.
- Robots replace human workers creating economic problems, such as lost salaries, and social problems, such as dissatisfaction and resentment among workers.
- Robots cannot respond in emergencies unless the situation is predicted and the response is included in the system. Safety measures are needed to ensure that they do not injure operators and machines working with them. This includes:
    - Inappropriate or wrong responses
    - A lack of decision-making power
    - A loss of power
    - Damage to the robot and other devices
    - Human injuries
- Robots, although superior in certain senses have limited capabilities in
    - Degrees of freedom
    - Dexterity
    - Sensors
    - Vision systems
    - Real-time response
- Robots are costly, due to
    - The initial cost of equipment
    - Installation costs
    - Need for peripherals
    - Need for training
    - Need for programming

## 6.12 Robotic Power Sources

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.

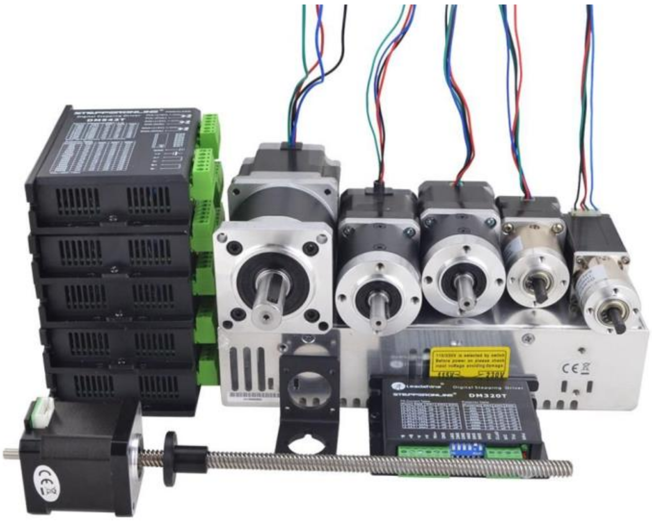


*Fig.6.17 - Robotic Power Sources*

### 6.12.1 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 servo motors 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.

Because electric robots do not require a hydraulic power unit, they conserve floor space and decrease factory noise. Direct drive models provide a 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 couplings, such as a lead screw, pulley block, spur gears, or harmonic drive.

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.

### 6.12.2 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.

The 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 non-linearities of joint motion inherent in linkwork conversion of linear to rotary motion.

An advantage of the pneumatic actuator is its inherently lightweight, 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 lightweight, 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.

### 6.12.3 Hydraulic Power Source

Hydraulic drives are either linear piston actuators or rotary vane configurations. 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 Revels.

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. The oil that is contaminated is costly to remove, and any leakage is considered an environmental contamination problem.

### 6.12.4 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 lightweight. 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.

## 6.13 Robotic Sensors

For certain robot applications, the type of workstation control using interlocks is not adequate. The robot must take on more human-like senses and capabilities to perform the task satisfactorily. These senses and capabilities include vision and hand-eye coordination, touch, and hearing.

Accordingly, we will divide the types of sensors used in robotics into the following three categories:

1 Vision sensors
2 Tactile and proximity sensors
3 Voice sensors

### 6.13.1 Vision Sensors

This is one of the areas that is receiving a lot of attention in robotics research. Computerized vision systems will be an important technology in future automated factories. Robot vision is made possible using a video camera, a sufficient light source, and a computer programmed to process image data.

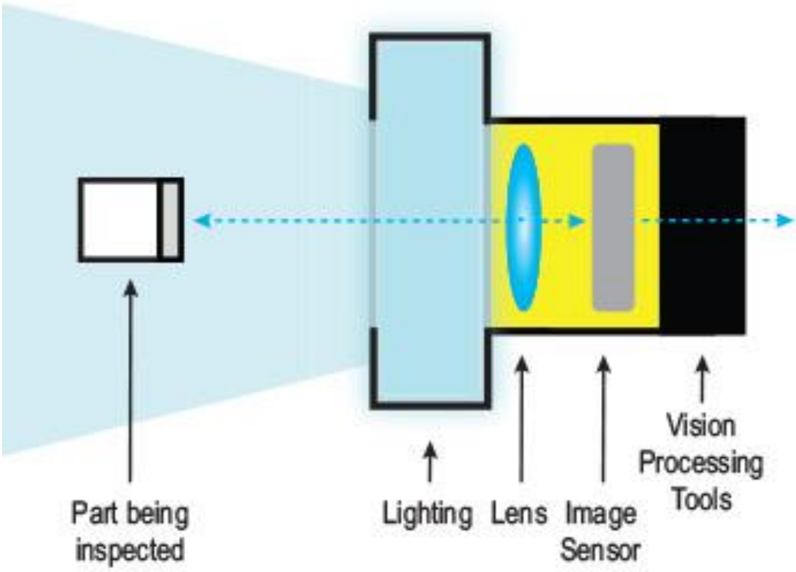



*Fig.6.18 – Vision Sensor*

The camera is mounted either on the robot or in a fixed position above the robot so that its field of vision includes the robot's work volume. The computer software enables the vision system to sense the presence of an object and its position and orientation.

Vision capability would enable the robot to carry out the following kinds of operations:

- Retrieve parts that are randomly oriented on a conveyor.
- Recognize particular parts which are intermixed with other objects.
- Perform visual inspection tasks.
- Perform assembly operations that require alignment.

All of these operations have been accomplished in research laboratories. It is merely a matter of time and economics before vision sensors become a common feature in robot applications.

### 6.13.2 Tactile and Proximity Sensors

Tactile sensors provide the robot with the capability to respond to contact forces between itself and other objects within its work volume. Tactile sensors can be divided into two types:

1 Touch sensors
2 Stress sensors (also called force sensors)

Touch sensors are used simply to indicate whether contact has been made with an object. A simple microswitch can serve the purpose of a touch sensor. Stress sensors are used to measure the magnitude of the contact force. Strain gauge devices are typically employed in force-measuring sensors.

Potential uses of robots with tactile sensing capabilities would be in assembly and inspection operations. In assembly, the robot could perform delicate part alignment and joining operations.

In inspection, touch sensing would be useful in gauging operations and dimensional-measuring activities. Proximity sensors are used to sense when one object is close to another object.

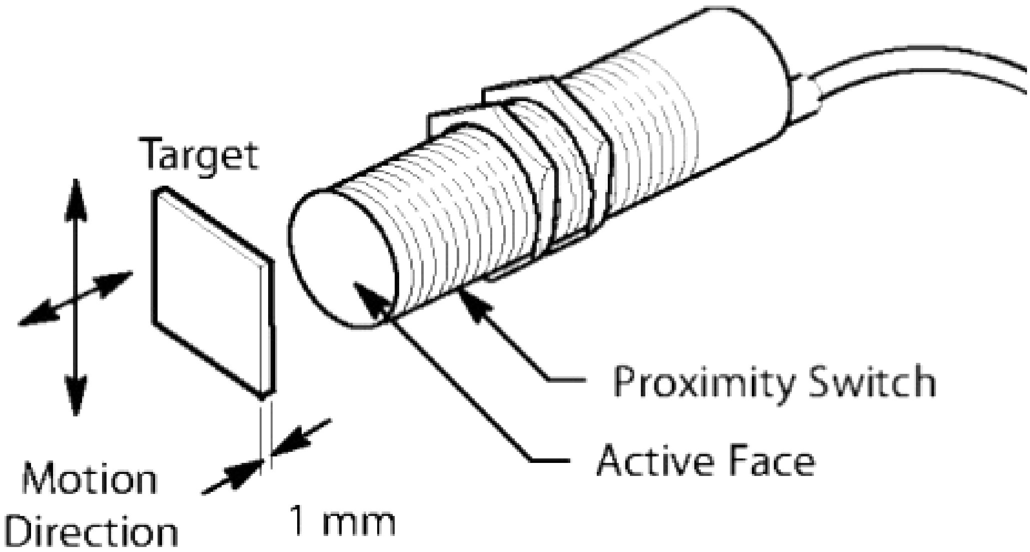



*Fig.6.19 - Proximity Sensor*

On a robot, the proximity sensor would be located on or near the end effector. engineered using optical-proximity devices, eddy-current proximity detectors, magnetic-field sensors, or other devices.

In robotics, proximity sensors might be used to indicate the presence or absence of a work part or other object. They could also help prevent injury to the robot's human coworkers in the factory.

### 6.13.3 Voice Sensors

Another area of robotics research is voice sensing or voice programming. Voice programming can be defined as the oral communication of commands to the robot or other machine.

The robot controller is equipped with a speech recognition system that analyzes the voice input and compares it with a set of stored word patterns. When a match is found between the input and the stored vocabulary word, the robot performs some action that corresponds to that word.

Voice sensors would be useful in robot programming to speed up the programming procedure, just as it does in NC programming. It would also be beneficial in especially hazardous working environments for performing unique operations such as maintenance and repair work.

The robot could be placed in a hazardous environment and remotely commanded to perform the repair chores using step-by-step instructions.

## 6.14 Programming of the Robot

There are various methods by which robots can be programmed to perform a given work cycle. Divide these programming methods into four categories:

1. Manual method
2. Walkthrough method
3. Lead through method
4. Off-line programming

### 6.14.1 Manual method

This method is not programming in the conventional sense of the world. It is more like setting up a machine rather than programming.

It is the procedure used for simpler robots and involves setting mechanical stops, cams, switches, or relays in the robot's control unit. For these low-technology robots used for short work cycles, the manual programming method is adequate.

### 6.14.2 Walkthrough method

In this method, the programmer manually moves the robot's arm and hand through the motion sequence of the work cycle. Each movement is recorded into memory for subsequent playback during production.

The speed with which the movements are performed can usually be controlled independently so that the programmer does not have to worry about the cycle time during the walkthrough.

The main concern is getting the position sequence correct. The walkthrough method would be appropriate for spray painting and arc welding robots.

### 6.14.3 Lead through method

The lead-through method makes use of a teach pendant to power drive the robot through its motion sequence. The teach pendant is usually a small hand-held device with switches and dials to control the robot's physical movement.

Each motion is recorded into memory for future playback during the work cycle. The lead-through method is very popular among robot programming methods because of its ease and convenience.

### 6.14.4 Off-line programming

This method involves the preparation of the robot program off-line, like NC part programming. Off-line robot programming is typically accomplished on a computer terminal. After the program has been prepared, it is entered into the robot memory for use during the work cycle.

The advantage of off-line robot programming is that the production time of the robot is not lost to delays in teaching the robot a new task. Programming off-line can be done while the robot is still in production on the preceding job. This means higher utilization of the robot and the equipment with which it operates.

## 6.15 Robot Programming Languages

Non-computer-controlled robots do not require a programming language. They are programmed by the walkthrough or lead-through methods while the simpler robots are programmed by manual methods. With the introduction of computer control for robots came the opportunity and the need to develop a computer-oriented robot programming language.

In this section, discuss two of these languages: VAL, developed for the Unimation PUMA robot; and MCL, and APT-based language developed by McDonnell-Douglas Corporation.

### 6.15.1 The VAL language

The VAL language was developed by Victor Scheinman for the PUMA robot, an assembly robot produced by Unimation Inc. Hence, VAL stands for Victor's Assembly Language. It is an off-line language in which the program defining the motion sequence can be developed off-line, but the various point locations used in the work cycle are most conveniently defined by lead through.

VAL statements are divided into two categories. Monitor Commands and Programming Instructions.

The Monitor Commands are a set of administrative instructions that direct the operation of the robot system. The Monitor Commands would be used for such functions as:

- Preparing the system for the user to write programs for the PUMA
- Defining points in space
- Commanding the PUMA to execute a program
- Listing programs on the CRT

The Program Instructions are a set of statements used to write robot programs. Programs in VAL direct the sequence of motions of the PUMA. One statement usually corresponds to one movement of the robot's arm or wrist. Examples of Program Instructions include:

- Move to a point
- Move to a point in a straight-line motion
- Open gripper
- Close gripper

The Program Instructions are entered into memory to form programs by first using the Monitor Command EDIT. This prepares the system to receive the Program Instruction statements in the proper order.

### 6.15.2 The MCL language

The MCL stands for Machine Control Language and was developed by McDonnell-Douglas Corporation under contract to the U.S. Air Force ICAM (Integrated Computer-Aided Manufacturing) Program.

The language is based on the APT NC language but is designed to control a complete manufacturing cell, including a cell with robots. MCL is an enhancement of APT which possesses additional options and features needed to do off-line programming of a robotic work cell.

Additional vocabulary words were developed to provide the supplementary capabilities intended to be covered by the MCL language. These capabilities include vision, inspection, and the control of signals to and from the various devices that constitute the robotic workstation. MCL also permits the user to define MACRO-like statements that would be convenient to use for specialized applications.

After the MCL program has been written, it is compiled to produce the CLFILE as output. The definition of the CLFILE has been extended to accommodate the new MCL features that go beyond the conventional cutter location data in APT. The extensions include such capabilities as:

- The definition of the various devices within the work cell and the tasks which are performed by these devices
- Predefined frames of reference which are associated with the different machines or devices in the cell
- User-defined frames of reference which could be used for defining the geometry of the work part
- The part identification and acquisition within the work cell
- MCL represents a significant enhancement of APT which can be used to perform offline programming of complex robotic work cells

## 6.16 Robot Safety

A robotic system is an integration of robots, machines, computerized information channels, and humans, no element of which can be considered perfect or immune from eventual failure and malfunction. The proximity of humans to the robots allows the risk of mutual damage, resulting in the formulation of safety guidelines that indicate how the conditions of conflict can be minimized.

The high productivity levels associated with robotic systems can be only realized if all the system elements are functioning safely and reliably.

However, until definitive regulations are imposed by law, attempting to determine the safety hazards of a robotic assembly system is best done on a piecemeal basis, whereby each element is analyzed for risk. The relationships between elements are known on a quantitative or qualitative basis. Therefore, the risk factors can be transferred from one element to the others.

*Fig.6.20 – Robot Safety*

There are four groups of humans at risk from direct personal injury from a robot:

**Programmers:** A robot programmer using any one of the previously mentioned programming methods is in direct contact with the robot. This closeness with the robot's work envelope, with its inherent danger of injury, distinguishes robotics from any other form of automation.

**Maintenance engineers:** A maintenance engineer is at risk from much the same dangers as programmers, with the added risk of electrocution. Also, because maintenance procedures often require that safety interlocks be disconnected, the inherent risk of injury is greater.

**Casual observers**: To the casual observer, robots are often seen standing still, apparently doing nothing, for long periods. The programmer, of course, would know whether or not these pauses are intentional: the robot may be performing a programmed delay or waiting. However, if, as is usually the case, the assembly robot is not rigidly guarded, then a casual observer may move toward a seemingly stationary robot and be injured when it continues its operation.

**Others outside the assumed danger zone**: Even though a robot has a known maximum work envelope, the risk of injury is not limited to encounters within this envelope. If components manipulated by the robot are not properly secured, then they can fly out of the grippers and strike personnel well outside the assumed danger zone of the robot.

In a practical sense, safety procedures and devices allow the authorized entry of humans into a robot's work envelope with minimal risk of injury. Hardware devices and sensors monitor all anticipated reasonable access to a robot's work envelope.

*Fig.6.21 - Fixed Barriers*

Physical safeguards are many and varied. They include. the following:

- Simple contact switches
- Restrained keys
- Pressure mats
- Infrared light beams
- Vision systems
- Flashing red lights within a work zone indicating that a stationary robot is activated but awaiting an input, or performing a time-delayed operation

## 6.17 Robot Kinematics and Dynamics

Robot arm kinematics involves the analytical study of the geometry of the motion of a robotic arm for a fixed reference coordinate system without regard to the forces/momenta that cause the motion.

In other words, robot kinematics deals with the analytical description of the spatial displacement of the robot as a function of time, in particular, the relations between the joint-variable space and the position and orientation of the end-effector of a robot arm.

There are two fundamental problems in robot-arm kinematics. The first is usually referred to as the direct (or forward) kinematics problem and the second is the inverse kinematics problem. If the locations of all of the joints and links of a robot arm are known, it is possible to compute the location of the end of the arm. This is defined as the direct kinematics problem.

The inverse kinematics problem is to determine the necessary positions of the joints and links to move the end of the robot arm to a desired position and orientation in space. Vector and matrix algebra are used to develop a systematic and generalized approach to describe and represent the locations of the links of a robot arm concerning a fixed reference frame.

Since the links of a robot arm can rotate and/or translate concerning a reference (world) coordinate frame, a body-attached (joint) coordinate frame is established along the joint axis for each link.

In general, the direct kinematics problem reduces to finding a transformation matrix that relates joint coordinates to world coordinates. Computer-based robots are usually servo-controlled in the joint-variable space, whereas objects to be manipulated are usually identified in the world or part coordinate system.

To control the position and orientation of the end-effector of a robot to reach the target object, the inverse kinematics solution is necessary to obtain the correct joint angle.

In other words, given the position and orientation of the end-effector of a six-axis arm and its joint and link parameters, it is possible to find the corresponding joint angles of the robot so that the end-effector can be positioned as desired.

### 6.17.1 Robot-Arm Dynamics

Robot-arm dynamics, on the other hand, deals with the mathematical formulation of the equations of robot arm motion. Specifically, dynamics is concerned with the use of information about the loads on a robot arm to adjust the servo operation to achieve optimum performance.

The information includes inertia, friction, gravity, velocity, and acceleration. The dynamic equations of motion of an arm are a set of mathematical equations describing the dynamic behavior of the manipulator.

Such mathematical formulation is useful for computer simulation of the robot-arm motion, the design of suitable control equations for a robot arm, and the evaluation of the kinematic design and structure of the robot.

**Robot-arm design**: A robot-arm designer may want to enter the geometry of a proposed arm design along with estimates of masses, loads, and so on, and simulate the dynamic performance of the arm.

**Path planning**: Basic path-control techniques provide a robot programmer with a tool to plan the desired path for a robot. However, as the robot moves, and speeds and accelerations increase, kinetic effects may result in an unexpected deviation from the planned path. Path simulation that considers the dynamic model can be used to develop worst-case estimates of path deviations at high speeds.

**Real-time control**: It is known that no single choice of servo gains is appropriate to provide the best performance of a robot. With the dynamic model of the arm.

The knowledge of kinematics and dynamics allows the control of an arm actuator to accomplish the desired task following the desired path. Trajectory planning and motion control are of considerable interest and importance, as these issues involve the degree of automation and intelligence of the robot.

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