## Unit 6 Industrial Robotics

**Assigned Core Text Reading for this Unit:**
Groover, M. P. (2008), *Automation, Production Systems, and Computer-Integrated Manufacturing*, 3rd ed., **Chapter 8.**



### Section 6.1 Unit Introduction

An industrial robot is a general-purpose, programmable machine possessing certain anthropomorphic characteristics—that is, human-like characteristics that resemble the human physical structure, or allow the robot to respond to sensory signals in a manner that is similar to humans. Such anthropomorphic characteristics include mechanical arms, used for various industry tasks, or sensory perceptive devices, such as sensors, which allow robots to communicate and interact with other machines and make simple decisions. The technology is quite similar to numerical control, as it has followed the same developmental path, and its history is related.

**KEYPOINT**
An industrial robot is a general-purpose, programmable machine possessing certain anthropomorphic characteristics.
**END KEYPOINT**

**LEARNING ACTIVITY 6.1**
Learn more about the history and application of industrial robots at web-site:
http://en.wikipedia.org/wiki/Industrial_robot
**END LEARNING ACTIVITY 6.1**

Both robots and numerical control are similar in that they seek to have co-ordinated control of multiple moving axes (called joints in robotics). Both use dedicated digital computers as controllers. Robots, however, are designed for a wider variety of tasks than numerical control. Typical applications include spot welding, material transfer (pick and place), machine loading, spray painting, and assembly. The general commercial and technological advantages of robot use are listed in Table 6.1.

Table 6.1: General Commercial and Technological Advantages of Robot Use

| Factor | Description |
|---|---|
| Work environment | Robots are ideal candidates for many harsh and dangerous working environments that are unsuitable for human personnel. |
| Work cycle | Robots have a level of consistency and repeatability in performing the work cycle, which cannot be attained by humans. |
| Reprogramming | Robots can be reprogrammed and equipped as necessary to perform different work tasks one after another. |
| Computing systems | Robots use computers which allow them to be networked with other computers and machines, thus enabling computer integrated manufacturing. |

This unit outlines basic robot anatomy and attributes, followed by an examination of robot control systems. End effectors, such as grippers and tools are then described, followed by an examination of specific sensors used for robotic functions. Industrial robot applications, such as for material handling, processing, assembly and inspection are then outlined followed by an analysis of the basic principles in robot programming. A discussion on robot accuracy and repeatability follows.

## Section 6.2 Unit Learning Objectives

After completing this unit, and the assigned reading and exercises supplied, you should be able to:

BULLET LIST
Outline the five types of mechanical joints for robots that may be classified

Outline the five basic body-and-arm configurations in robotics

Explain the joint notation system for the five joint types of a robotic arm

Define the work envelope

Explain the different types of control available in robotics

List the sorts of grippers deployed by robots

Outline the general characteristics of industrial work situations that promote the substitution of robots for human labour

Explain what is meant by a robot programme

Outline the use of computer-like programming languages

Characterise the elements of robotic precision
ENDLIST

**Section 6.3 Robot Anatomy and Related Attributes**

The manipulator of an industrial robot consists of a series of joints and links. Different joints and links comprise the study of robot anatomy, as well as other aspects of the manipulator's physical construction. A robotic joint provides relative motion between two links of the robot. Each joint, or axis, provides a certain degree-of-freedom (dof) of motion. In most cases only one degree-of-freedom is associated with each joint; so a robot's complexity can be classified according to the total number of degrees-of-freedom they possess.

**KEYPOINT**
The manipulator of an industrial robot consists of a series of joints and links.
**END KEYPOINT**

Each joint is connected to two links, an input link and an output link, with the joint providing controlled relative movement between the input link and output link. A robotic link is the rigid component of the robot manipulator. Most robots are mounted upon a stationary base, such as the floor. From this basis a joint-link numbering scheme may be recognised (see Figure 6.1). The robotic base and its connection to the first joint is termed as link 0, and the first joint in the sequence is joint 1; link 0, therefore, is the input link for joint 1, while the output link from joint 1 is link 1—which leads to joint 2. Thus link 1 is, simultaneously, the output link for joint 1 and the input link for joint 2. This joint-link numbering scheme follows in the same fashion for all joints and links in the robotic system.

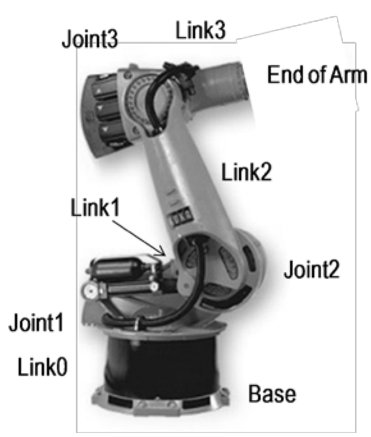


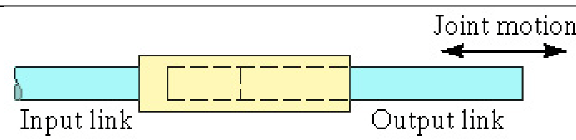
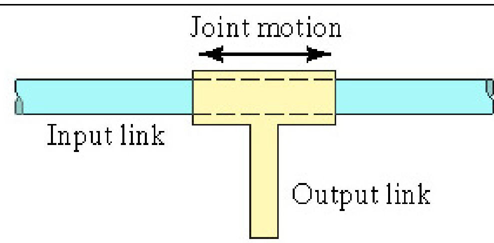
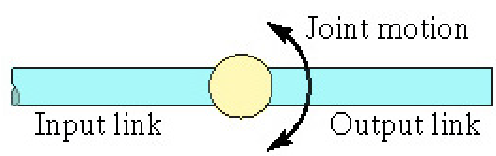
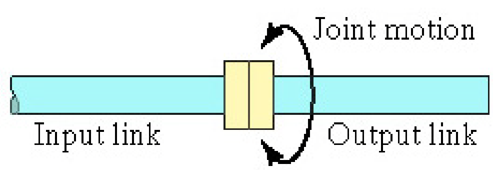
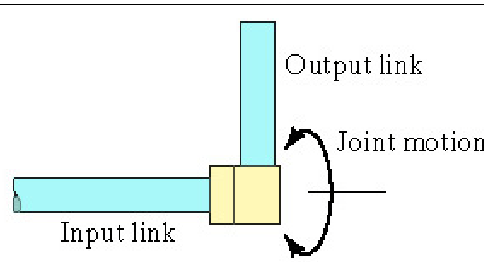
Figure 6.1: Joint-link scheme for robot manipulator

**KEYPOINT**

The joint-link numbering scheme counts all the joints and links which comprise the robotic system. The number scheme is ordered from the robot's base to the last joint and link in the robotic system.
**END KEYPOINT**

Five types of mechanical joints for robots may be classified; these are outlined in Table 6.2.

Table 6.2: Mechanical Joints for Robots

| **Joint** | **Description** | **Schematic** |
|---|---|---|
| Linear joint | Type L joint; the relative movement between the input link and the output link is a translational sliding motion, with the axes of the two links parallel. |  |
| Orthogonal joint | Type O joint; the relative movement between the input link and the output link is a translational sliding motion, but the output link is perpendicular to the input link. |  |
| Rotational joint | Type R joint; this provides rotational relative motion, with the axis of rotation perpendicular to the axes of the input and output links. |  |
| Twisting joint | Type T joint; this provides rotary motion, but the axis of rotation is parallel to the axes of the two links. |  |
| Revolving joint | Type V joint; the axis of the input link is parallel to the axis of rotation of the joint, and the axis of the output link is perpendicular to the axis of rotation. |  |

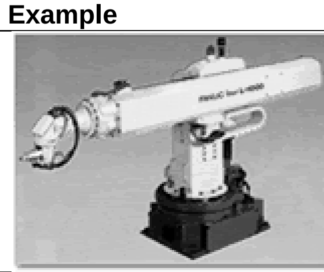
**KEYPOINT**
Five types of mechanical joints for robots may be classified; these are linear joints, orthogonal joints, rotational joints, twisting joints, and revolving joints.
**END KEYPOINT**

There are two main parts to the robot manipulator: a body-and-arm assembly, with typically three degrees-of-freedom; and a wrist assembly, with typically two or three degrees-of-freedom. At the end of the manipulator's wrist assembly is a device related to the task that must be accomplished by the robot. The device is called an end effector, and can be either a gripper for holding a workpart, or a specific tool for performing some process. The body-and-arm of the robot is used to position the end effector, and the robot's wrist is used to orient the end effector. In total a robot typically has up to six degrees of freedom to position and orient the end effector to a point or line in space.

**KEYPOINT**
There are two parts to the robot manipulator: a body-and-arm assembly, with three degrees-of-freedom; and a wrist assembly, with two or three degrees-of-freedom.
**END KEYPOINT**

For body-and-arm configurations, there are many different combinations possible for a three-degree-of-freedom robot manipulator, comprising any of the five joint types outlined above. Five common body-and-arm configurations are outlined in Table 6.3.

Table 6.3: Common Body-and-Arm configurations

| **Configuration** | **Description** | **Example** |
|---|---|---|
| Polar configuration | Consists of a sliding arm L joint, actuated relative to the body, which rotates around both a vertical axis (T joint), and horizontal axis (R joint). |  |
| Cylindrical configuration | Consists of a vertical column, relative to which an arm assembly is moved up or down. The arm can be moved in and out relative to the axis of the column. Common configuration is to use a T joint to rotate the column about its axis. An L joint is used to move the arm assembly vertically along the column, while an O joint is used to achieve radial movement of the arm. |  |

| | | |
|---|---|---|
| Cartesian co-ordinate robot | Also known as rectilinear robot and x-y-z robot. Consists of three sliding joints, two of which orthogonal (O joint). |  |
| Jointed-arm robot | General configuration of a human arm, this consists of a vertical column that swivels about the base using a T joint. At the top of the column is a shoulder joint (an R joint), output to an elbow joint (another R joint). |  |
| SCARA | Selective Compliance Assembly Robot Arm. Similar in construction to the jointer-arm robot, except that the shoulder and elbow rotational axes are vertical, which means that the arm is very rigid in the vertical direction, but compliant in the horizontal direction. |  |

**KEYPOINT**
There are five common body-and-arm configurations: polar; cylindrical; cartesian co-ordinate; jointed-arm; and SCARA.
**END KEYPOINT**

Robot wrist assemblys consist of either two or three degrees-of-freedom. A typical three-degree-of-freedom wrist joint is depicted in Figure 6.2: the roll joint is accomplished by use of a T joint; the pitch joint is achieved by recourse to an R joint; and the yaw joint, a right-and-left motion, is gained by deploying a second R joint. Care should be taken to avoid confusing pitch and yaw motions, as both utilise R joints.

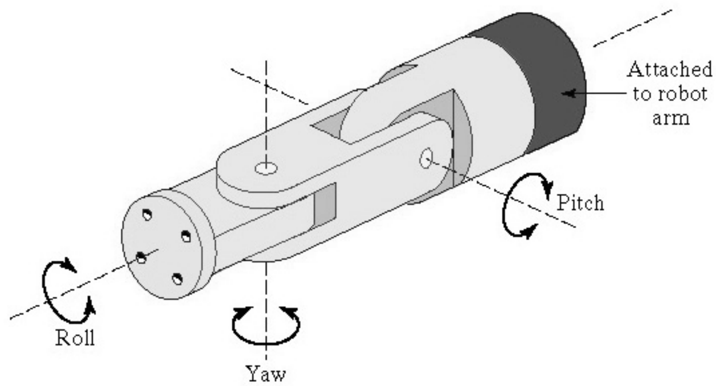


Figure 6.2: Robotic wrist joint

The SCARA body-and-arm configuration typically does not use a separate wrist assembly; its usual operative environment is for insertion-type assembly operations where wrists joints are unnecessary. The other four body-and-arm configurations more-or-less follow the wrist-joint configuration given above, by deploying various combinations of rotary joints type R and T.

**KEYPOINT**
Robot wrists consist of either two or three degrees-of-freedom, typically deploying various combinations of rotary joints type R and T.
**END KEYPOINT**

A specific joint notation system, using the letter symbols for the five joint types (L, O, R, T, and V), is sometimes used to define a particular joint to be used for the robot manipulator. In the system the manipulator is described by its joint types, and this is followed by the joint symbols that comprise the wrist separated by a colon. An example is outlined below:

TLR : TR

Body-and-arm manipulator:
T = Twisting joint for joint 1;
L = Linear joint for joint 2; and
R = Rotational joint for joint 3.

Wrist:
T = Twisting joint for joint 4; and
R = Rotational joint for joint 5.

**KEYPOINT**
A specific joint notation system that uses the letter symbols for the five joint types (L, O, R, T, and V) may be used to define the joint configurations of a robotic arm.
**END KEYPOINT**

The work volume, or work envelope, is the three-dimensional space in which the robot can manipulate the end of its wrist (See Figure 6.3). Work volume is determined by the number and types of joints in the manipulator, the ranges of the various joints, and the physical size of the links. Its actual shape is dependent on the robot's configuration: a polar robotic configuration tends to produce a spherical (or near-spherical) work volume; a cylindrical configuration has a cylindrical work envelope; and a Cartesian co-ordinate robot produces a rectangular work volume.

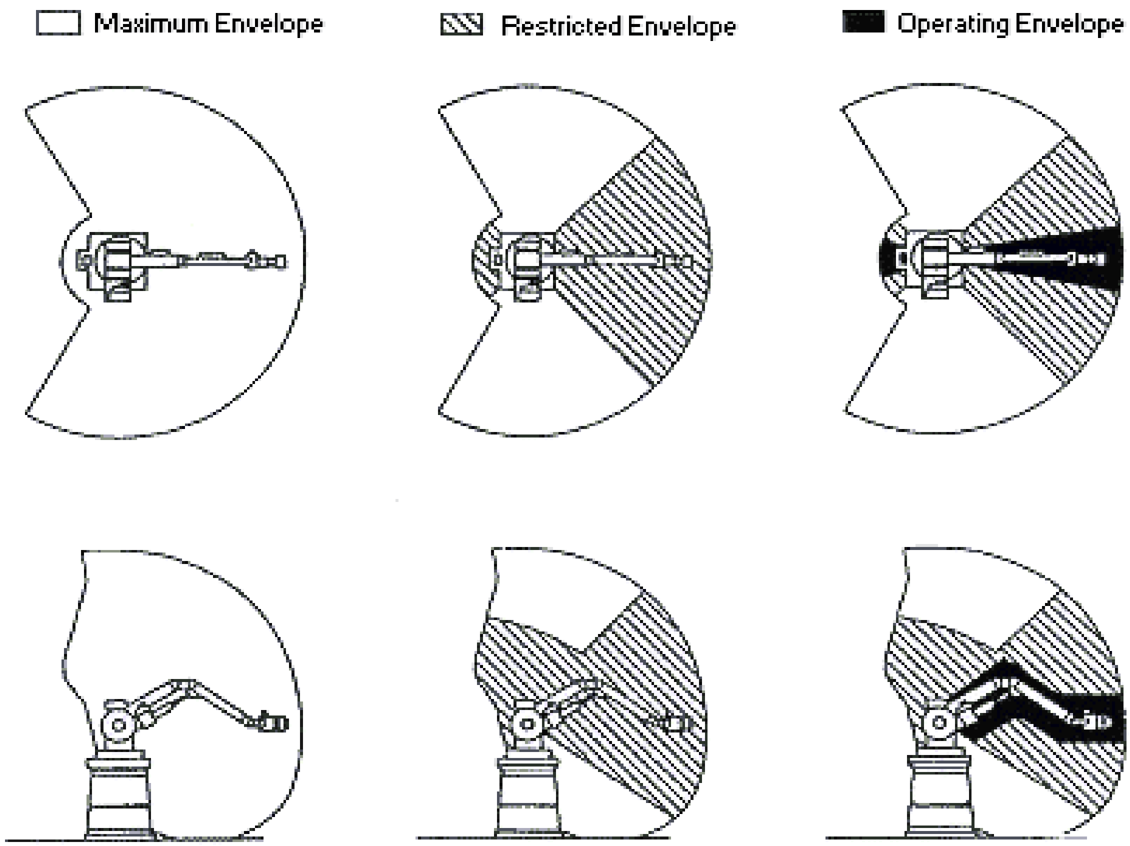



Figure 6.3: Work Envelope

**KEYPOINT**
The work volume, or work envelope, is the three-dimensional space in which the robot can manipulate the end of its wrist.
**END KEYPOINT**

The drive systems that can be used to actuate robotic joints are of three types: electric; hydraulic; and pneumatic. Electric motors constitute the main type of electric drive system mechanism that is deployed; typically servo-motors or steeper motors are used. Hydraulic and pneumatic drive systems use devices such as linear pistons and rotary vane actuators to accomplish the motion of the joint.

Pneumatic drive is regularly used for smaller, simpler robotic applications; whereas electric and hydraulic drives may be found on more sophisticated industrial robots. Electric drives are generally favoured in commercial applications, as they readily take advantage of the advances in electric motor technology made in recent years, and owing to their ready compatibility to computing systems; while hydraulic systems, although not as flexible, are generally noted for their greater speeds and strengths in deployment.

**KEYPOINT**
The drive systems that can be used to actuate robotic joints are of three types: electric; hydraulic; and pneumatic.
**END KEYPOINT**

The combination of drive system, sensors, and feedback control system determines the dynamic response characteristics of the manipulator. Speed in robotic terms refers to the absolute velocity of the manipulator at its end-of-arm. It can be programmed into the work cycle so that different portions of the cycle are carried out at different velocities. Acceleration and deceleration control are also important factors, especially in a confined work envelope. The robot's ability to control this switching between velocities is a key determinant of the manipulator's capabilities. Other key determinants are the weight (mass) of the object being manipulated, and the precision that is required to locate and position the object correctly. All of these determinants are gathered under the term 'speed of response', which is defined as the time required for the manipulator to move from one point in space to the next. Speed of response influence's the robot's cycle time, which in turn affects the production rate that can be achieved.

**KEYPOINT**
For robots speed refers to the absolute velocity of the manipulator at its end-of-arm.
**END KEYPOINT**

Stability refers to the amount of overshoot and oscillation that occurs in the robot motion at the end-of-arm as it attempts to move to the next programmed location. The more oscillation there is in the robotic motion, the less stability in the robotic manipulator. However, greater stability generally means that robots' response times are slower. Load carrying capacity is also an important factor, which is determined by weight of the gripper used to grasp the objects in question. Clearly, a heavy gripper puts a greater load upon the robotic manipulator, when combined with the object mass, than the combination of the object mass and a light gripper. Commercial robots can carry loads of up to 900kg, while medium-sized robots designed for industrial applications have capacities of up to 45kg.

**PROFESSIONAL TRANSFERABLE SKILLS [CRIT]**
**LEARNING ACTIVITY 6.2**
Using the internet source an industrial robot from a leading manufacturer (e.g. Kuka) and determine the specification details for one of their robots. Write a brief report that discusses links and joints, body-and-arm configuration, wrist configuration, drive system, speed of response, stability, envelope, and load carrying capacity.
**END LEARNING ACTIVITY 6.2**

## Section 6.4 Robot Control Systems

Joint movements must be controlled if the robot is to perform as desired. Micro-processor-based controllers are regularly used to perform this control action. Typically the controller is organised in a hierarchical fashion, as illustrated in Figure 6.4, so that each joint can feed back control data individually, with an overarching supervisory controller co-ordinating the combined actuations of the joints according to the sequence of the robot programme.

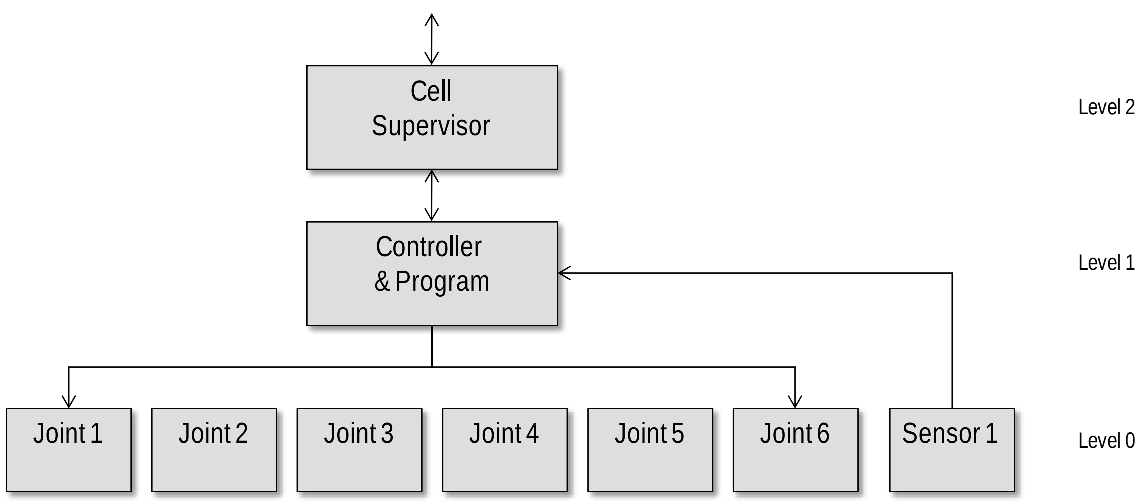



Figure 6.4: Hierarchical control structure

**KEYPOINT**
Joint movements are controlled by the robot controller.
**END KEYPOINT**

Different types of control are possible and are outlined in Table 6.4.

Table 6.4: Control types for robots

| **Control type** | **Comments** |
|---|---|
| Limited Sequence Control | Elementary control type, it is used for simple motion cycles, such as pick-and-place operations. It is implemented by fixing limits or mechanical stops for each joint and sequencing the movement of joints to accomplish operation. Feedback loops may be used to inform the controller that the action has been performed, so that the programme can move to the next step. No servo-control exists for precise positioning of joint. Many pneumatically driven robots are this type. |
| Playback with Point-to-Point Control | Playback control uses a controller with memory to record motion sequences in a work cycle, as well as associated locations and other parameters, and then plays back the work cycle during programme execution. Point-to-point control means individual robot positions are recorded in the memory; these positions include both mechanical stops for each joint, and the set of values that represent locations in the range of each joint. Feedback control is used to confirm that the individual joints achieve the specified locations in the programme. |
| Playback with Continuous Path Control | Playback is as described above. Continuous path control refers to a control system capable of continuous simultaneous control of two or more axes. The following advantages are noted with this type of playback control: greater storage capacity—the number of locations that can be stored is greater than in point-to-point; and interpolation calculations may be used, especially linear and circular interpolations. |
| Intelligent Control | An intelligent robot is one that exhibits behaviour that makes it seem intelligent; for example, capacities to interact with its ambient surroundings; decision-making capabilities; communication with humans; computational analysis during the work cycle; and responsiveness to advanced sensor inputs. They may also possess the playback facilities of the above two instances. Requires a high level of computer control, and an advanced programming language to input the decision-making logic and other ‘intelligence’ into the memory. |

**KEYPOINT**

Different types of control are available; these include: limited sequence control; playback with point-to-point control; playback with continuous path control; and intelligent control.

**END KEYPOINT**

## Section 6.5 End Effectors

An end effector is usually attached to the robot’s wrist, and it allows the robot to accomplish a specific task. This means that end effectors are generally custom-engineered and fabricated for each different operation. The two general categories of end effectors are grippers and tools.

**KEYPOINT**

An end effector is usually attached to the robot's wrist: it allows the robot to accomplish a specific task.
**END KEYPOINT**

Grippers grasp and manipulate objects during the work cycle. Typically the objects grasped are workparts that need to be loaded or unloaded from one station to another. Grippers may be custom-designed to suit the physical specifications of the workparts they have to grasp. As end effectors, grippers are described in further detail in Table 6.5.

Table 6.5: End-Effectors: Grippers

| **Type** | **Comment** |
|---|---|
| Mechanical gripper | Two or more fingers that can be actuated by robot controller to open and close on a workpart. |
| Vacuum gripper | Suction cups are used to hold flat objects. |
| Magnetised devices | Making use of the principles of magnetism, these are used for holding ferrous workparts. |
| Adhesive devices | Deploying adhesive substances these hold flexible materials, such as fabric. |
| Simple mechanical devices | For example, hooks and scoops. |
| Dual grippers | Mechanical gripper with two gripping devices in one end effector for machine loading and unloading. Reduces cycle time per part by gripping two workparts at the same time. |
| Interchangeable fingers | Mechanical gripper whereby, to accommodate different workpart sizes, different fingers may be attached. |
| Sensory feedback fingers | Mechanical gripper with sensory feedback capabilities in the fingers to aid locating the workpart; and to determine correct grip force to apply (for fragile workparts). |
| Multiple fingered grippers | Mechanical gripper with the general anatomy of the human hand. |
| Standard grippers | Mechanical grippers that are commercially available, thus reducing the need to custom-design a gripper for each separate robot application. |

**KEYPOINT**
Grippers grasp and manipulate objects during the work cycle.
**END KEYPOINT**

The robot end effecter may also use tools. Tools are used to perform processing operations on the workpart. Typically the robot uses the tool relative to a stationary or slowly-moving object; in this way the process is carried-out. For example, spot welding, arc welding, and spray painting—which all use a tool for processing the operation—may all be carried-out in this way. Other examples where a tool is held by the robotic manipulator, and used against the workpart include: rotating spindle for drilling, routing, grinding, and similar operations; the use of a heating torch; and when using a water jet cutting tool. For each instance, the robot controls both the position of the workpart, and the position of the tool relative to the workpart; for this purpose, therefore, the robot must be able to transmit control signals to the tool for starting, stooping, and otherwise regulating the tools actions. Figure 6.5 illustrates a sample gripper and tool.

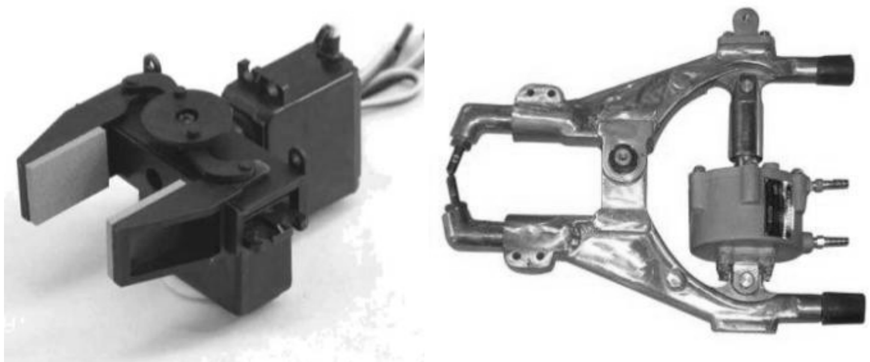


Figure 6.5: Robotic Gripper and Tool (spot welding)

**KEYPOINT**
Tools are used to perform processing operations on the work part; typically the robot uses the tool relative to a stationary or slowly-moving object.
**END KEYPOINT**

**Section 6.6 Sensors in Robotics**

There are generally two categories of sensors used in robotics; these are for internal purposes, and those for external purposes. Internal sensors are used to monitor and control the various joints of the robot; they form a feedback control loop with the robot controller. Examples of internal sensors include potentiometers and optical encoders, while tachometers of various types can be deployed to control the speed of the robot arm.

External sensors are external to the robot itself, and are used when we wish to control the operations of the robot with other pieces of equipment in the robotic work cell. External sensors can be relatively simple devices, such as limit switches that determine whether a part has been positioned properly, or whether a part is ready to be picked up from an unloading bay.

**KEYPOINT**
There are generally two categories of sensors used in robotics; these are for internal purposes, and those for external purposes.
**END KEYPOINT**

A number of advanced sensor technologies may also be used; these are outlined in Table 6.6.

Table 6.6: Advanced sensor technologies for robotics

| Sensor Type | Description |
|---|---|
| Tactile sensors | Used to determine whether contact is made between sensor and another object. Two types: touch sensors—which indicate when contact is made, and no more; and force sensors—which indicate the magnitude of the force with the object. |
| Proximity sensors | Used to determine how close an object is to the sensor. Also called a range sensor. |
| Optical sensors | Photocells and other photometric devices that are used to detect the presence or absence of objects. Often used in conjunction to proximity sensors. |
| Machine vision | Used in robotics for inspection, parts identification, guidance, and other uses. |
| Others | Miscellaneous category of sensors may also be used; including devices for measuring: temperature, fluid pressure, fluid flow, electrical voltage, current, and other physical properties. |

**KEYPOINT**
In robotics a number of advanced sensor technologies may also be used; these include: tactile sensors; proximity sensors; optical sensors; machine vision; and others.
**END KEYPOINT**

## Section 6.7 Industrial Robot Applications

The general characteristics of industrial work situations that tend to promote the substitution of robots for human labour are outlined in Table 6.7.

Table 6.7: Characteristics of situations where robots may substitute for humans

| Situation | Description |
|---|---|
| Hazardous work for humans | In situations where the work environment is unsafe, unhealthy, uncomfortable, or otherwise unpleasant for humans, robot application may be considered. |
| Repetitive work cycle | If the sequence of elements in the work cycle is the same, and the elements consist of relatively simple motions, robots usually perform the work with greater consistency and repeatability than humans. |
| Difficult handling for humans | If the task requires the use of heavy or difficult-to-handle parts or tools for humans, robots may be able to perform the operation more efficiently. |
| Multi-shift operation | A robot can replace two or three workers at a time in second or third shifts, thus they can provide a faster financial payback. |
| Infrequent changeovers | Robot use is justified for long production runs where there are infrequent changeovers, as opposed to batch or job shop production where changeovers are more frequent. |
| Part position and orientation are established in the work cell | Robots generally don’t have vision capabilities, which means parts must be precisely placed and oriented for successful robotic operations. |

**KEYPOINT**
**I**ndustrial work situations that promote the substitution of robots for human labour include: hazardous work environments; repetitive work cycles; difficult handling; multi-shift environments; infrequent changeovers; and part position and orientation are established in the work cell i.e. repetitive tasks.
**END KEYPOINT**

Robots are being used mainly in three types of applications: material handling; processing operations; and assembly and inspection. In material handling robots move parts between various locations by means of a gripper type end effector. Two sub-divisions may be noted in material handling: material transfer; and machine loading and/or unloading. These are outlined further in Table 6.8.

Table 6.8: Material handling applications

| **Application** | **Description** |
|---|---|
| Material transfer | Chief purpose is to pick up parts at one location and place them at a new location. Part re-orientation may be accomplished during the transfer. The most basic application is a pick-and-place procedure, by a low-technology robot (often pneumatic), using only up to 4 joints.<br>More complex is palletising, where robots retrieve objects from one location, and deposit them on a pallet in a specific area of the pallet, thus the deposit location is slightly different for each object transferred. The robot must be able to compute the correct deposit location via powered lead-through method, or by dimensional analysis.<br>Other applications of material transfer include de-palletising, stacking, and insertion operations. |
| Machine loading and/or unloading | Chief purpose is to transfer parts into or out-of a production machine. There are three classes to consider: machine loading—where the robot loads the machine only; machine unloading—where the robot unloads the machine only; and machine loading and unloading—where the robot performs both actions. Machine loading and/or unloading is used in the following processes: die casting, plastic moulding, metal machining operations, forging, press-working, and heat treating. |

**KEYPOINT**
Robots are being used in three types of applications: material handling; processing operations; and assembly and inspection.
**END KEYPOINT**

In processing operations the robot performs some processing actions, such as grinding, milling, etc. on the workpart. The end effector is equipped with the specialised tool required for the process, and the tool is moved relative to the surface of the workpart. Table 6.9 outlines examples of processing operations that deploy robots.

Table 6.9: Robotic process operations

| **Process** | **Description** |
|---|---|
| Spot Welding | Metal joining process in which two sheet metal parts are fused together at localised points of contact by the deployment of two electrodes that squeeze the metal together and apply an electric current. The electrodes |

| | |
|---|---|
| | constitute the spot welding gun, which is the end effector tool of the welding robot. |
| Arc Welding | Metal joining process that utilises a continuous rather than contact welding point process, in the same way as above. Again the end effector is the electrodes used to achieve the welding arc. The robot must use continuous path control, and a jointed arm robot consisting of six joints is frequently used. |
| Spray Coating | Spray coating directs a spray gun at the object to be coated. Paint or some other fluid flows through the nozzle of the spray gun, which is the end effector, and is dispersed and applied over the surface of the object. Again the robot must use continuous path control, and is typically programmed using manual lead-through. Jointed arm robots seem to be the most common anatomy for this application. |
| Other applications | Other applications include: drilling, routing, and other machining processes; grinding, wire brushing, and similar operations; waterjet cutting; and laser cutting. |

**KEYPOINT**
In processing operations the robot performs some processing actions, such as grinding, milling, etc. on the work part.
**END KEYPOINT**

In assembly and inspection robots can be used for material handling applications, and for processing applications, so it is in effect a hybrid of the previous two application categories. Traditionally, assembly and inspection are seen as labour-intensive activities: they require high levels of effort, although they can be very repetitive and boring, which has meant that robots can be seen as ideal candidates for the work. Assembly, however, can consist of a number of difficult tasks, which are unsuitable for robot application; while inspection work requires high precision and patience, and—often—a level of judgement not readily associated with robots, although it is found in humans. Thus, owing to difficulties in both assembly and inspection, the application of robots to these tasks has been found to be somewhat difficult.

**KEYPOINT**
In assembly and inspection robots can be used for both material handling applications and for processing applications.
**END KEYPOINT**

**LEARNING ACTIVITY 6.3**
Go to Youtube.com and investigate many of the robotic applications mentioned above. Copy the hyperlinks of the most educational video and share them through the discussion forum. Find unusual applications for industrial robots.
**END LEARNING ACTIVITY 6.3**

## Section 6.8 Robot Programming

A robot program is a path in space to be followed by the manipulator, combined with peripheral actions that support the work cycle. To programme a robot, specific commands are entered into the robot's controller memory, and this action may be performed in a number of ways. For limited sequence robots programming occurs when limit switches and mechanical stops are set to control the endpoints of its motions. A sequencing device controls the occurrence of the motions, which in turn controls the movement of the joints that completes the motion cycle.

**KEYPOINT**
A robot programme is a path in space to be followed by the manipulator, combined with peripheral actions that support the work cycle.
**END KEYPOINT**

For industrial robots with digital computers as controllers, three programming methods can be distinguished; these are lead-through programming; computer-like robot programming languages; and off-line programming. Lead-through methodologies, and associated programming methods, are outlined in detail in Table 6.10.

Table 6.10: Lead-through programming methods for industrial robots

| **Method** | **Description** |
|---|---|
| Lead-through programming | Task is 'taught' to the robot by manually moving the manipulator through the required motion cycle, and simultaneously entering the programme into the controller memory for playback. Two methods are used for teaching: powered lead-through; and manual lead-through. |
| Motion programming | To overcome difficulties of co-ordinating individual joints associated with lead-through programming, two mechanical methods can be used: the world-co-ordinate system—whereby the origin and axes are defined relative to the robot base; and the tool-co-ordinate system—whereby the alignment of the axis system is defined relative to the orientation of the wrist faceplate. These methods are typically used with Cartesian co-ordinate robots, and not for robots with rotational joints. These latter robotic types must rely on interpolation processes to gain straight line motion. Two types of interpolation processes may be outlined: straight line interpolation—where the control computer calculates the necessary points in space that the manipulator must move through to connect two points; and joint interpolation—where joints are moved simultaneously at their own constant speed such that all joints start/stop at the same time. |

**KEYPOINT**
Lead-through programming requires the task to be 'taught' to the robot by moving the manipulator through the required motion cycle, and simultaneously entering the programme into the controller memory for playback.
**END KEYPOINT**

Computer-like programming languages use on-line/off-line methods of programming. The advantage of textual programming over its lead-through counterpart includes:

BULLETLIST
The use of enhanced sensor capabilities, including the use of analogue and digital inputs

Improved output capabilities for controlling external equipment

Extended programme logic, beyond lead-through capabilities

Advanced computation and data processing capabilities

Communications with other computer systems
ENDLIST

**KEYPOINT**
Computer-like programming languages are on-line/off-line methods of programming that rely on the predominant use of digital computers in robotics.
**END KEYPOINT**
For motion programming there is a combination of textual statements and lead-through techniques. Textual statements describe the motion, while the lead-through techniques define robot position and orientation, during and at the end of the motion. The basic motion statement is

**MOVE P1**

which commands the robot to move from its current location to a position and orientation defined as P1. P1 itself is defined via lead-through methods. Statements such as

**HERE P1**

or

**LEARN P1**

are used to indicate the variable name for the point in lead-through methods.

Variants of the MOVE statement exist; these include the definition of straight line interpolation motions, incremental motions, approach and depart moves, and paths.

**KEYPOINT**
Computer-like robot programming languages use motion programming techniques also, whereby a combination of textual statements and lead-through

techniques are deployed. Textual statements describe the motion, while the lead-through techniques define robot position and orientation.
**END KEYPOINT**

Interlock and Sensor commands also exist in motion programming; the two basic interlock commands are WAIT and SIGNAL, where the former is used to implement an input interlock, while the latter is used to communicate to some external piece of equipment. In the case of grippers, the basic commands are OPEN and CLOSE, which cause the gripper to actuate to a position of being fully open or closed, respectively. Other special sets of statements are used to control the operation of tool-type end effectors, such as spot welding guns, arc welding tools, spray painting guns, and powered spindles.

Both of the above techniques of robotic programming are inhibited by requiring the robot to be removed from active service while the programming takes place. Methods have also been developed to overcome this; off-line programming allows a robot programme to be prepared at a remote computer terminal and downloaded to the robot controller for execution without interrupting production. Graphical computer simulation is used to validate the programmes developed off-line; once it is validated, the programme may be converted into textual language corresponding to the language requirements of the robot that is expected to deploy the programme. Once this is done, the robot is ready to download and deploy the new programme without interrupting its operational processes.

**KEYPOINT**
Off-line programming allows a robot programme to be prepared at a remote computer terminal and downloaded to the robot controller for execution without interrupting production.
**END KEYPOINT**

**EXAMPLE 6.1**
A robot performs a loading and unloading operation for a machine tool. The work cycle consists of the following sequence of activities:

**NUMLIST**
Robot reaches and picks part from incoming conveyor and loads into fixture on machine tool. (Time=5.5 sec)
Machining cycle (automatic). (Time=33.0 sec)
Robot reaches in, retrieves part from machine tool, and deposits it onto outgoing conveyor. (Time=4.8 sec)
Move back to pickup position. (Time=1.7 sec)
**ENDLIST**

The activities are performed sequentially as listed. Every 30 workparts, the cutting tools in the machine must be changed. This irregular cycle takes 3.0 minutes to accomplish. The uptime efficiency of the robot is 97%; and the uptime efficiency of the machine tool is 98%, not including interruptions for tool changes. These two efficiencies are assumed not to overlap (i.e., if the robot breaks down, the cell will cease to operate, so the machine tool will not have the opportunity to break down; and vice versa). Downtime results from electrical and mechanical malfanctions of the robot, machine tool, and fixture. Determine the hourly production rate, taking into account the lost time due to tool changes and the uptime efficiency.

**Solution**

$T_c = 5.5 + 33.0 + 4.8 + 1.7 = 45$ sec/cycle

Tool change time $T_{tc} = 180$ sec/30 pc = 6 sec/pc

Robot uptime E = 0.97, lost time = 0.03. Machine tool uptime E = 0.98, lost time = 0.02. These two inefficiencies are assumed not to overlap in the following solution.

$T_c + T_{tc}/30 = 45 + 6 = 51$ sec = 0.85 min/pc

$R_c = 60/0.85 = 70.59$ pc/hr

Accounting for uptime efficiencies,

$R_p = 70.59(1.0 \quad 0.03 \quad 0.02) = 67.06$ pc/hr

**END EXAMPLE 6.1**

**Section 6.9 Robot Accuracy and Repeatability**

An important control attribute in industrial applications is accuracy and repeatability. Precision is an important consideration with some tasks—such as positioning systems—requiring fine positional requirements; while others make do with more general precision abilities (such as spot welding). Three factors may be examined as important here:

BULLETLIST

Control resolution—the capability of the robot's positioning system to divide the range of the joint into closely spaced points, called addressable points, to which the joint can be moved by the controller.

Repeatability—the measure of the robot's ability to position its end-of-wrist at a previously taught point in the work volume.

Accuracy—the robot's ability to position its end-of-wrist at a desired location in the work volume.

ENDLIST

For control resolution, the joint-link combination consists of a lead-screw drive mechanism identical with numerical control mechanisms outlined earlier, so the control resolution equations used there may be deployed here once again. This electro-mechanical control resolution may be denoted $CR_1$. Owing to the wide variety of joints used by robots, and their individual mechanical characteristics, it is not possible to characterise each joint in detail. There is, however, a mechanical limit on the capacity to divide the range of each joint-link system into addressable points, and that limit is given by $CR_1$.

$CR_2$ is the bit storage capacity of the controller. This is given by:

$$CR_2 = \frac{R}{2^B - 1}$$

where $CR_2$ is the control resolution determined by the robot controller; $R$ is the range of the joint-link combination, expressed in linear or angular units; and $B$ is the number of bits in the bit storage register devoted to a particular joint. The maximum of $CR_1$ and $CR_2$ gives the control resolution.

For repeatability, the mechanical errors that make the robot's end-of-wrist return to slightly different locations than the programmed point are to blame. For a single joint-link mechanism:

$$\text{Re} = \pm 3\sigma$$

where *Re* is repeatability; and $\sigma$ is the standard deviation of the error distribution.

For accuracy, we have:

$$Acc = \frac{CR}{2} + 3\sigma$$

where *CR* is control resolution; and $\sigma$ is the standard deviation of the error distribution.

**KEYPOINT**
Robot precision is determined by three important considerations; these are: control resolution, repeatability, and accuracy.
**END KEYPOINT**

**Section 6.10 Unit Review**

BULLETLIST
An industrial robot is a general-purpose, programmable machine possessing certain anthropomorphic characteristics.

The manipulator of an industrial robot consists of a series of joints and links.

A robotic joint provides relative motion between two parts of the robot: each joint, or axis, provides a certain degree-of-freedom (dof) of motion.

There are two types of robot manipulator: a body-and-arm assembly, with three degrees-of-freedom; and a wrist assembly, with two or three degrees-of-freedom.

There are five basic body-and-arm configurations; these are: polar configuration; cylindrical configuration; cartesian co-ordinate robot; jointed-arm robot; and SCARA.

Robot wrists consist of either two or three degrees-of-freedom, typically deploying various combinations of rotary joints.

The work volume, or work envelope, is the three-dimensional space in which the robot can manipulate the end of its wrist.

For robots speed refers to the absolute velocity of the manipulator at its end-of-arm. Key determinants are the manipulator's ability to accelerate and decelerate, the mass of the object manipulated, and the precision necessary to position the object. It is measured by determining the speed of response associated with the manipulator.

Robotic stability refers to the amount of overshoot and oscillation that occurs in the robot motion at the end-of-arm as it attempts to move to the next programmed location.

Joint movements must be controlled if the robot is to perform as desired. Typically the controller is organised in a hierarchical fashion so that each joint can feed back control data individually, while an overall supervisory controller may be used to co-ordinate the combined actuations of the joints according to the sequence of the robot programme.

An end effector is usually attached to the robot's wrist: it allows the robot to accomplish a specific task.

Grippers grasp and manipulate objects during the work cycle. There are many varieties, including: mechanical grippers; vacuum grippers; magnetised devices; adhesive devices; simple mechanical devices; dual grippers; interchangeable fingers; sensory feedback fingers; multiple fingered grippers; and standard grippers.

Tools are used to perform processing operations on the workpart; typically the robot uses the tool relative to a stationary or slowly-moving object.

The general characteristics of industrial work situations that tend to promote the substitution of robots for human labour include: where there is hazardous work environments for humans; where there is a repetitive work cycle; where there is difficult handling for humans; in multi-shift operative environments; where there are infrequent changeovers; and where part position and orientation are established in the work cell.

Robots are being used in three types of applications: material handling; processing operations; and assembly and inspection.

A robot programme is a path in space to be followed by the manipulator, combined with peripheral actions that support the work cycle.

Lead-through programming requires the task to be 'taught' to the robot by moving the manipulator through the required motion cycle, and simultaneously entering the programme into the controller memory for playback. Motion programming overcomes difficulties of co-ordinating individual joints associated with lead-through programming.

Computer-like programming languages are on-line/off-line methods of programming that rely on the predominant use of digital computers in robotics.

Computer-like robot programming languages use motion programming techniques also, whereby a combination of textual statements and lead-through techniques are deployed. Textual statements describe the motion, while the lead-through techniques define robot position and orientation.

Off-line programming allows a robot programme to be prepared at a remote computer terminal and downloaded to the robot controller for execution without interrupting production.

Robot precision is determined by three important considerations; these are: control resolution, repeatability, and accuracy.
ENDLIST

**Section 6.11 Self-Assessment Questions**

NUMLIST
What is the difference between a link and a joint in robotics?

What are the five types of mechanical joints for robots that may be classified?

What are the five basic body-and-arm configurations in robotics?

Characterise the joint notation system used for the five joint types of a robotic arm.

Define the work envelope.

What different types of control are available in robotics?

What sorts of grippers are deployed by robots?

What are the general characteristics of industrial work situations that promote the substitution of robots for human labour?

What is meant by a robot programme?

Define lead-through programming.

What use is made of computer-like programming languages?

Explain the usefulness of off-line programming.

What are the important characteristics of robotic precision?
ENDLIST

**Section 6.12 Answers to Self-Assessment Questions**

NUMLIST
A robotic joint provides relative motion between two parts of the robot: each joint, or axis, provides a certain degree-of-freedom (dof) of motion. A link is the rigid component of the robot manipulator, which is connected to a robotic joint. Two types of links are connected to each joint: an input link and an output link.

The five types of mechanical joints for robots are: linear joints, orthogonal joints, rotational joints, twisting joints, and revolving joints.

The five basic body-and-arm configurations in robotics are: polar configuration; cylindrical configuration; cartesian co-ordinate robot; jointed-arm robot; and SCARA.

The joint notation system uses the letter symbols for the five joint types (L, O, R, T, and V) to define the joint configurations of a robotic arm. In the system the manipulator is described by its joint types, and this is followed by the joint symbols that comprise the wrist separated by a colon.

The work envelope, or work volume, is the three-dimensional space in which the robot can manipulate the end of its wrist.

The different types of control available in robotics include: limited sequence control; playback with point-to-point control; playback with continuous path control; and intelligent control.

The sorts of grippers are deployed by robots include: mechanical grippers; vacuum grippers; magnetised devices; adhesive devices; simple mechanical devices; dual grippers; interchangeable fingers; sensory feedback fingers; multiple fingered grippers; and standard grippers.

The general characteristics of industrial work situations that tend to promote the substitution of robots for human labour include: where there is hazardous work environments for humans; where there is a repetitive work cycle; where there is difficult handling for humans; in multi-shift operative environments; where there are infrequent changeovers; and where part position and orientation are established in the work cell.

A robot programme is a path in space to be followed by the manipulator, combined with peripheral actions that support the work cycle.

Lead-through programming requires the task to be ‘taught’ to the robot by moving the manipulator through the required motion cycle, and simultaneously entering the programme into the controller memory for playback.

Computer-like programming languages are on-line/off-line methods of programming that rely on the predominant use of digital computers in robotics. Computer-like robot programming languages use motion programming techniques, whereby a combination of textual statements and lead-through techniques are deployed. Textual statements describe the motion, while the lead-through techniques define robot position and orientation.

Off-line programming allows a robot programme to be prepared at a remote computer terminal and downloaded to the robot controller for execution without interrupting production. This has the advantage of not having to remove the robot from its production operations for programming set-up.

Robot precision is determined by three important considerations; these are: control resolution, repeatability, and accuracy.
END LIST