BEE 009 ROBOTICS AND AUTOMATION

UNIT I BASIC CONCEPTS:

History of Robot (Origin):

1968	Shakev, first mobile robot with vision capacity made at SRI.
1970	The Stanford Arm designed eith electrical actuators and controlled by a computer
1973	Cincinnati Milacron‘s (T3) electrically actuated mini computer controlled by industrial robot.
1976	Viking II lands on Mars and an arm scoops Martian soil for analysis.
1978	Unimation Inc. develops the PUMA robot- even now seen in university labs
1981	Robot Manipulators by R. Paul, one of the first textbooks on robotics.
1982	First educational robots by Microbot and Rhino.
1983	Adept Technology, maker of SCARA robot, started.
1995	Intuitive Surgical formed to design and market surgical robots.
1997	Sojourner robot sends back pictures of Mars; the Honda P3 humanoid robot, started in unveiled
2000	Honda demonstrates Asimo humanoid robot capable of walking.
2001	Sony releases second generation Aibo robot dog.
2004	Spirit and Opportunity explore Mars surface and detect evidence of past existence of water.
2007	Humanoid robot Aiko capable of ―feeling‖ pain.
2009	Micro-robots and emerging field of nano-robots marrying biology with engineering.

An advance in robotics has closely followed the explosive development of computers and electronics. Initial robot usage was primarily in industrial application such as part/material handling, welding and painting and few in handling of hazardous material. Most initial robots operated in teach-playback mode, and replaced ‗repetitive‘ and ‗back-breaking‘ tasks. Growth and usage of robots slowed significantly in late 1980‘s and early 1990‘s due to ―lack of intelligence‖ and ―ability to adapt‖ to changing environment – Robots were essentially blind, deaf and dumb!.Last 15 years or so, sophisticated sensors and programming allow robots to act much more intelligently, autonomously and react to changes in environments faster.

Present-day robots:

1. Used in cluttered workspaces in homes and factories,
2. Interact safely with humans in close proximity,
3. Operate autonomously in hazardous environments,
4. Used in entertainment and in improving quality of life.

GENERATIONS OF ROBOT

The various generations of robots are as follows.

~~First generation~~: The first generation robots are repeating, non-servo controlled type used for pick and place and point to point operations.

~~Second generation~~: The addition of sensing devices and enabling the robot to alter its movements in response to sensory feedback marked in the second generation. These robots exhibit path control capabilities.

Third generation: This generation is introduced in late 1970‘s have human like intelligence. The growth in computers led to high speed processing of information, robot acquired artificial intelligence. self – learning and decision making capability by past experiences. Online computations & control, artificial vision and active force/torque interaction with the environment are the significant characteristics of these robots.

~~Fourth generation~~: These are artificial biological robots or a super humanoid capable of producing its own clones

Definition for Robot:

The Robot Institute of America (1969) defines robot as ―.... a re-programmable, multi-functional manipulator designed to move materials, parts, tools or specialized devices through various programmed motions for the performance of a variety of tasks‖.

Asimov's laws of robotics:

1. A robot may not injure a human being or, through inaction, allow a human being to come to harm.
2. A robot must obey the orders given it by human beings except where such orders would conflict with the First Law.
3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Laws.

Robotics system components:

- **Mechanical platforms or hardware base** is a mechanical device, such as a wheeled platform, arm, fixed frame or other construction, capable of interacting with its environment and any other mechanism involve with his capabilities and uses.
- **Sensors** systems is a special feature that rest on or around the robot. This device would be able to provide judgment to the controller with relevant information about the environment and give useful feedback to the robot.
- **Joints** provide more versatility to the robot itself and are not just a point that connects two links or parts that can flex, rotate, revolve and translate. Joints play a very crucial role in the ability of the robot to move in different directions providing more degree of freedom.
- **Controller** functions as the "brain" of the robot. Robots today have controllers that are run by programs - sets of instructions written in code. In other words, it is a computer used to command the robot memory and logic. So it, be able to work independently and automatically.
- **Power Source** is the main source of energy to fulfill all the robots needs. It could be a source of direct current as a battery, or alternate current from a power plant, solar energy, hydraulics or gas.
- **Artificial intelligence** represents the ability of computers to "think" in ways similar to human beings. Present day "AI" does allow machines to mimic certain simple human thought processes, but cannot begin to match the quickness and complexity of the brain. On the other hand, not all robots possess this type of capability. It requires a lot of programming and sophisticates controllers and sensorial ability of the robot to reach this level.

- **Actuators** are the muscles of robot. An actuator is a mechanism for activating process control equipment by the use of pneumatic, hydraulic or electronic signals. There are several types of actuators in robotic arms namely synchronous actuator – brush and brushless DC servo, stepper motor and asynchronous actuator – AC servo motor, traction motor, pneumatic, hydraulic.

~~CLASSIFICATION OF ROBOT~~

The ways of classifying a robot as follows

1) According to the structural capability of robot – i) mobile or ii) fixed robot.

i) **Mobile robot:** A mobile robot is an automatic machine that is capable of locomotion. . Example: spying robot. Mobile robots have the capability to move around in their environment and are not fixed to one physical location. Mobile robots can be "autonomous" (AMR - autonomous mobile robot) which means they are capable of navigating an uncontrolled environment without the need for physical or electro-mechanical guidance devices. Alternatively, mobile robots can rely on guidance devices that allow them to travel a pre-defined navigation route in relatively controlled space (AGV - autonomous guided vehicle). By contrast, industrial robots are usually more-or-less stationary, consisting of a jointed arm (multi-linked manipulator) and gripper assembly (or end effector), attached to a fixed surface

ii) **Fixed Robot:** Most industrial robots are fixed with the base but the arms are moving.

2) According to the control

To perform as per the program instructions, the joint movements an industrial robot must accurately be controlled. Micro-processor-based controllers are used to control the robots. Different types of control that are being used in robotics are given as follows.

a. Limited Sequence Control:

It is an 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 program can move to the next step. Precision of such control system is less. It is generally used in pneumatically driven robots.

b. 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 program 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 program.

c. Playback with Continuous Path Control

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.

d. Intelligent Control

An intelligent robot exhibits behavior that makes it seems to be intelligent. For example, it may have capacity to interact with its ambient surroundings; decision-making capability; ability to communicate with humans; ability to carry out computational analysis during the work cycle; and responsiveness to advanced sensor inputs. They may also possess the playback facilities. However, it requires a high level of computer control, an advanced programming language for decision-making logic and other _intelligence' into the memory.

ROBOT ANATOMY

Joints and Links:

The manipulator of an industrial robot consists of a series of joints and links. Robot anatomy deals with the study of different joints and links and 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 of the cases, only one degree-of-freedom is associated with each joint. Therefore the robot's complexity can be classified according to the total number of degrees-of-freedom they possess.

Each joint is connected to two links, an input link and an output link. Joint provides controlled relative movement between the input link and output link. A robotic link is the rigid component of the robot manipulator. Most of the robots are mounted upon a stationary base, such as the floor. From this base, a joint-link numbering scheme may be recognized as shown in Figure 1. The robotic base and its connection to the first joint are termed as link-0. The first joint in the sequence is joint-1. Link-0 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 is further followed for all joints and links in the robotic systems.

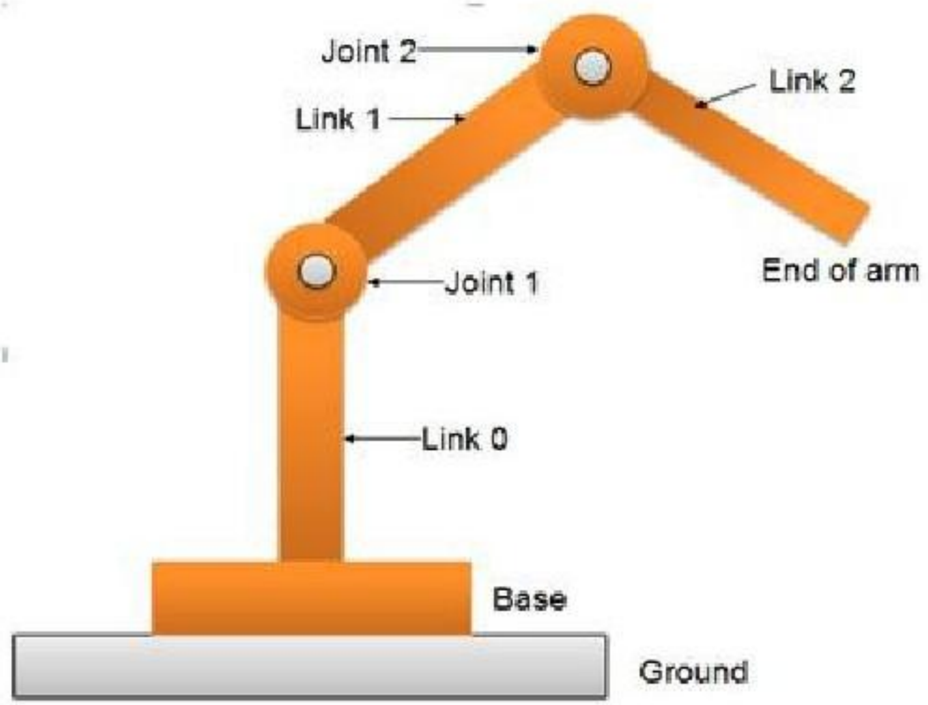


Fig. 1 Joint-link scheme for robot manipulator

Nearly all industrial robots have mechanical joints that can be classified into following five types as shown in Figure 2.

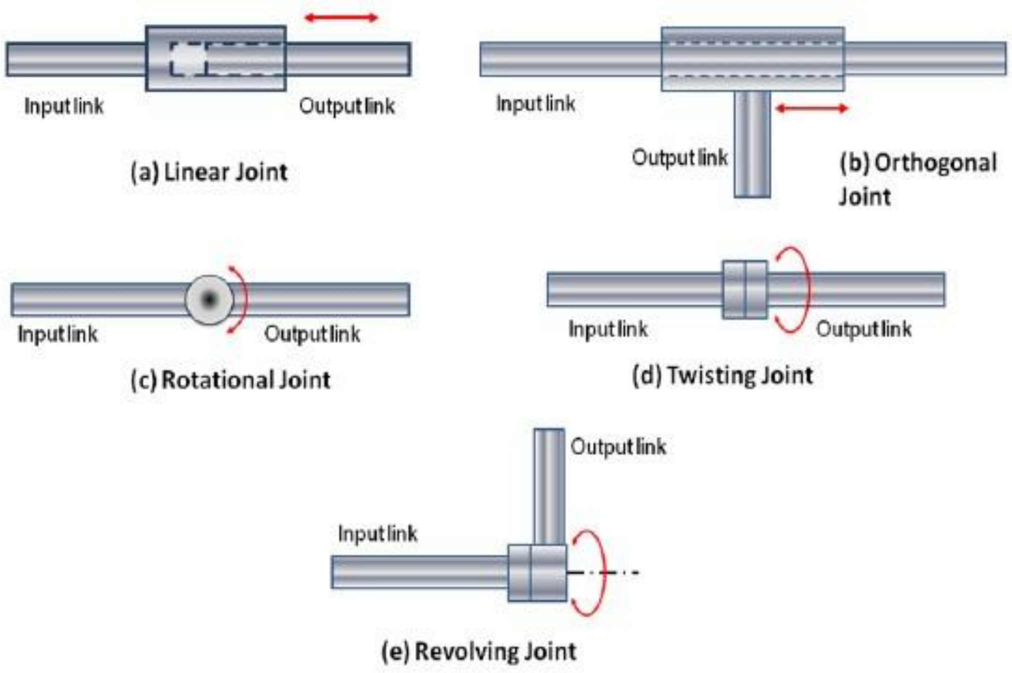


Fig. 2 Types of Joints

a) 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 being parallel.

b) Orthogonal joint (type U joint)

This is also a translational sliding motion, but the input and output links are perpendicular to each other during the movement.

c) Rotational joint (type R joint)

This type provides rotational relative motion, with the axis of rotation perpendicular to the axes of the input and output links.

d) Twisting joint (type T joint)

This joint also involves rotary motion, but the axis or rotation is parallel to the axes of the two links.

e) Revolving joint (type V-joint, V from the “v” in revolving)

In this type, axis of input link is parallel to the axis of rotation of the joint. However the axis of the output link is perpendicular to the axis of rotation.

Robotic arm configurations:

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.

Common body-and-arm configurations are as follows.

1) Polar coordinate arm configuration
2) Cylindrical coordinate arm configuration
3) Cartesian coordinate arm configuration
4) Jointed arm configuration

1) Polar coordinate arm configuration (RRP):

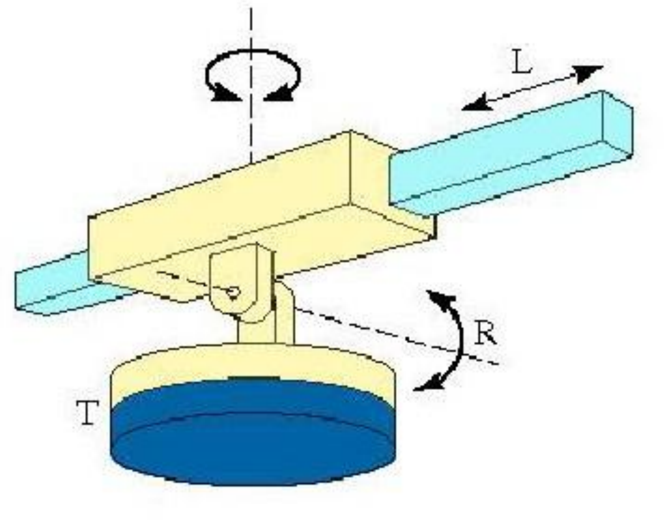


Fig 3: 3-dof polar arm configuration

The polar arm configuration is shown in the fig 3.It consists of a prismatic joint that can be raised or lowered about a horizontal revolute joint. The two links are mounted on a rotating base. These various joints provide the capability of moving the arm endpoint within a partial spherical space. Therefore it is called as ―Spherical co-ordinate‖ configuration. This configuration allows manipulation of objects on the floor.

Drawbacks:

i. Low mechanical stiffness
ii. Complex construction
iii. Position accuracy decreases with the increasing radial stroke.

Applications: Machining, spray painting

Example: Unimate 2000 series, MAKER 110

2) Cylindrical coordinate arm configuration (RPP):

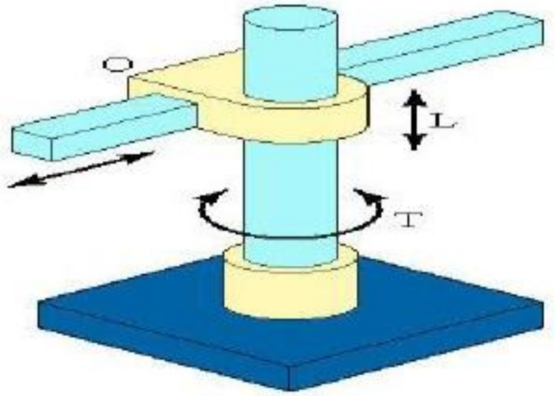


Fig 4: 3-dof cylindrical arm configuration

The cylindrical configuration uses two perpendicular prismatic joints and a revolute joint as shown in fig 4.This configuration uses a vertical column and a slide that can be moved up or down along the column. The robot arm is attached to the slide, so that it can be moved radially with respect to column. By rotating the column, the robot is capable of achieving a workspace that approximates a cylinder. The cylindrical configuration offers good mechanical stiffness.

Drawback: Accuracy decreases as the horizontal stroke increases.

Applications: suitable to access narrow horizontal capabilities, hence used for machine loading operations. **Example:** GMF model M-1A.

3) Cartesian coordinate arm configuration (PPP):

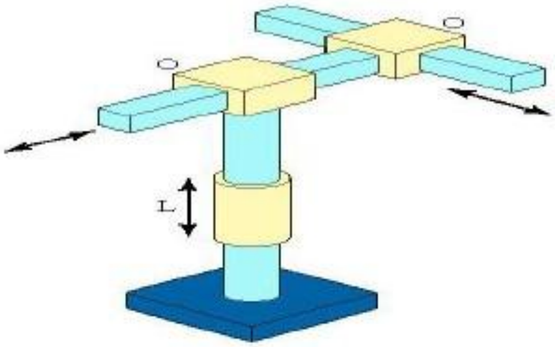


Fig 5: 3-dof Cartesian arm configuration

From fig 5.Cartesian coordinate or rectangular coordinate configuration is constructed by three perpendicular slides, giving only linear motions along the three principal axes. It consists of three prismatic joints. The endpoints of the arm are capable of operating in a cuboidal space. Cartesian arm gives high precision and is easy to program.

Drawbacks:

- limited manipulatability
- low dexterity (not able to move quickly and easily)

Applications: use to lift and move heavy loads.

Examples: IBM RS-1

4) Jointed arm configuration (RRP) or articulated configuration:

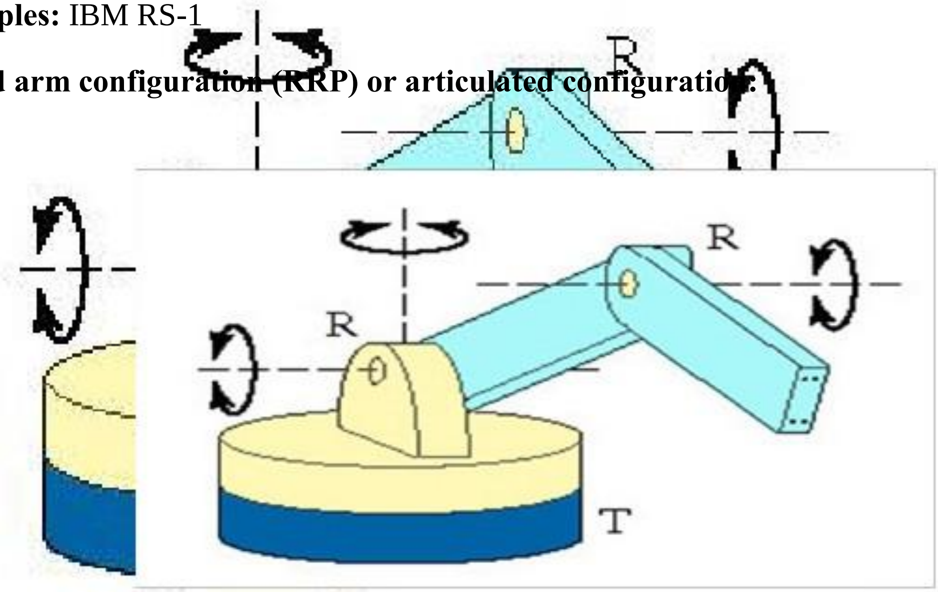


Fig 6. 3-dof jointed arm configuration

From fig 6. jointed arm configurations are similar to that of human arm. It consists of two straight links, corresponding to human _fore arm‘ and _upper arm‘ with two rotary joint corresponding to the elbow and shoulder joints. These two are mounted on a vertical rotary table corresponding to human waist joint. The work volume is spherical. This structure is the most dexterous one. This configuration is very widely used.

Applications: Arc welding, Spray coating.

Example: SCARA robot (Selective compliance Assembly Robot Arm)

Its full form is _Selective Compliance Assembly Robot Arm'. It is similar in construction to the jointed-arm robot, except the shoulder and elbow rotational axes are vertical. It means that the arm is very rigid in the vertical direction, but compliant in the horizontal direction.

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 wrist joints are unnecessary. The other four body-and-arm configurations more-or-less follow the wrist-joint configuration by deploying various combinations of rotary joints viz. type R and T

Robot Wrist:

Wrist assembly is attached to end-of-arm. End effectors are attached to wrist assembly Function of wrist assembly is to orient end effectors .Body-and-arm determines global position of end effector It has three degrees of freedom:

- **Roll (R)** axis – involves rotation of the wrist mechanism about the arm axis.
- **Pitch (P)** axis – involves up or down rotation of the wrist.
- **Yaw (Y)axis** - involves right or left rotation of the wrist.

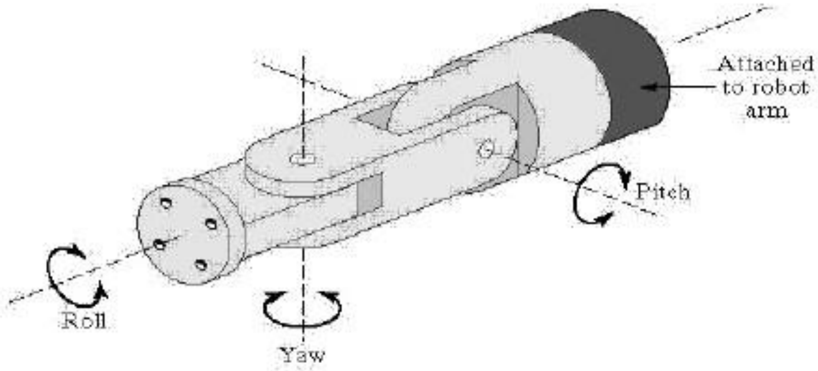


Fig 7: Robotic wrist

Robot wrist assembly consists of either two or three degrees-of -freedom. A typical three-degree-of-freedom wrist joint is depicted in Figure 7,: 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 utilize R joints.

Degree of freedom:

In mechanics, the degree of freedom (DOF) of a mechanical system is the number of independent parameters that define its configuration. It is the number of parameters that determine the state of a physical system and is important to the analysis of systems of bodies in mechanical engineering, aeronautical engineering, robotics, and structural engineering.

The position and orientation of a rigid body in space is defined by three components of translation and three components of rotation, which means that it has six degrees of freedom.

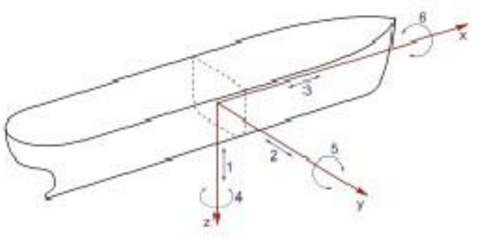


Fig 8.The six degrees of freedom of movement of a ship

The motion of a ship at sea has the six degrees of freedom of a rigid body, and is described as shown in fig 8 .

Translation:

1. Moving up and down (heaving);
2. Moving left and right (swaying);
3. Moving forward and backward (surging);

Rotation:

4. Tilts forward and backward (pitching);
5. Swivels left and right (yawing);
6. Pivots side to side (rolling).

From fig 9.The trajectory of an airplane in flight has three degrees of freedom and its attitude along the trajectory has three degrees of freedom, for a total of six degrees of freedom.

Fig 9 .Attitude degrees of freedom for an airplane.

Robot work volume:

A space on which a robot can move and operate its wrist end is called as a work volume. It is also referred as the work envelope and work space. For developing a better work volume, some of the physical characteristics of a robot should be considered such as:

- The anatomy of various robots
- The maximum value for moving a robot joint
- The size of the robot components like wrist, arm, and body

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.

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.

Table 2.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.

Need for Automation:

Automation refers to the use of computers and other automated machinery for the execution of business-related tasks. Automated machinery may range from simple sensing devices to robots and other sophisticated equipment. Automation of operations may encompass the automation of a single operation or the automation of an entire factory.

There are many different reasons to automate. Increased productivity is normally the major reason for many companies desiring a competitive advantage. Automation also offers low operational variability. Variability is directly related to quality and productivity. Other reasons to automate include the presence of a hazardous working environment and the high cost of human labor. Some businesses automate processes in order to reduce production time, increase manufacturing flexibility, reduce costs, eliminate human error, or make up for a labor shortage. Decisions associated with automation are usually concerned with some or all of these economic and social considerations.

Types of Automation:

Automation of production systems can be classified into three basic types:

1. Fixed automation (Hard Automation)
2. Programmable automation (Soft Automation)
3. Flexible automation.

1. **Fixed automation** (Hard automation): Fixed automation refers to the use of special purpose equipment to automate a fixed sequence of processing or assembly operations. Each of the operation in the sequence is usually simple, involving perhaps a plain linear or rotational motion or an uncomplicated combination of two. It is relatively difficult to accommodate changes in the product design. This is called hard automation.

Advantages:

i. Low unit cost
ii. Automated material handling
iii. High production rate.

Disadvantages:

i. High initial Investment
ii. Relatively inflexible in accommodating product changes.

2. **Programmable automation:** In programmable automation, the production equipment is designed with the capability to change the sequence of operations to accommodate different product configurations. The operation sequence is controlled by a program, which is a set of instructions coded. So, that they can be read and interpreted by the system. New programs can be prepared and entered into the equipment to produce new products.

Advantages:

i. Flexible to deal with design variations.
ii. Suitable for batch production.

Disadvantages:

i. High investment in general purpose equipment

ii. Lower production rate than fixed automation.

Example: Numerical controlled machine tools, industrial robots and programmable logic controller.

3. **Flexible Automation** (Soft automation): Flexible automation is an extension of programmable automation. A flexible automation system is capable of producing a variety of parts with virtually no time lost for changeovers from one part style to the next. There is no lost production time while reprogramming the system and altering the physical set up.

Advantages:

i. Continuous production of variable mixtures of product.

ii. Flexible to deal with product design variation.

Disadvantages:

i. Medium production rate

ii. High investment.

iii. High _unit cost relative to fixed automation.

UNIT II SENSORS AND TRANSDUCERS

Sensors:

Sensors are devices that can sense and measure physical properties of the environment, e.g. temperature, luminance, resistance to touch, weight, size, etc. Transduction (engineering) is a process that converts one type of energy to another. They deliver low-level information about the environment.

Transducers and sensors:

Transducer is a device that converts one type of physical variable (eg; force, temperature, velocity, flow rate etc) into another form. Generally we convert this to electrical voltages. The reason for this is that the converted signal is more convenient to use and evaluate.

Sensor is just used to sense the signals. Any transducer or sensor requires calibration in order to be useful as a measuring device calibration is the procedure by which the relation between the measured variable and the converted output signal is established.

Types of transducers:

1.Analog Trancducers.
Provides a continuous signal such as electrical voltage or current as output .
2.Digital Trancducers:
Provides digital output signal in the form of status bits or series of pulses that can be counted. Output value represents the measured value.Digital trancducers are more easy to read the output and they offer high accuracy and more compatible with digital computer than analog based sensors.

Desirable features of Sensors:

1. Accuracy

Accuracy should be high. How close output to the true value is the accuracy of the device.

2. Precision

There should not be any variations in the sensed output over a period of time precision of the sensor should be high.

3. Operating Range

Sensor should have wide range of operation and should be accurate and precise over this entire range.

4. Speed of Response

Should be capable of responding to the changes in the sensed variable in minimum time.

5. Calibration

Sensor should be easy to calibrate time and trouble required to calibrate should be minimum. It should not require frequent recalibration.

6. Reliability

It should have high reliability. Frequent failure should not happen.

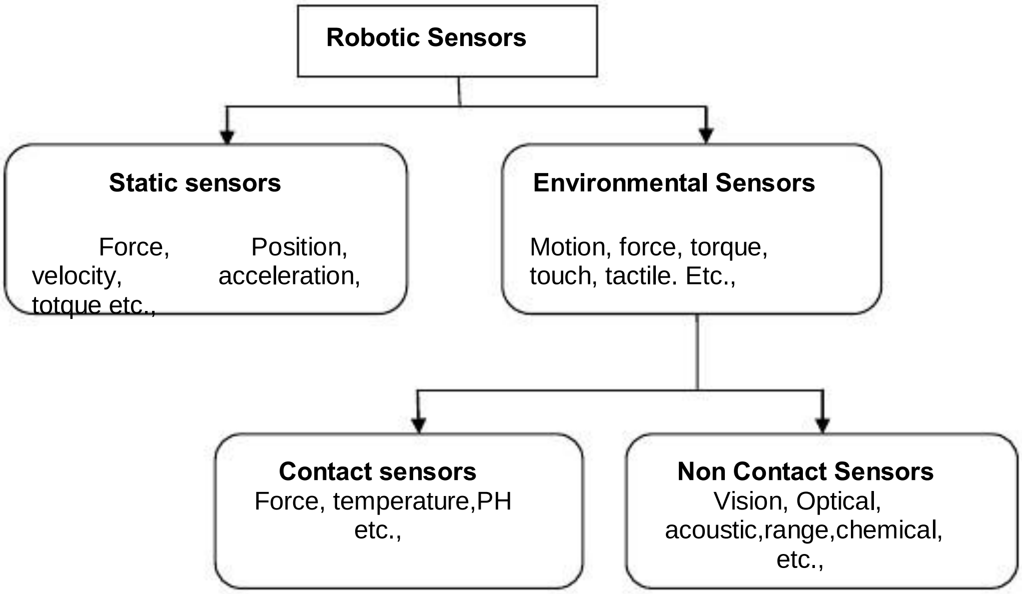
7. Cost and Ease of operation

Cost should be as low as possible, installation, operation and maintenance should be easy and should not required skilled or highly trained persons.

Examples of Sensors:

- A) Potentiometers
- B) Thermocouples, thermistors.
- C) Strain gauge
- D) Load cell
- E) Infrared sensors
- F) LVDT
- G) Pyrometers
- H) Pizeo electric devices
- I) Pressure Transducers
- J) Vision and voice sensors.

Robotic Sensors:



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.

ROBOTIC SENSORS For certain robot application, the type of workstation control using interlocks is not adequate the robot must take on more human like senses and capabilities in order to perform the task in a satisfactory way these senses and capability includes vision and hand eye coordination, touch, hearing accordingly we will dived the types of sensors used in robotics into the following three categories.

A number of advanced sensor technologies may also be used; these are outlined in Table 1.

Table 1: 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.

Range sensor:

Ranging sensors include sensors that require no physical contact with the object being detected. They allow a robot to see an obstacle without actually having to come into contact with it. This can prevent possible entanglement, allow for better obstacle avoidance (over touch-feedback methods), and possibly allow software to distinguish between obstacles of different shapes and sizes. There are several methods used to allow a sensor to detect obstacles from a distance.

Light-based ranging sensors use multiple methods for detecting obstacles and determining range. The simplest method uses the intensity of the reflected light from an obstacle to estimate distance. However, this can be significantly affected by the color/reflectivity of the obstacle and external light sources. A more common method is to use a beam of light projected at an angle and a strip of detectors spaced away from the emitter as in the animation to the right. The pictured Sharp sensor uses this method. This method is less affected by the color/reflectivity of the object and ambient light.

LIDAR, a more advanced method of range detection, uses a laser that is swept across the sensor's field of view. The reflected laser light is usually analyzed one of two ways. Units with longer ranges sometimes actually determine distance by measuring the time it takes for the laser pulse to return to the sensor. This requires extremely fast timing circuitry. Another method uses phase shift detection to determine range by analyzing the incoming light and comparing it to a reference signal.

Tactile sensor

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

Touch sensors are used simply to indicate whether contact has been made with an object. A simple micro switch 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 use 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 used in gauging operations and dimensional measuring activities.

Proximity sensor

Proximity sensors are used to sense when one object is close to another object. On a robot, the proximity sensors would be located n or near the end effectors. This sensing capability can be engineered by means of 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 be helpful in preventing injury to the robots human coworkers in the factory.

Optical or Infrared Light-Based sensors

This is one of the areas that is receiving a lot of attention in robotics research computerized visions systems will be an important technology in future automated factories. Robot vision is made possible by means of video camera a sufficient light source and a computer programmed to process image data. The camera is mounted either on the robot or in a fixed position above the robot so that its field of vision includes the robots 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 which are randomly oriented on a conveyor Recognize particular parts which are intermixed with other objects Perform assembly operations which require alignment.

Another very popular method uses projected light waves, usually infrared, to detect obstacles. This system projects a pulse of light and looks for the reflection. Properties of the reflected light are analyzed to determine characteristics about the object detected. Light has the advantages of traveling extremely fast, allowing for fast sensor response time, high resolution, and less error to account for. Light from this type of sensor is often formed into a narrow beam or many times a laser is used. This provides good resolution over large distances.9

Proximity sensors

The simplest light-based obstacle sensor projects a light and looks for a reflection of certain strength. If the reflection is strong enough, it can be inferred that an obstacle lies within a certain range of the sensor. Multiple light sources can be pulsed on in sequence to give some resolution to the sensor as in the figures.

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 which 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 actions which corresponds to the word. Voice sensors could 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 in hazardous working environments for performing unique operations such as maintenance and repair work. The robot could be placed in hazardous environment and remotely commanded to perform the repair chores by means of step by step instructions.

Internal sensor

Internal sensors measure the robot's internal state. They are used to measure its position, velocity and acceleration.

Position sensor

Position sensors measure the position of a joint (the degree to which the joint is extended). They include:

Encoder: a digital optical device that converts motion into a sequence of digital pulses.

Potentiometer: a variable resistance device that expresses linear or angular displacements in terms of voltage.

Linear variable differential transformer: a displacement transducer that provides high accuracy. It generates an AC signal whose magnitude is a function of the displacement of a moving core.

Synchronous and Resolvers

Velocity Sensor

A velocity or speed sensor measures consecutive position measurements at known intervals and computes the time rate of change in the position values.

Acceleration Sensors:

Accelerometer

An accelerometer measures acceleration (change in speed) of anything that it's mounted on. How does it work? Inside an accelerator MEMS device are tiny micro-structures that bend due to momentum and gravity. When it experiences any form of acceleration, these tiny structures bend by an equivalent amount which can be electrically detected. Today, accelerometers are easily and cheaply available, making it a very viable sensor for cheap robotics hobbyists like you and me

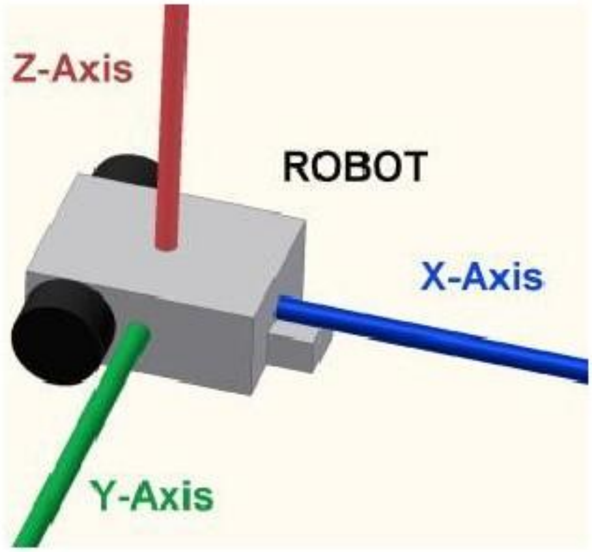
Applications for Accelerometers are very important in the sensor world because they can sense such a wide range of motion. They're used in the latest Apple Power books (and other laptops) to detect when the computer's suddenly moved or tipped, so the hard drive can be locked up during movement. They're used in cameras, to control image stabilization functions. They're used in pedometers, gait meters, and other exercise and physical therapy devices. They're used in gaming controls to generate tilt data. They're used in automobiles, to control airbag release when there's a sudden stop. There are countless other applications for them.

Possible uses for accelerometers in robotics:

- Self balancing robots
- Tilt-mode game controllers
- Model airplane auto pilot
- Alarm systems
- Collision detection
- Human motion monitoring
- Leveling sensor, inclinometer
- Vibration Detectors for Vibration Isolators
- G-Force Detectors

Axis of acceleration

The tiny micro-structures can only measure force in a single direction, or axis of acceleration. This means with a single axis measured, you can only know the force in either the X, Y, or Z directions, but not all. So if say your X-axis accelerometer endowed robot was running around and ran into a wall (in the X direction). Your robot could detect this collision. But if say another robot rammed into it from the side (the Y direction), your robot would be oblivious to it. There are many other situations where a single axis would not be enough. It is always a good idea to have at least 2 axes (more than one axis).



Gravity

Gravity is acceleration. Your accelerometer will always be subject to a -9.81 m/s^2 acceleration (negative means towards the ground). Because of this, your robot can detect what angle it is in respect to gravity. If your robot is a biped, and you want it to always remain balanced and standing up, just simply use a 2-axis accelerometer. As long as the X and Y axes detect zero acceleration, this means your robot device is perfectly level and balanced.

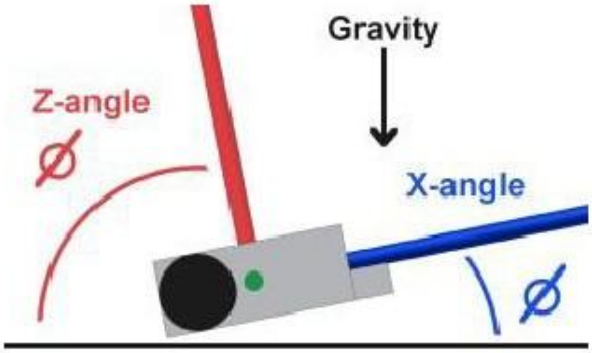
Accelerometers, Rated G When you buy your accelerometer, you will notice it saying something like 'rated at 2g' or '3g accelerometer.' This is the maximum g force your sensor can report. Gravity accelerates objects at 1g, or 9.81 m/s^2. For example, if your robot is moving at 1g upwards, then that means you sensor will detect 2g. For most robotics applications a 2g rating will be fine. So why not just get the highest rating possible? The lower the rating, the more sensitive it will be to changes in motion. You will always have a finer tuned sensor the lower the rating. But then again, more sensitive sensors are more affected by vibration interference.

Calculate Acceleration and Angle wrt Gravity To calculate the magnitude of acceleration for a

single-axis accelerometer	acceleration_max = sqrt(x^2) = x
2-axis accelerometer	acceleration_max = sqrt(x^2+y^2)
3-axis accelerometer	acceleration_max = sqrt(x^2+y^2+z^2)

To calculate the detected force on an accelerometer due to gravity:

Force_gravity = -g*cos(angle) (depends on starting axis of sensor)



Chances are you would have no need to measure the force, but if you reverse the equation you can calculate the angle by knowing the

detected force : cos(sensor_value*conversion_constant / -g)^-1 = angle

Availability and cost

The MEMS IC's are easily available and very affordable. However they all require support circuitry and come as surface mounts. I highly discourage buying an IC and doing your own wiring. However there are many already setup accelerometer packages you can buy. For example, Dimension Engineering has a great plug and play dual axis accelerometer which requires no additional support circuitry. There are several other great sensors out there, some as a 3-axis, and now some even with built in rotation sensor.

Wiring Requirements Any accelerometer package will have a power and ground line, and a single output analog pin for each axis of acceleration. Some of the sensors come with additional features/pins, read their datasheets. Additional Tips and Uses Placing an accelerometer on a mobile robot that experiences bumps can trigger the accelerometer unintentionally. Use a capacitor to smooth out output over several hundred milliseconds (testing required) to prevent this. Also, read the interpret sensor data tutorial to enhance your accelerator sensor accuracy.

Touch, Force, Torque :

A tactile sensor is a device that measures information arising from physical interaction with its environment. Tactile sensors are generally modeled after the biological sense of coetaneous touch which is capable of detecting stimuli resulting from mechanical stimulation, temperature, and pain (although pain sensing is not common in artificial tactile sensors). Tactile sensors are used in robotics, computer hardware and security systems. A common application of tactile sensors is in touchscreen devices on mobile phones and computing.

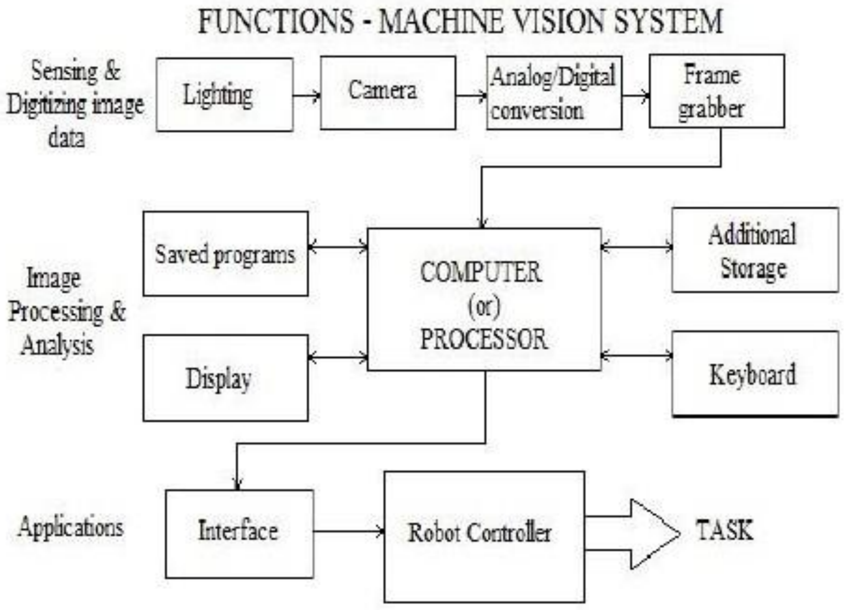
Tactile sensors may be of different types including piezoresistive, piezoelectric, capacitive and elasto-resistive sensors

Force Sensors (Force Transducers) There are many types of force sensors, usually referred to as torque cells (to measure torque) and load cells (to measure force). From this point on I will refer to them as 'force transducers.' Force transducers are devices useful in directly measuring torques and forces within your mechanical system. In order to get the most benefit from a force transducer, you must have a basic understanding of the technology, construction, and operation of this unique device.

Machine Vision System

Machine vision system is a sensor used in the robots for viewing and recognizing an object with the help of a computer. It is mostly used in the industrial robots for inspection purposes. This system is also known as artificial vision or computer vision. It has several components such as a camera, digital computer, digitizing hardware, and an interface hardware & software. The machine vision process includes three important tasks, namely:

1. Sensing & Digitizing Image Data
2. Image Processing & Analysis
3. Applications



Sensing & Digitizing Image Data:

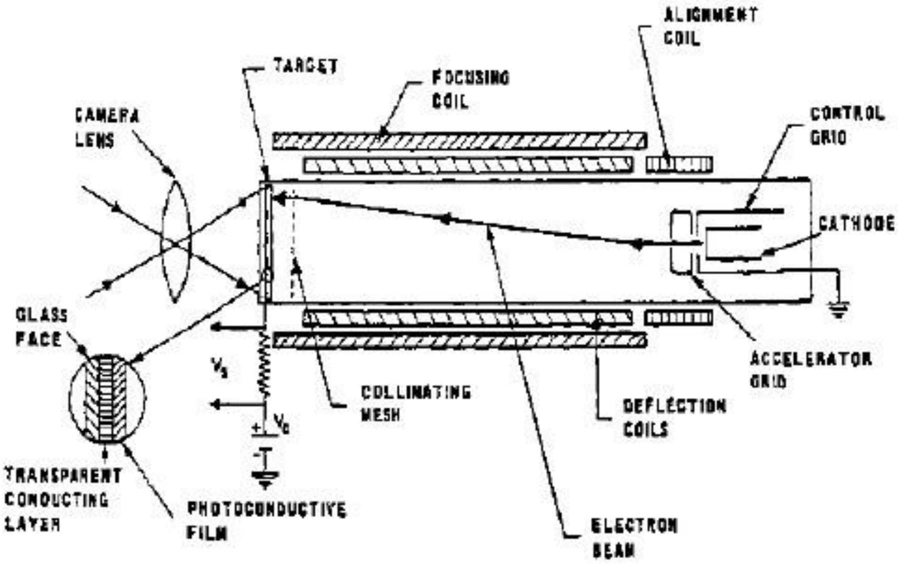
A camera is used in the sensing and digitizing tasks for viewing the images. It will make use of special lighting methods for gaining better picture contrast. These images are changed into the digital form, and it is known as the frame of the vision data. A frame grabber is incorporated for taking digitized image continuously at 30 frames per second. Instead of scene projections, every frame is divided as a matrix. By performing sampling operation on the image, the number of pixels can be identified. The pixels are generally described by the elements of the matrix. A pixel is decreased to a value for measuring the intensity of light. As a result of this process, the intensity of every pixel is changed into the digital value and stored in the computer's memory.

Imaging devices:

There are a variety of commercial imaging devices available. Camera technologies available include the older black and white and vidicon camera and the newer second generation solid state cameras. Solid state camera used for robot vision include charge coupled devices (CCD), charge injection devices (CID) and silicon bipolar sensor cameras. For our use two devices in this subsection, the vidicon camera and the charge coupled devices.

1. Vidicon camera:

A vidicon tube is a video camera tube design in which the target material is a photoconductor. The vidicon is a storage-type camera tube in which a charge-density pattern is formed by the imaged scene radiation on a photoconductive surface which is then scanned by a beam of low-velocity electrons. The fluctuating voltage coupled out to a video amplifier can be used to reproduce the scene being imaged. The electrical charge produced by an image will remain in the face plate until it is scanned or until the charge dissipates. Pyroelectric photocathodes can be used to produce a vidicon sensitive over a broad portion of the infrared spectrum



2. CHARGE-COUPLED DEVICE (CCD):

A **charge-coupled device** (CCD) is a device for the movement of electrical charge, usually from within the device to an area where the charge can be manipulated, for example conversion into a digital value. This is achieved by "shifting" the signals between stages within the device one at a time. CCDs move charge between capacitive *bins* in the device, with the shift allowing for the transfer of charge between bins.

The CCD is a major piece of technology in digital imaging. In a CCD image sensor, pixels are represented by p-doped MOS capacitors. These capacitors are biased above the threshold for inversion when image acquisition begins, allowing the conversion of incoming photons into electron charges at the semiconductor-oxide interface; the CCD is then used to read out these charges. Although CCDs are not the only technology to allow for light detection, CCD image sensors are widely used in professional, medical, and scientific applications where high-quality image data is required. In applications with less exacting quality demands, such as consumer and professional digital cameras, active pixel sensors (CMOS) are generally used; the large quality advantage CCDs enjoyed early on has narrowed over time.

In a CCD for capturing images, there is a photoactive region (an epitaxial layer of silicon), and a transmission region made out of a shift register (the CCD, properly speaking).

An image is projected through a lens onto the capacitor array (the photoactive region), causing each capacitor to accumulate an electric charge proportional to the light intensity at that location. A one-dimensional array, used in line-scan cameras, captures a single slice of the image, whereas a two-dimensional array, used in video and still cameras, captures a two-dimensional picture corresponding to the scene projected onto the focal plane of the sensor. Once the array has been exposed to the image, a control circuit causes each capacitor to transfer its contents to its neighbor (operating as a shift register). The last capacitor in the array dumps its charge into a charge amplifier, which converts the charge into a voltage. By repeating this process, the controlling circuit converts the entire contents of the array in the semiconductor to a sequence of voltages. In a digital device, these voltages are then sampled, digitized, and usually stored in memory; in an analog device (such as an analog video camera), they are processed into a continuous analog signal (e.g. by feeding the output of the charge amplifier into a low-pass filter), which is then processed and fed out to other circuits for transmission, recording, or other processing.

Image Processing & Analysis:

In this function, the image interpretation and data reduction processes are done. The threshold of an image frame is developed as a binary image for reducing the data. The data reduction will help in converting the frame from raw image data to the feature value data. The feature value data can be calculated via computer programming. This is performed by matching the image descriptors like size and appearance with the previously stored data on the computer.

The image processing and analysis function will be made more effective by training the machine vision system regularly. There are several data collected in the training process like length of perimeter, outer & inner diameter, area, and so on. Here, the camera will be very helpful to identify the match between the computer models and new objects of feature value data.

Applications:

Some of the important applications of the machine vision system in the robots are:

- Inspection
- Orientation
- Part Identification
- Location

There are some of the future improvements researches are going on for providing highly-developed machine vision system in the complicated areas.

Image data reduction:

In image data reduction , the objective is to reduce the volume of data. As a prelimnary step in the data analysis, the following two schemes have found common usafe for data reduction.

1.Digital conversion

2.Windowing.

Digital conversion reduces the number of grey levels used by the machine vision systems. Example: an 8 bit register used for each pixel could have $2_8 = 256$. Gray levels. Depending on the requirements of the application, digital conversion can be used to reduce the number of gray levels by using fewer bits to represent the pixel light intensity. Four bits would reduce the number of grey levels to 16. This kind of conversion reduces the magnitude of the image – processing problem.

Windowing involves using only a portion of the total image stored in the frame buffer for image processing and analysis this portion is called the window. **Example:** for inspection of printed circuit board, one may wish to inspect and analysis only one component on the board. A rectangular window is selected to surround the component of interest and only pixels only the windows are analyzed.

Segmentation:

Segmentation is a general term which is applies to the various methods of data reduction. In segmentation , the objective is to group areas of an image having similar charecterestics or features into distinct entities representing the parts of the image.

Example: Boundaries (Edges) or regions (areas) represents two natural segments of an image. There are many ways to segment an image

- Thresholding
- Region growing
- Edge detection

1. Thresholding

Thresholding is the binary conversion technique in which each pixel is converted into a binary value, either black or white. This is accomplished by utilizing a frequency histogram of the image and establishing what intensity is to be border between the black and white. Thersholding is the most widely used techniques for segmentation in industrial vision application. It is the fast and easily implemented and that the lighting is usually controllable is an industrial setting.

2. Region growing

Region growing is a collection of segmentation techniques in which the pixels are grouped in regions called grid elements based on attribute similarities. To differentiate between the object and the background assign 1for any grid element occupied by an object. A typical region growing techniques for complete images could have the following procedures

- Select the pixel, In the simplest case select white pixel and assign a value of 1
- Compare the pixel, selected with all adjacent pixels
- Go to an equivalent adjacent pixel and repeat the until no equivalent pixels can be added to the region.

3.Edge detection

Edge detection is considered as the intensity change that occurs in the pixels at the boundary or edges of a part. The boundary can be determined by a simple edge following procedure is to scan a image until a pixel within the region is encountered. For a pixel within the region, turn left and step, otherwise turn right and step.

Feature Extraction

In machine vision application, it is often necessary to distinguish one object from another. This is usually accomplished by means of features that uniquely characterized the object. Some features of object that can be used in machine vision include area, diameter and perimeter. The region growing procedures described before can be used to determine the area of an object image.

Object Recognition

The next step in image data processing is to identify the object the object the image represents. The object recognition techniques used in industry today may be classified into two major categories

a) Template matching techniques
b) Structural techniques

Template matching techniques are a subset of the more general statistical pattern recognition techniques that serve to classify objects in an image into predetermined categories. The basic problem in template matching is to match the object into a stored pattern feature set defined as a model template. These techniques are applicable if there is no requirement for a large number of model templates. When the match is found, allowing for a certain statistical variations in the comparison process. Then the object has been properly classified.

Structural techniques of pattern recognition consider relationships between features or edges of an object. For examples, if an image of an object can be divided into four straight lines (the lines are called primitives)connected at their endpoints and the connected lines are at right angles, then the object is rectangle . This kind of technique is known as syntactic pattern recognition is the most widely used structural techniques.

Structural techniques differ from decision theoretic techniques in that the later deals with a pattern on a quantitative basis and ignores for the most interrelationship among object primitives.

Training the vision system:

The process of vision system training is to program the vision system with known objects. The system stores these objects in the form of extracted feature values which can be subsequently compared against the corresponding features values from images of unknown objects. Physical parameters such as camera placemet, aperture setting, part position and lighting are the critical conditions that should be simulated as closely as possible during the training vision.

Robot applications:

1. The object can be controlled in both position and appearance
2. Either position or appearance of the object can be controlled but not both.
3. The third level of difficulty requires advanced vision capabilities.
4. Large scale industrial manufacture
5. Short iron unique object manufacture.
6. Inspection of pre manufactured objects.
7. Visual stock control and management systems(counting , barcode reading , store interfaces for digital systems)
8. Control of automated guided vehicles(AGV's)
9. Quality control and refinement of food prodects.
10. Retail automation.
11. Machine vision systems are widely used in semiconductor fabrication. Inspect silicon wafers, processor chips and subcomponents such as resistors and capacitors.
12. In the automotive industry machine vision systems are used to guide industrial robots.

These levels depend on whether the object to be viewed is controlled in position and or appearance. Controlling the position of an object in a manufacturing environment usually requires precise fixturing. Controlling the appearance of an object is accomplished by lighting techniques.

Robot applications of machine vision fall into the three categories

a) Inspection

b) Identification

c) Visual servoing and navigation

Inspection:

The first category is one in which the primary function is the inspection process. This is carried out by the machine vision system and the robot is used in a secondary role to support the applications

The objectives of the machine vision inspection include checking for

- Gross surface defects
- Discovery of flaws in labeling verification of the presence of components in assembly
- Measuring for dimensional accuracy
- Checking for presence of holds and other feature in a part.

When these kinds of inspection operation are performed manually, there is a tendency for human error and also time required in manual inspection operation requires sampling basis. With machine vision these procedures are carried out automatically using hundred percent inspections and usually in much less time.

Identification:

The second category identification is concerned with applications in which the purpose of the machine vision system is to recognize and classify an object rather than to inspect it. Inspection implies the part must be either accepted or rejected. Identification implies that the part involves recognition process in which the part itself or its position and / or orientation is determined. This is usually followed by a subsequent decision and action taken by the robot. Identification applications of machine vision include

- Part sorting
- Palletizing
- Depalletizing
- Picking parts

Visual servoing and navigation:

In the third application category, visual servoing and navigational control the purpose of the vision system is to direct the actions of the robot based on its visual input. The generic example of the robot visual servoing is where the machine vision system is used to control the trajectory of the robots end effecter toward an object in the workspace. Industrial example of this applications include part positioning, retrieving parts moving along the conveyor retrieving and reorienting parts moving along a conveyor, assembly, bin picking and tracking in continuous arc welding.

An example of navigational control would be in automatic robot path planning and collision avoidance using visual data. The bin picking application is an interesting and complex application of machine vision in robotics which involves both identification and servoing. Bin picking involves the use of a robot to grasp and retrieve randomly oriented parts will be overlapping each other.

The vision system must first recognize a target part and its orientation in the container and then it must direct the end effecter to a position to permit grasping and pickup. Solution of the bin picking problem owes much to the pioneering work in vision research at the University of Rhode Island. There are two commercially available bin picking systems one offered by object recognition systems inc called the i-bot 1 system and the other by general electric co called bin vision. Tracking in continuous arc welding is another example of the visual servoing and navigation in robotic vision systems.

Model questions

Part A

1. What are the desirable features of sensors?
2. What are the essential requirements for success in robot vision?
3. Give one example for velocity sensor.
4. Distinguish between tactile and non-tactile sensors. Give examples of each type.
5. Compare the internal state and external state sensors.

Part B

1. What are the types of fiber optic sensors? Explain in detail how they work.
2. Explain robot machine vision with suitable diagram.
3. With neat sketch explain ultrasonic proximity sensor.
4. Discuss the different sensors used in robotics.
5. What are the functions of a vision processor? What are the steps necessary in the image processing?
6. Discuss various sensors used in robots for various applications.

UNIT III – ROBOT PROGRAMMING AND GRIPPER

Introduction

In robotics, an end-effector is the device at the end of a robotic arm, designed to interact with the environment. The exact nature of this device depends on the application of the robot.

In the strict definition, which originates from serial robotic manipulators, the end effector means the last link (or end) of the robot. At this endpoint the tools are attached. In a wider sense, an end effector can be seen as the part of a robot that interacts with the work environment. This does not refer to the wheels of a mobile robot or the feet of a humanoid robot which are also not end effectors—they are part of the robot's mobility

Considerations in robot gripper selection and design

The industrial robots use grippers as an end effector for picking up the raw and finished work parts. A robot can perform good grasping of objects only when it obtains a proper gripper selection and design. Therefore, Joseph F. Engelberger, who is referred as Father of Roboticshas described several factors that are required to be considered in gripper selection and design.

- The gripper must have the ability to reach the surface of a work part.
- The change in work part size must be accounted for providing accurate positioning.
- During machining operations, there will be a change in the work part size. As a result, the gripper must be designed to hold a work part even when the size is varied.
- The gripper must not create any sort of distort and scratch in the fragile work parts.
- The gripper must hold the larger area of a work part if it has various dimensions, which will certainly increase stability and control in positioning.
- The gripper can be designed with resilient pads to provide more grasping contacts in the work part. The replaceable fingers can also be employed for holding different work part sizes by its interchangeability facility.

Moreover, it is difficult to find out the magnitude of gripping force that a gripper must apply to pick up a work part. The following significant factors must be considered to determine the necessary gripping force.

- Consideration must be taken to the weight of a work part.
- It must be capable of grasping the work parts constantly at its center of mass.

- The speed of robot arm movement and the connection between the direction of movement and gripper position on the work part should be considered.
- It must determine either friction or physical constriction helps to grip the work part.
- It must consider the co-efficient of friction between the gripper and work part

Various types of artificial gripper mechanisms

Gripper mechanisms can be classified into the following major categories:

1) Mechanical finger grippers – sub classification is based on method of actuation.
2) Vacuum and magnetic grippers – sub-classification is based on type of the force-exerting elements.
3) Universal grippers – sub-classification is inflatable fingers, soft fingers & three fingered grippers.
4) Adhesive grippers
5) Hooks, scoops

Mechanical finger grippers

(a) Linkage grippers: there is no cam, screw, gear. There is movement only because of links because of links attached to input and output. There must be perfect design of mechanism such that input actuator’s motion is transformed into the gripping action at the output.

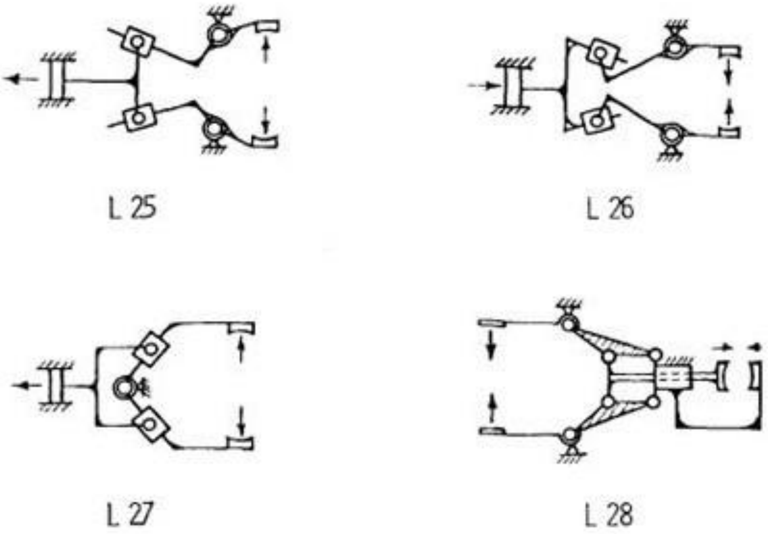


Fig 3.1: Linkage Grippers

Gear and Rack Grippers: movement of input due to gear motion which makes connecting links to go in motion to make gripping action at the output link.

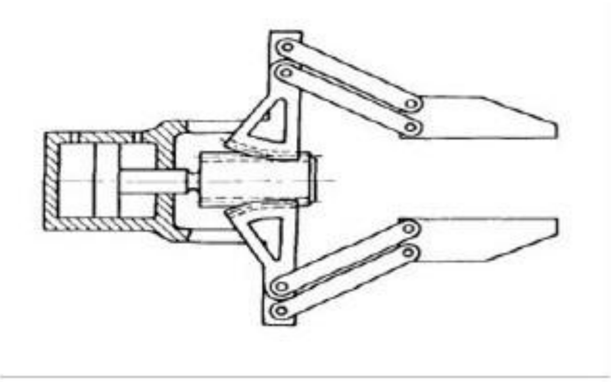


Fig 3.2: Gear and Rack Grippers

Cam-actuated Grippers:

Reciprocating motion of the cam imparts motion to the follower, thus causing fingers toproduce a grabbing action. A variety of cam profiles can be employed- constant velocity, circular arcs, harmonic curves etc.

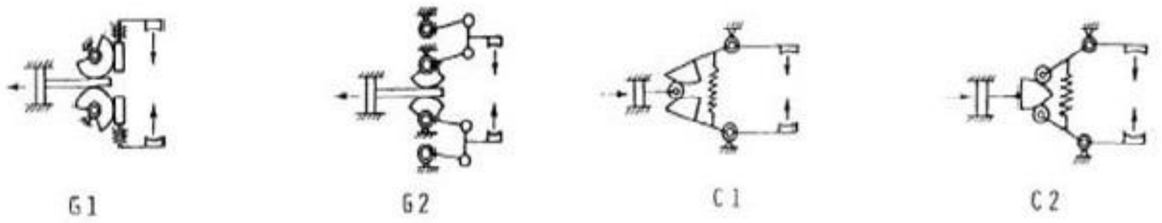


Fig 3.3 Cam-actuated Grippers

Screw-driven Grippers:

Operated by turning screw, in turn giving motion to connecting links and thus giving griping motion to output. Screw motion can be controlled by motor attached.

Fig 3.4: Screw-driven Grippers

Rope & Pulley Grippers:

Motor attached to the pulley makes the winding and unwinding motion of rope in turn it set gripper action into motion via connecting link.

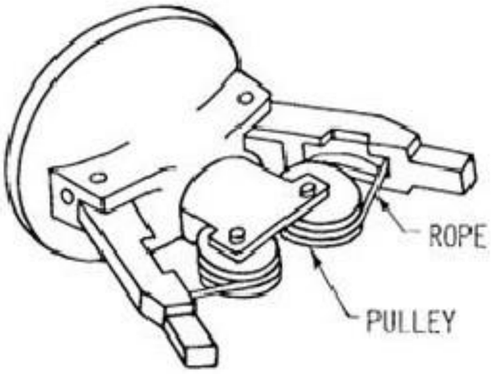
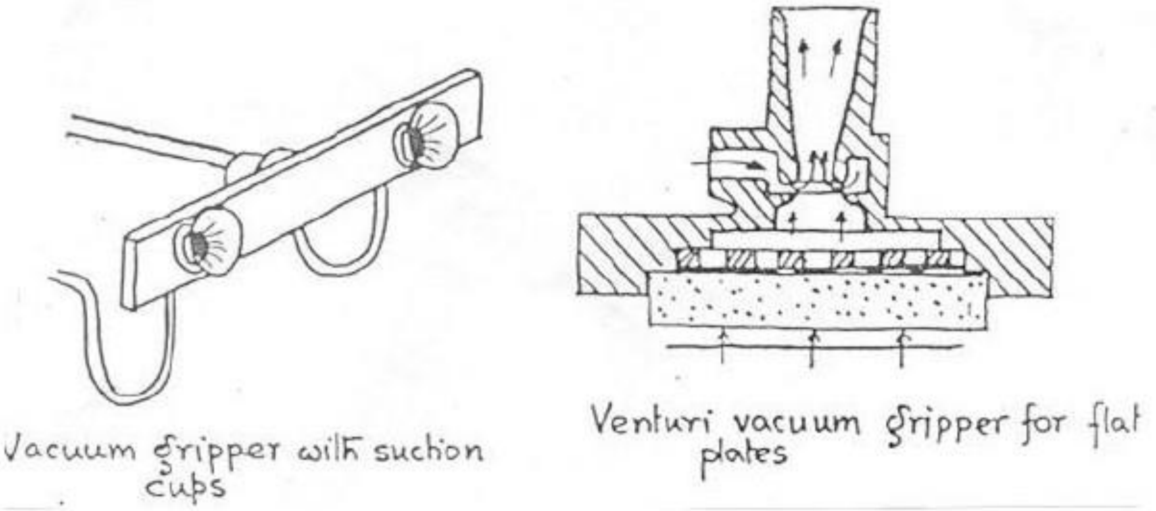


Fig 3.5: Rope & Pulley Grippers

Vacuum & Magnetic Grippers

Vacuum Grippers:

For non-ferrous components with flat and smooth surfaces, grippers can be built using standard vacuum cups or pads made of rubber-like materials. Not suitable for components with curved surfaces or with holes.



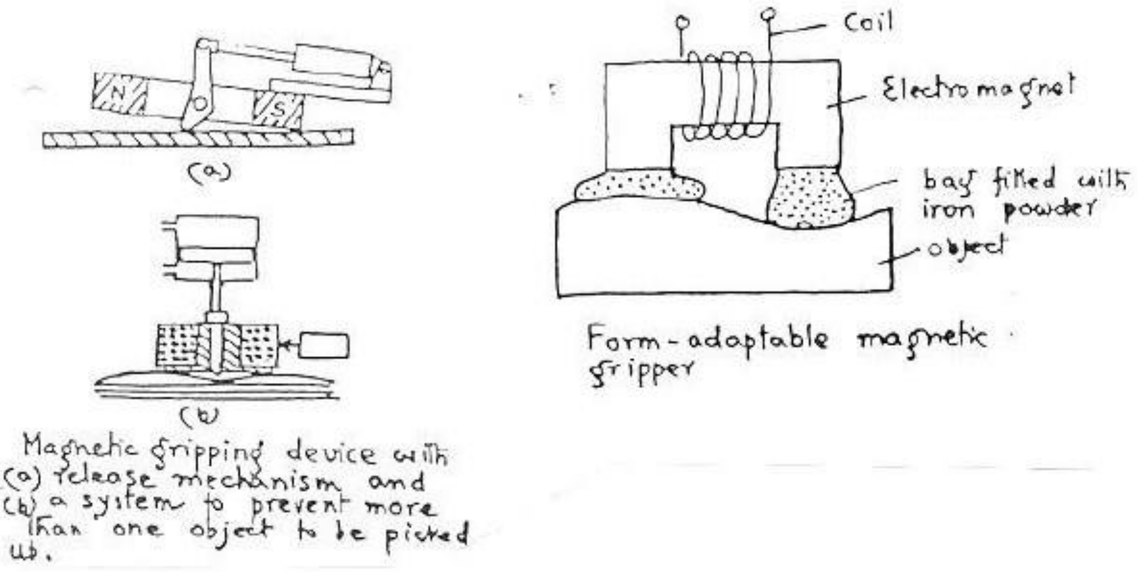
Vacuum gripper with suction cups

Venturi vacuum gripper for flat plates

Fig 3.6: Vacuum Grippers

Magnetic Gripper:

It is used to grip ferrous materials. Magnetic gripper uses a magnetic head to attract ferrous materials like steel plates. The magnetic head is simply constructed with a ferromagnetic core and conducting coils.



Magnetic gripping device with (a) release mechanism and (b) a system to prevent more than one object to be picked up.

Form-adaptable magnetic gripper

Fig 3.7: Magnetic Grippers

Versatile or universal Grippers

Inflatable grippers

It is used for picking up irregular and fragile objects without concentrated loading. In the initial position before gripping, the lever 1, are opened up, the bellows are in a compressed condition because the gas pressure in the bags,3, with the spheres is close, even ah slight pressure of the object on a bag is sufficient enough to cause the bag wall to be deeply depressed and surround the object. When the degree of the surrounding is adequate the lever motion ceases, and pressure in the bags is reduced by bellows, diaphragm device or vacuum pump, causing bags to harden without changing shape and hence gripping the object. To release the object operation is done in reverse.

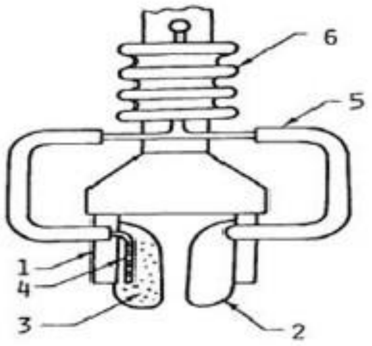


Fig 3.8: Inflatable Grippers

Soft Grippers:

It consists of multi-links and a series of pulleys actuated by a pair of wires. The soft gripper can actively conform to the periphery of objects of any shape and hold them with uniform pressure.

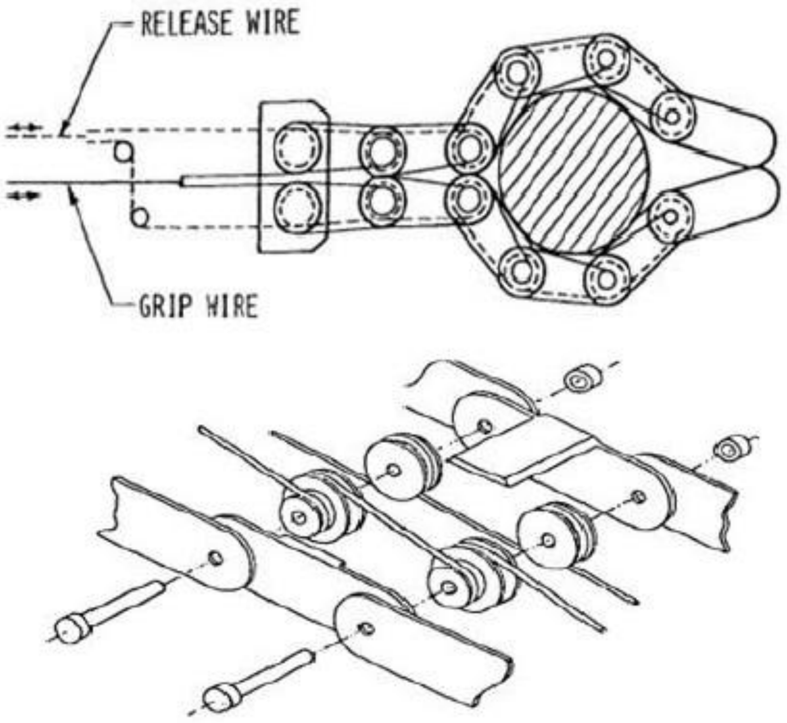


Fig 3.9: Soft Grippers

Three Fingered Grippers:

The clamping movement of two-fingered type normally executes

(a) beat movement
(b) bite movement
(c) Parallel movement of the jaw.

They are capable only of grasping or releasing movement.

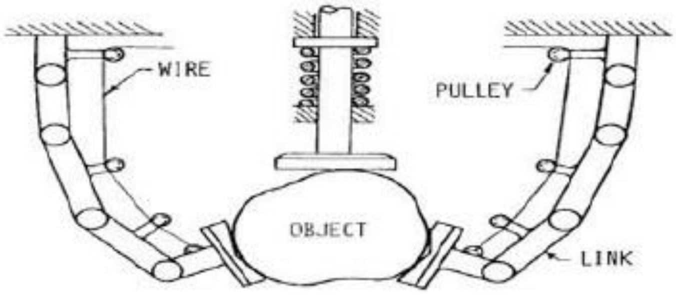


Fig 3.10: Three Fingered Grippers

Adhesive grippers

An adhesive substance can be used for grasping action in gripping design. The requirements on the items to be handled are that they must be gripped on one side only. The reliability of this gripping device is diminished with each successive operation cycle as the adhesive substance loses its tackiness on repeated use. To overcome this limitation, the adhesive material can be loaded in the form of a continuous ribbon into a feeding mechanism attached to the robot wrist.

Hooks, scoops

Hooks can be used as end-effectors to handle containers and to load and unload parts hanging from overhead conveyors. The item to be handled by a hook must have some sort of handle to enable the hook to hold it.

Ladles and scoops can be used to handle certain materials in liquid or powder form. One of the limitations is that the amount of material being scooped by the robot is sometimes difficult to control.

Introduction to manipulators

Industry-specific robots perform several tasks such as picking and placing objects, movement adapted from observing how similar manual tasks are handled by a fully-functioning human arm. Such robotic arms are also known as robotic manipulators. These manipulators were originally used for applications with respect to bio-hazardous or radioactive materials or for use in inaccessible places.

A series of sliding or jointed segments are put together to form an arm-like manipulator that is capable of automatically moving objects within a given number of degrees of freedom. Every commercial robot manipulator includes a controller and a manipulator arm. The performance of the manipulator depends on its speed, payload weight and precision. However, the reach of its end-effectors, the overall working space and the orientation of the work is determined by the structure of the manipulator.

Kinematics of a Robotic Manipulator

A robot manipulator is constructed using rigid links connected by joints with one fixed end and one free end to perform a given task (e.g., to move a box from one location to the next). The joints to this robotic manipulator are the movable components, which enables relative motion between the adjoining links. There are also two linear joints to this robotic manipulator that ensure non-rotational motion between the links, and three rotary type joints that ensure relative rotational motion between the adjacent links.

The manipulator can be divided into two parts, each having different functions:

Arm and Body – The arm and body of the robot consists of three joints connected together by large links. They can be used to move and place objects or tools within the work space.

Wrist – The function of the wrist is to arrange the objects or tools at the work space. The structural characteristic of the robotic wrist includes two or three compact joints.

Robotic Manipulator Arm Configuration

Manipulators are grouped into several types based on the combination of joints, which are as follows:

- Cartesian geometry arm – This arm employs prismatic joints to reach any position within its rectangular workspace by using Cartesian motions of the links.
- Cylindrical geometry arm – This arm is formed by the replacement of the waist joint of the Cartesian arm with a revolute joint. It can be extended to any point within its cylindrical workspace by using a combination of translation and rotation.
- Polar/spherical geometry arm – When a shoulder joint of the Cartesian arm is replaced by a revolute joint, a polar geometry arm is formed. The positions of end-effectors of this arm are described using polar coordinates.
- Articulated/revolute geometry arm - Replacing the elbow joint of the Cartesian arm with the revolute joint forms an articulated arm that works in a complex thick-walled spherical shell.
- Selective compliance automatic robot arm (SCARA) – This arm has two revolute joints in a horizontal plane, which allow the arm to extend within a horizontal planar workspace. The TH650A SCARA Robot by TM Robotics is a great example to demonstrate pick and place functionality of robotic manipulators

Introduction to robot dynamics

While Kinematics deals with finding position, velocity & acceleration based on geometrical constraints, dynamics is concerned with solving for these when an external force acts on the system or the system is released to evolve from some initial position (e.g. Pendulum).

Now we will consider some simple examples to make clear understanding of dynamics.Consider a block sliding on the frictionless floor. A force of constant magnitude F is applied to block. Dynamical equation can be easily found out in this case. Basically dynamical equations are mathematical model governing dynamic behavior of system. These equations are the force-mass-acceleration or the torque-inertia-angular acceleration relationships. By knowing the magnitude of applied force & mass of block, velocity & acceleration can be easily found out at every instant of time if we know initial conditions such as whether body is at rest or moving with certain velocity.

In this portion, we analyze the dynamic behavior of robot mechanisms. The dynamic behavior is described in terms of the time rate of change of the robot configuration in relation to the joint torques exerted by the actuators. This relationship can be expressed by a set of differential equations, called equations of motion, that govern the dynamic response of the robot linkage to input joint torques. In the next chapter, we will design a control system on the basis of these equations of motion.

Two methods can be used in order to obtain the equations of motion: the Newton-Euler formulation, and the Lagrangian formulation. The Newton-Euler formulation is derived by the direct interpretation of Newton's Second Law of Motion, which describes dynamic systems in terms of force and momentum. The equations incorporate all the forces and moments acting on the individual robot links, including the coupling forces and moments between the links. The equations obtained from the Newton-Euler method include the constraint forces acting between adjacent links. Thus, additional arithmetic operations are required to eliminate these terms and obtain explicit relations between the joint torques and the resultant motion in terms of joint displacements. In the Lagrangian formulation, on the other hand, the system's dynamic behavior is described in terms of work and energy using generalized coordinates. This approach is the extension of the indirect method discussed in the previous chapter to dynamics. Therefore, all the workless forces and constraint forces are automatically eliminated in this method. The resultant equations are generally compact and provide a closed-form expression in terms of joint torques and joint displacements. Furthermore, the derivation is simpler and more systematic than in the Newton-Euler method.

The robot’s equations of motion are basically a description of the relationship between the input joint torques and the output motion, i.e. the motion of the robot linkage. As in kinematics and in statics, we need to solve the inverse problem of finding the necessary input torques to obtain a desired output motion. This inverse dynamics problem is discussed in the last section of this chapter. Efficient algorithms have been developed that allow the dynamic computations to be carried out on-line in real time.

Newton-Euler Formulation of Equations of Motion

Basic Dynamic Equations

In this section we derive the equations of motion for an individual link based on the direct method, i.e. Newton-Euler Formulation. The motion of a rigid body can be decomposed into the translational motion with respect to an arbitrary point fixed to the rigid body, and the rotational motion of the rigid body about that point. The dynamic equations of a rigid body can also be represented by two equations: one describes the translational motion of the centroid (or center of mass), while the other describes the rotational motion about the centroid. The former is Newton's equation of motion for a mass particle, and the latter is called Euler's equation of motion.

Dynamic Analysis and Forces

TRANSFORMATION OF FORCES AND MOMENTS BETWEEN COORDINATE FRAMES

Displacements relative to the two frames are related to each other by the following relationship.

$$\left[{}^{B}D\right]=\left[{}^{B}J\right]\left[D\right]$$

The forces and moments with respect to frame B is can be calculated directly from the following equations:

$$\begin{aligned}
{}^{B}f_x &= \bar{n}\cdot\bar{f} & \qquad {}^{B}m_x &= \bar{n}\cdot\left[\left(\bar{f}\times p\right)+\bar{m}\right]\\
{}^{B}f_y &= \bar{o}\cdot\bar{f} & \qquad {}^{B}m_y &= \bar{o}\cdot\left[\left(\bar{f}\times p\right)+\bar{m}\right]\\
{}^{B}f_y &= \bar{o}\cdot\bar{f} & \qquad {}^{B}m_z &= \bar{a}\cdot\left[\left(\bar{f}\times \bar{p}\right)+\bar{m}\right]
\end{aligned}$$

LAGRANGIAN MECHANICS:

A SHORT OVERVIEW

Lagrangian mechanics is based on the differentiation energy terms only, with respect to the system’s variables and time.

Definition: L = Lagrangian, K = Kinetic Energy of the system, P = Potential Energy, F = the summation of all external forces for a linear motion, T = the summation of all torques in a rotational motion, x = System variables

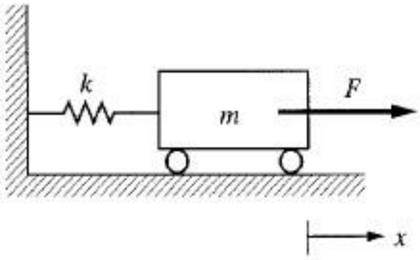
$$L = K - P$$

$$F_i = \frac{\partial}{\partial t}\left(\frac{\partial L}{\partial \dot{x}_i}\right) - \frac{\partial L}{\partial x_i}$$

$$T_i = \frac{\partial}{\partial t}\left(\frac{\partial L}{\partial \dot{\theta}_i}\right) - \frac{\partial L}{\partial \theta_i}$$

Derive the force-acceleration relationship for the one-degree of freedom system.

The appropriate form of the dynamic equations therefore consists of equations described in terms of all independent position variables and input forces, i.e., joint torques, that are explicitly involved in the dynamic equations. Dynamic equations in such an explicit input- output form are referred to as closed-form dynamic equations. As discussed in the previous chapter, joint displacements q are a complete and independent set of generalized coordinates that locate the whole robot mechanism, and joint torques are a set of independent inputs that are separated from constraint forces and moments. Hence, dynamic equations in terms of joint displacements q and joint torques are closed-form dynamic equations.



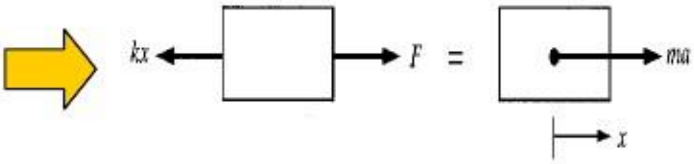


Fig. 3.11 Schematic of a simple cart-spring system

Fig. 3.12 Free-body diagram for the sprint-cart system

$$K=\frac{1}{2}mv^2=\frac{1}{2}m\dot{x}^2,P=\frac{1}{2}kx^2 \Rightarrow L=K-P=\frac{1}{2}m\dot{x}^2-\frac{1}{2}kx^2$$

.

Lagrangian mechanics	Newtonian mechanics
$\frac{\partial L}{\partial \dot{x}_i}=m\dot{x},\frac{d}{dt}(m\dot{x})=m\ddot{x},\frac{\partial L}{\partial x}=-kx$	$\sum\bar{F}=m\cdot\bar{a}$
$F=m\ddot{x}+kx$	$F-kx=ma\rightarrow F=ma+kx$

The complexity of the terms increases as the number of degrees of freedom and variables.

Derive the equations of motion for the two-degree of freedom system.

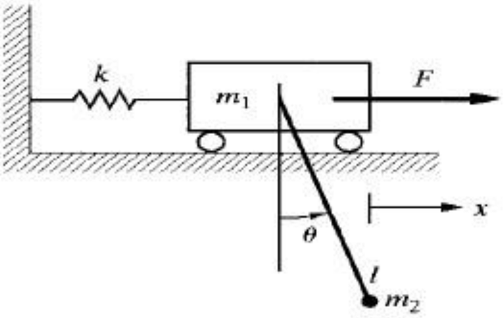


Fig. 3.13 Schematic of a cart-pendulum system.

In this system

- It requires two coordinates, x and □.
- It requires two equations of motion:
  1. The linear motion of the system.
  2. The rotation of the pendulum.

$$\begin{bmatrix} F \\ T \end{bmatrix} = \begin{bmatrix} m_1 + m_2 & m_2 l\cos\theta \\ m_2 l\cos\theta & m_2 l^2 \end{bmatrix} \begin{bmatrix} \ddot{x} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} 0 & m_2 l\sin\theta \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{x}^2 \\ \dot{\theta}^2 \end{bmatrix} + \begin{bmatrix} kx \\ m_2 g l\sin\theta \end{bmatrix}$$

Using the Lagrangian method, derive the equations of motion for the two-degree of freedom robot arm.

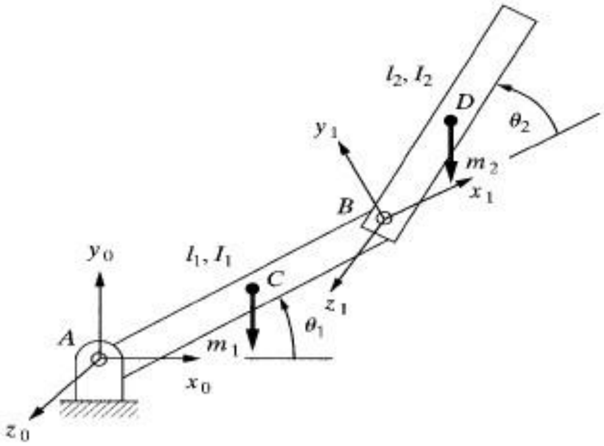


Fig. 3.14 A two-degree-of-freedom robot arm.

Follow the same steps as before

- Calculates the velocity of the center of mass of link 2 by differentiating its position:
- The kinetic energy of the total system is the sum of the kinetic energies of links 1 and 2.
- The potential energy of the system is the sum of the potential energies of the two links:

Thus, the same equations of motion have been obtained based on Lagrangian Formulation. Note that the Lagrangian Formulation is simpler and more systematic than the Newton-Euler Formulation. To formulate kinetic energy, velocities must be obtained, but accelerations are not needed. Remember that the acceleration computation was complex in the Newton-Euler Formulation, as discussed in the previous section. This acceleration computation is automatically dealt with in the computation of Lagrange’s equations of motion. The difference between the two methods is more significant when the degrees of freedom increase, since many workless constraint forces and moments are present and the acceleration computation becomes more complex in Newton-Euler Formulation.

EFFECTIVE MOMENTS OF INERTIA

To simplify the equation of motion, Equations can be rewritten in symbolic form.

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} D_{ii} & D_{ij} \\ D_{ji} & D_{jj} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_i \\ \ddot{\theta}_j \end{bmatrix} + \begin{bmatrix} D_{iii} & D_{ijj} \\ D_{jii} & D_{jjj} \end{bmatrix} \begin{bmatrix} \dot{\theta}_1^2 \\ \dot{\theta}_2^2 \end{bmatrix} = \begin{bmatrix} D_{iii} & D_{ijj} \\ D_{jii} & D_{jjj} \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \dot{\theta}_2 \\ \dot{\theta}_2 \dot{\theta}_1 \end{bmatrix} + \begin{bmatrix} D_i \\ D_j \end{bmatrix}$$

DYNAMIC EQUATIONS FOR MULTIPLE-DEGREE-OF-FREEDOM ROBOTS

Kinetic Energy Equations for a multiple-degree-of-freedom robot are very long and complicated, but can be found by calculating the kinetic and potential energies of the links and the joints, by defining the Lagrangian and by differentiating the Lagrangian equation with respect to the joint variables.

The kinetic energy of a rigid body with motion in three dimensions:

$$K = \frac{1}{2} m \overline{V}^2 + \frac{1}{2} \overline{\omega}\, \overline{h}_G$$

The kinetic energy of a rigid body in planar motion

$$K = \frac{1}{2} m \overline{V}^2 + \frac{1}{2} \overline{I} \omega^2$$

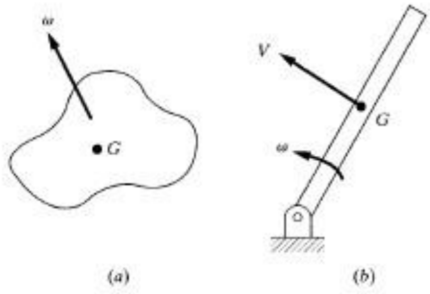


Fig. 3.15 A rigid body in three-dimensional motion and in plane motion.

DYNAMIC EQUATIONS FOR MULTIPLE-DEGREE-OF-FREEDOM ROBOTS

Kinetic Energy

The velocity of a point along a robot’s link can be defined by differentiating the position equation of the point.

$$p_i = {}^{R}T_i r_i = {}^{0}T_i r_i$$

- The velocity of a point along a robot’s link can be defined by differentiating the position equation of the point.

$$K_i = \frac{1}{2}\sum_{i=1}^{n}\sum_{p=1}^{i}\sum_{r=1}^{i} Trace\left(U_{ip}J_iU_{ir}^{T}\right)\dot{q}_p\dot{q}_r + \frac{1}{2}\sum_{i=1}^{n} I_{i(act)}\dot{q}_i^{2}$$

DYNAMIC EQUATIONS FOR MULTIPLE-DEGREE-OF-FREEDOM ROBOTS

Potential Energy

The potential energy of the system is the sum of the potential energies of each link.

$$P = \sum_{i=1}^{n} p_i = \sum_{i=1}^{n}\left[-m_i g^{T} \cdot \left({}^{0}T_i\bar{r}_i\right)\right]$$

The potential energy must be a scalar quantity and the values in the gravity matrix are dependent on the orientation of the reference frame.

DYNAMIC EQUATIONS FOR MULTIPLE-DEGREE-OF-FREEDOM ROBOTS

Lagrangian Formulation of Robot Dynamics

Lagrangian Dynamics

In the Newton-Euler formulation, the equations of motion are derived from Newton's Second Law, which relates force and momentum, as well as torque and angular momentum. The resulting equations involve constraint forces, which must be eliminated in order to obtain closed-form dynamic equations. In the Newton-Euler formulation, the equations are not expressed in terms of independent variables, and do not include input joint torques explicitly. Arithmetic operations are needed to derive the closed-form dynamic equations. This represents a complex procedure that requires physical intuition, as discussed in the previous section.

An alternative to the Newton-Euler formulation of manipulator dynamics is the Lagrangian formulation, which describes the behavior of a dynamic system in terms of work and energy stored in the system rather than of forces and moments of the individual members involved. The constraint forces involved in the system are automatically eliminated in the formulation of Lagrangian dynamic equations. The closed-form dynamic equations can be derived systematically in any coordinate system.

$$L = K - P = \frac{1}{2}\sum_{i=1}^{n}\sum_{p=1}^{i}\sum_{r=1}^{i} Trace\left(U_{ip}J_iU_{ir}^{T}\right)\dot{q}_p\dot{q}_r + \frac{1}{2}\sum_{i=1}^{n} I_{i(act)}\dot{q}_i^{2} - \sum_{i=1}^{n}\left[-m_i g^{T} \cdot \left({}^{0}T_i\bar{r}_i\right)\right]$$

Inertia Matrix

In this section we will extend Lagrange’s equations of motion obtained for the two degree of freedom. planar robot to the ones for a general n degree of freedom. robot. Central to

Lagrangian formulation is the derivation of the total kinetic energy stored in all of the rigid bodies involved in a robotic system. Examining kinetic energy will provide useful physical insights of robot dynamic. Such physical insights based on Lagrangian formulation will supplement the ones we have obtained based on Newton-Euler formulation.

DYNAMIC EQUATIONS FOR MULTIPLE-DEGREE-OF-FREEDOM ROBOTS

Robot's Equations of Motion

The Lagrangian is differentiated to form the dynamic equations of motion. The final equations of motion for a general multi-axis robot is below.

$$T_i = \sum_{j=1}^{n} D_{ij}\ddot{q}_j + I_{i(act)}\ddot{q}_i + \sum_{j=1}^{n}\sum_{k=1}^{n} D_{ijk}\dot{q}_j\dot{q}_k + D_i$$

where,

$$D_{ij} = \sum_{p=\max(i,j)}^{n} Trace(U_{pj} J_p U_{pi}^T)$$

$$D_{ijk} = \sum_{p=\max(i,j,k)}^{n} Trace(U_{pjk} J_p U_{pi}^T)$$

$$D_i = \sum_{p=i}^{n} - m_p g^T U_{pi} \bar{r}_p$$

Using the aforementioned equations, derive the equations of motion for the two-degree of freedom robot arm. The two links are assumed to be of equal length.

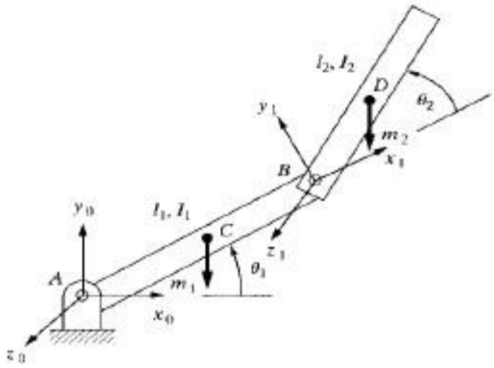


Fig: 3.16 The two-degree-of-freedom robot arm of Example

Follow the same steps as before

- Write the A matrices for the two links;
- Develop the hand for the robot.

The final equations of motion without the actuator inertia terms are the same as below.

$$T_1=\left(\frac{1}{3}m_1l^2+\frac{4}{3}m_2l^2+m_2l^2C_2\right)\ddot{\theta}_1+\left(\frac{1}{3}m_2l^2+\frac{1}{2}m_2l^2C_2\right)\ddot{\theta}_2$$

$$+\left(\frac{1}{2}m_2l^2S_2\right)\dot{\theta}_2^2+\left(m_2l^2S_2\right)\dot{\theta}_1\dot{\theta}_2+\frac{1}{2}m_1glC_1+\frac{1}{2}m_2glC_{12}+m_2glC_1+I_{1(act)}\ddot{\theta}_1$$

$$T_2=\left(\frac{1}{3}m_2l^2+\frac{1}{2}m_2l^2C_2\right)\ddot{\theta}_1+\left(\frac{1}{3}m_2l^2\right)\ddot{\theta}_2+\left(\frac{1}{2}m_2l^2S_2\right)+\frac{1}{2}m_2glC_{12}+I_{2(act)}\ddot{\theta}_1$$

These centrifugal and Coriolis terms are present only when the multi-body inertia matrix is configuration dependent. In other words, the centrifugal and Coriolis torques are interpreted as nonlinear effects due to the configuration-dependent nature of the multi-body inertia matrix in Lagrangian formulation.

STATIC FORCE ANALYSIS OF ROBOTS

- Robot Control means Position Control and Force Control.
  - Position Control: The robot follows a prescribed path without any reactive force.
  - Force Control : The robot encounters with unknown surfaces and manages to handle the task by adjusting the uniform depth while getting the reactive force.
- Tapping a Hole - move the joints and rotate them at particular rates to create the desired forces and moments at the hand frame.
- Peg Insertion – avoid the jamming while guiding the peg into the hole and inserting it to the desired depth.

STATIC FORCE ANALYSIS OF ROBOTS

To relate the joint forces and torques to forces and moments generated at the hand frame of the robot.

□ H F □ □ □H H fx Hfy Hfz Hmx Hmy Hmz T□
□ □ □ □

□ f is the force and m is the moment along the axes of the hand frame.

$$\delta W=\left[{}^{H}F\right]^{T}\left[{}^{H}D\right]=\left[T\right]^{T}\left[D_{\theta}\right]$$

- The total virtual work at the joints must be the same as the total work at the hand frame.

□ dx □
□ dy □
□ □
□W □ □ f x□ fy fz mx my …… □ mz □ z
□ dz □
mz □ □ □ □ f x dx □
□ □x
□ □
□ □y □
□ □
□ □z □

$$\left[T\right]=\left[{}^{H}J\right]^{T}\left[{}^{H}F\right]$$

TRANSFORMATION OF FORCES AND MOMENTS BETWEEN COORDINATE FRAMES

An equivalent force and moment with respect to the other coordinate frame by the principle of virtual work.

$$\begin{array}{lcl} [F]^T = [f_x \ f_y \ f_z \ m_x \ m_y \ m_z] & \Rightarrow & [{}^B F]^T = [{}^B f_x \ {}^B f_y \ {}^B f_z \ {}^B m_x \ {}^B m_y \ {}^B m_z] \\ [D]^T = [d_x \ d_y \ d_z \ \delta_x \ \delta_y \ \delta_z] & & [{}^B D]^T = [{}^B d_x \ {}^B d_y \ {}^B d_z \ {}^B \delta_x \ {}^B \delta_y \ {}^B \delta_z] \end{array}$$

The total virtual work performed on the object in either frame must be the same.

$$\delta W = [F]^T [D] = [{}^B T]^T [{}^B D]$$

TRANSFORMATION OF FORCES AND MOMENTS BETWEEN COORDINATE FRAMES

Displacements relative to the two frames are related to each other by the following relationship.

$$[{}^B D] = [{}^B J][D]$$

The forces and moments with respect to frame B is can be calculated directly from the following equations:

$$\begin{array}{ll} {}^B f_x = \bar{n} \cdot \bar{f} & {}^B m_x = \bar{n} \cdot [(\bar{f} \times \bar{p}) + \bar{m}] \\ {}^B f_y = \bar{o} \cdot \bar{f} & {}^B m_y = \bar{o} \cdot [(\bar{f} \times \bar{p}) + \bar{m}] \\ {}^B f_y = \bar{o} \cdot \bar{f} & {}^B m_z = \bar{a} \cdot [(\bar{f} \times \bar{p}) + \bar{m}] \end{array}$$

UNIT IV KINEMATICS AND PATH PLANNING

Forward Kinematics – Denavit Hartenberg Representation - Inverse Kinematics – Geometric approach.

ROBOT KINEMATICS

Robot kinematics applies geometry to the study of the movement of multi-degree of Freedom kinematic chains that form the structure of robotic systems. The emphasis on geometry means that the links of the robot are modeled as rigid bodies and its joints are assumed to provide pure rotation or translation.

Robot kinematics studies the relationship between the dimensions and connectivity of kinematic chains and the position, velocity and acceleration of each of the links in the robotic system, in order to plan and control movement and to compute actuator forces and torques. The relationship between mass and inertia properties, motion, and the associated forces and torques is studied as part of robot dynamics. The robot kinematics concepts related to both open and closed kinematics chains. Forward kinematics is distinguished from inverse kinematics.

SERIAL MANIPULATOR:

Serial manipulators are the most common industrial robots. They are designed as a series of links connected by motor-actuated joints that extend from a base to an end-effector. Often they have an anthropomorphic arm structure described as having a "shoulder", an "elbow", and a "wrist". Serial robots usually have six joints, because it requires at least six degrees of freedom to place a manipulated object in an arbitrary position and orientation in the workspace of the robot. A popular application for serial robots in today's industry is the pick-and-place assembly robot, called a SCARA robot, which has four degrees of freedom.

Fig 4.1 SCARA robot

STRUCTURE:

In its most general form, a serial robot consists of a number of rigid links connected with joints.
Simplicity considerations in manufacturing and control have led to robots with only revolute or prismatic
joints and orthogonal, parallel and/or intersecting joint axes the inverse kinematics of serial manipulators with six revolute joints, and with three consecutive joints intersecting, can be solved in closed-form, i.e. analytically this result had a tremendous influence on the design of industrial robots. robot and the floor space it occupies. The main disadvantages of these robots are:

- The low stiffness inherent to an open kinematic structure,
- Errors are accumulated and amplified from link to link,
- The fact that they have to carry and move the large weight of most of the actuators, and
- The relatively low effective load that they can manipulate.

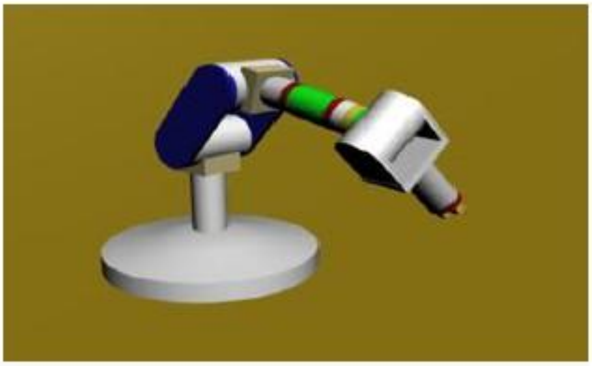


Fig.4.2 Serial manipulator with six DOF in a kinematic chain

PARALLEL MANIPULATOR:

A parallel manipulator is a mechanical system that uses several computer-controlled serial chains to support a single platform, or end-effector. Perhaps, the best known parallel manipulator is formed from six linear actuators that support a movable base for devices such as flight simulators. This device is called a Stewart platform or the Gough-Stewart platform in recognition of the engineers whofirst designed and used them.

actuators are paired together on both the basis and the platform), these systems are articulated robots that use similar mechanisms for the movement of either the robot on its base, or one or more manipulator arms. Their 'parallel' distinction, as opposed to a serial manipulator, is that the end effector (or 'hand') of this linkage (or 'arm') is connected to its base by a number of (usually three or six) separate and independent linkages working in parallel. 'Parallel' is used here in the computer science sense, rather than the geometrical; these linkages act together, but it is not implied that they are aligned as parallel lines; here parallel means that the position of the end point of each linkage is independent of the position of the other linkages.

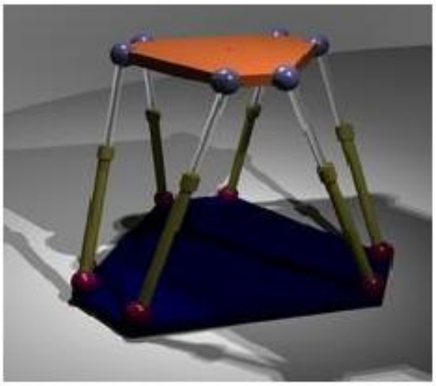


Fig: 4.3 Abstract render of a Hexapod platform (Stewart Platform)

Forward Kinematics:

It is used to determine where the robot’s hand, if all joint variables are known)

Inverse Kinematics:

It is used to calculate what each joint variable, if we desire that the hand be located at a particular point.

~~ROBOTS AS MECHA~~NISMS

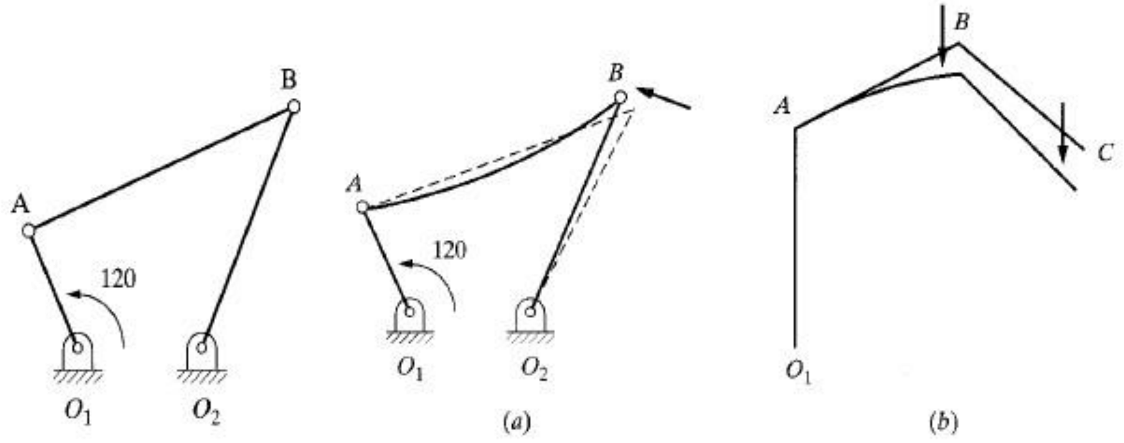
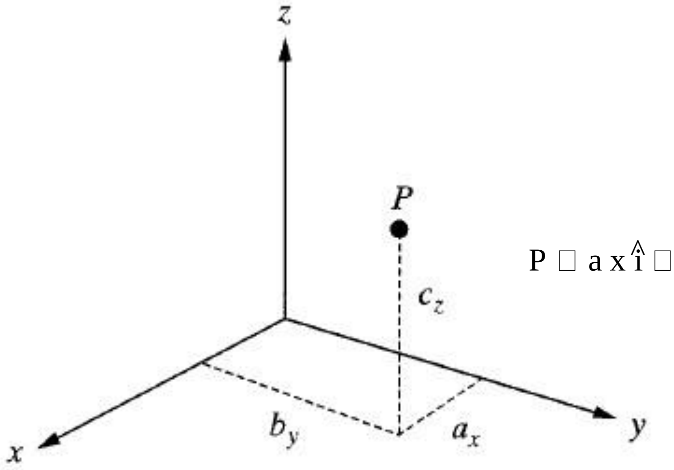


Fig 4.4 a one-degree-of-freedom closed-loop (a) Closed-loop versus (b) open-loop mechanism Four-bar mechanism

MATRIX REPRESENTATION

Representation of a Point in Space

A point P in space: 3 coordinate relative to a reference frame

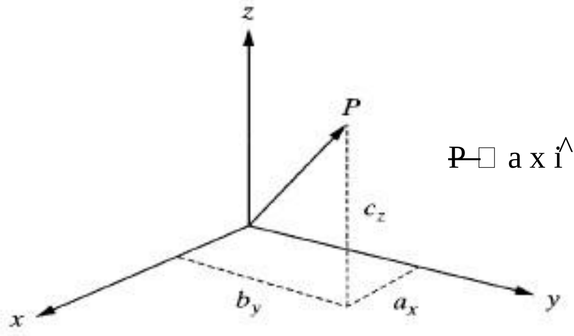


$P = a_x\hat{i} + b_y\hat{j} + c_z\hat{k}$

Fig. 4.5 Representation of a point in space

Representation of a Vector in Space

A Vector P in space: 3 coordinates of its tail and of its head



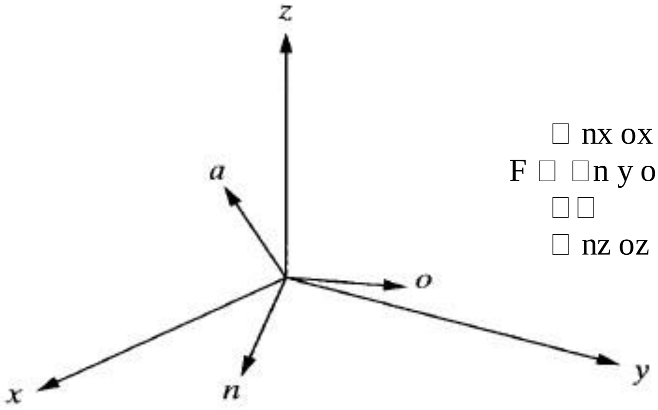
$\overline{P} = a_x\hat{i} + b_y\hat{j} + c_z\hat{k}$

Fig. 4.6 Representation of a vector in space

$$\overline{P} = \begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix}$$

Representation of a Frame at the Origin of a Fixed-Reference Frame

Each Unit Vector is mutually perpendicular: normal, orientation, approach vector



□ nx ox a x □
F □ □n y o y a y □
□□
□ nz oz a z □□□

Fig. 4.7 Representation of a frame at the origin of the reference frame

Representation of a Frame in a Fixed Reference Frame

Each Unit Vector is mutually perpendicular: normal, orientation, approach vector

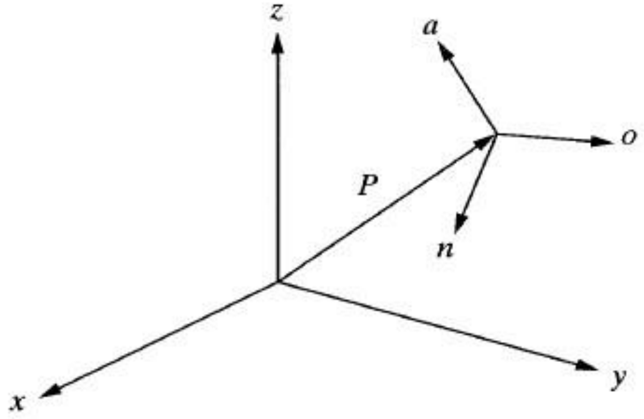


Fig. 4.8 Representation of a frame in a frame

□ nx ox ax Px □
□n Py □
F □□ y oy ay □
□ nz oz az Pz □
□ 0 0 □
□0 1□

Representation of a Rigid Body

An object can be represented in space by attaching a frame to it and representing the frame in space.

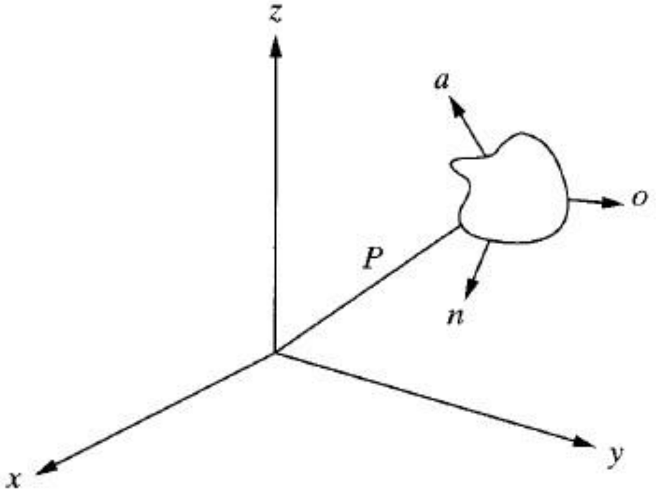


Fig. 4.9 Representation of an object in space

$$F_{object} = \begin{bmatrix} n_x & o_x & a_x & P_x \\ n_y & o_y & a_y & P_y \\ n_z & o_z & a_z & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

HOMOGENEOUS TRANSFORMATION MATRICES

Transformation matrices must be in square form. It is much easier to calculate the inverse of square matrices. To multiply two matrices, their dimensions must match.

Representation of a Pure Translation

- A transformation is defined as making a movement in space.
- A pure translation.
- A pure rotation about an axis.
- A combination of translation or rotations

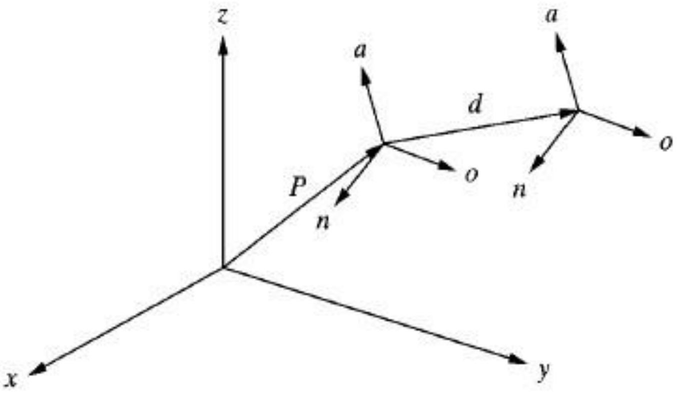
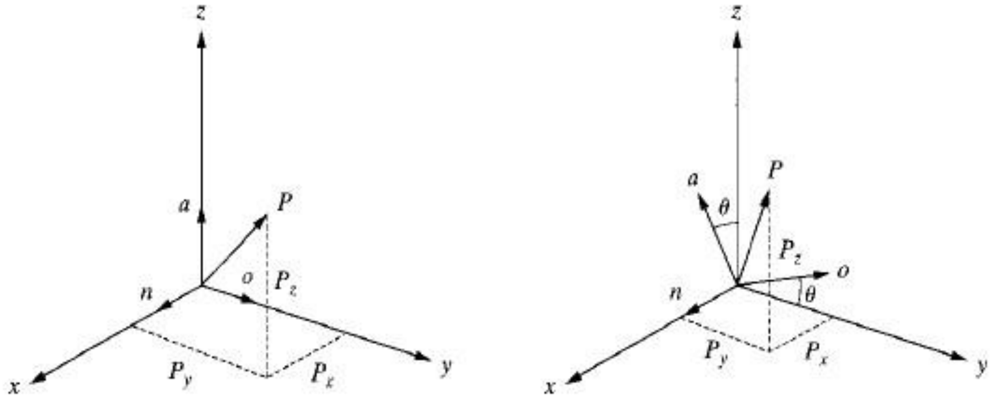


Fig. 4.10 Representation of a pure translation in space

$$T = \begin{bmatrix} 1 & 0 & 0 & dx \\ 0 & 1 & 0 & dy \\ 0 & 0 & 1 & dz \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Representation of a Pure Rotation about an Axis

Assumption: The frame is at the origin of the reference frame and parallel to it.



Before rotation

(a)

After rotation

(b)

Fig. 4.11 Coordinates of a point in a rotating frame before and after rotation

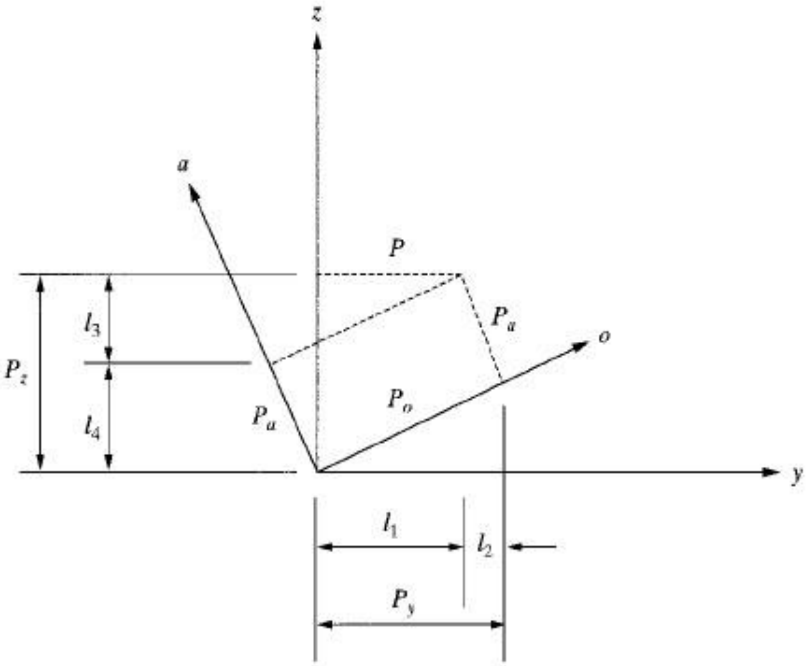
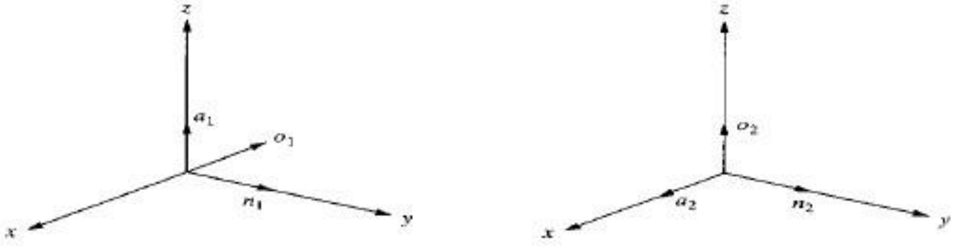


Fig. 4.12 Coordinates of a point relative to the reference

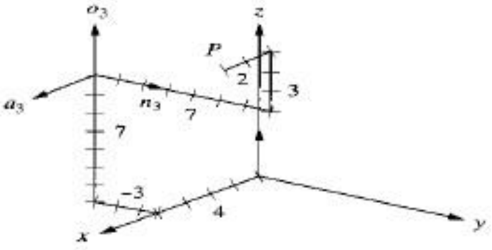
Representation of Combined Transformations

A number of successive translations and rotations



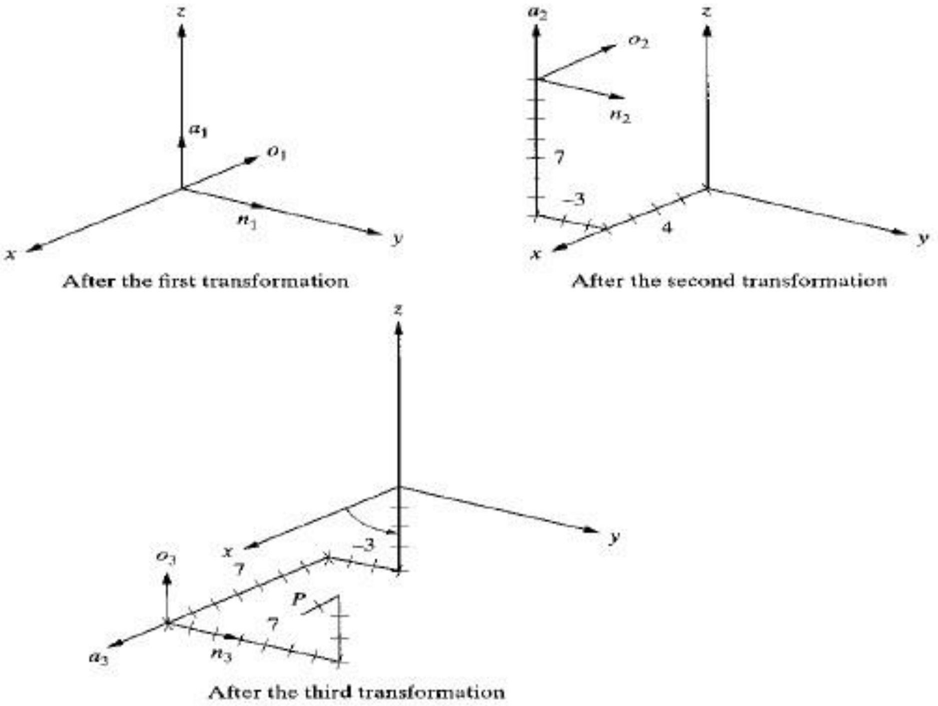
After the first transformation

After the second transformation



After the third transformation

Fig. 4.13 Effects of three successive transformations



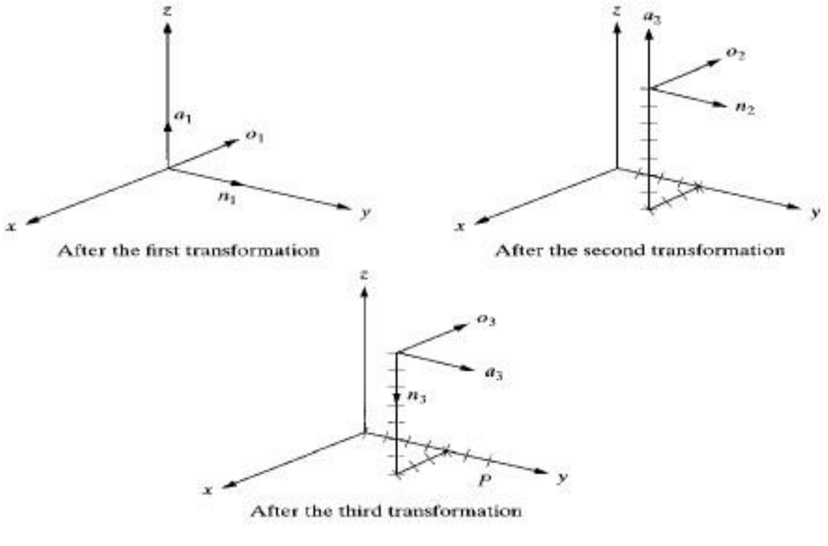
After the first transformation

After the second transformation

After the third transformation

Fig 4.14 changing the order of transformations will change the final result

Transformations Relative to the Rotating Frame



After the first transformation

After the second transformation

After the third transformation

Fig. 4.15 Transformations relative to the current frames

~~KINEMATICS EQUAT~~IONS:

A fundamental tool in robot kinematics is the kinematics equations of the kinematic chains that form the robot. These non-linear equations are used to map the joint parameters to the configuration of the robot system. Kinematics equations are also used in biomechanics of the skeleton and computer animation of articulated characters.

Forward kinematics uses the kinematic equations of a robot to compute the position of the end-effector from specified values for the joint parameters. The reverse process that computes the joint parameters that achieve a specified position of the end-effector is known as inverse kinematics. The dimensions of the robot and its kinematics equations define the volume of space reachable by the robot, known as its workspace.

There are two broad classes of robots and associated kinematics equations serial manipulators and parallel manipulators. Other types of systems with specialized kinematics equations are air, land, and submersible mobile robots, hyper-redundant, or snake, robots and humanoid robots.

~~DENAVIT-HARTENBERG~~ PARAMETERS:

The Denavit–Hartenberg parameters (also called DH parameters) are the four parameters associated with a particular convention for attaching reference frames to the links of a spatial kinematic chain, or robot manipulator.

~~Denavit-Hartenberg conventio~~n:

A commonly used convention for selecting frames of reference in robotics applications is the Denavit and Hartenberg (D–H) convention. In this convention, coordinate frames are attached to the joints between two links such that one transformation is associated with the joint, [Z], and the second is associated with the link [X]. The coordinate transformations along a serial robot consisting of n links form the kinematics equations of the robot,

$$[T] = [Z_1][X_1][Z_2][X_2]\dots[X_{n-1}][Z_n],$$

Where, [T] is the transformation locating the end-link.

In order to determine the coordinate transformations [Z] and [X], the joints connecting the links are modeled as either hinged or sliding joints, each of which have a unique line S in space that forms the joint axis and define the relative movement of the two links. A typical serial robot is characterized by a sequence of six lines Si, i=1,...,6, one for each joint in the robot. For each sequence of lines Si and Si+1, there is a common normal line Ai,i+1. The system of six joint axes Si and five common normal lines Ai,i+1 form the kinematic skeleton of the typical six degree of freedom serial robot. Denavit and Hartenberg introduced the convention that Z coordinate axes are assigned to the joint axes Si and X coordinate axes are assigned to the common normal’s Ai,i+1.

This convention allows the definition of the movement of links around a common joint axis Si by the screw displacement,

$$[Z_i] = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & 0 \\ \sin\theta_i & \cos\theta_i & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

Where θi is the rotation around and di is the slide along the Z axis---either of the parameters can be constants depending on the structure of the robot. Under this convention the dimensions of each link in the serial chain are defined by the screw displacement around the common normal Ai,i+1 from the joint Si to Si+1, which is given by

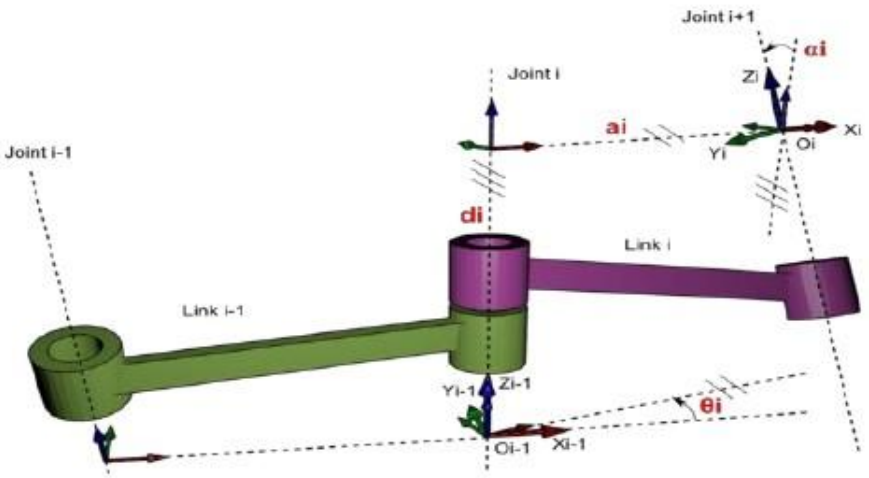
$$[X_i] = \begin{bmatrix} 1 & 0 & 0 & r_{i,i+1} \\ 0 & \cos\alpha_{i,i+1} & -\sin\alpha_{i,i+1} & 0 \\ 0 & \sin\alpha_{i,i+1} & \cos\alpha_{i,i+1} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

Where αi,i+1 and ri,i+1 define the physical dimensions of the link in terms of the angle measured around and distance measured along the X axis.

In summary, the reference frames are laid out as follows:

- ☐ the z-axis is in the direction of the joint axis
- ☐ the x-axis is parallel to the common normal: $x_n = z_{n-1} \times z_n$ If there is no unique common normal (parallel axes), then d (below) is a free parameter. The direction of x_n is from z_{n-1} to z_n, as shown in the video below.
- ☐ the y-axis follows from the x- and z-axis by choosing it to be a right-handed coordinate system.

Four parameters



The four parameters of classic DH convention are $\theta_i, d_i, a_i, \alpha_i$. With those four parameters, we can translate the coordinates from $O_{i-1}X_{i-1}Y_{i-1}Z_{i-1}$ to $O_iX_iY_iZ_i$.

The transformation the following four parameters known as D–H parameters:

d: offset along previous z to the common normal

θ: angle about previous z, from old x to new x

r: length of the common normal. Assuming a revolute joint, this is the radius about previous z.

α: angle about common normal, from old z axis to new z axis

There is some choice in frame layout as to whether the previous x axis or the next x points along the common normal. The latter system allows branching chains more efficiently, as multiple frames can all
point away from their common ancestor, but in the alternative layout the ancestor can only point toward one successor. Thus the commonly used notation places each down-chain x axis collinear with the common normal, yielding the transformation calculations shown below.

We can note constraints on the relationships between the axes:

- x_n-axis is perpendicular to both the z_{n-1} and z_n axes
- x_n-axis intersects both z_{n-1} and z_n axes
- Origin of joint n is at the intersection of x_n and z_n
- y_n completes a right-handed reference frame based on x_n and z_n

Denavit-Hartenberg Matrix:

It is common to separate a screw displacement into the product of a pure translation along a line and a pure rotation about the line,[5][6] so that

$$[Z_i] = \mathrm{Trans}_{Z_i}(d_i)\,\mathrm{Rot}_{Z_i}(\theta_i),$$

And,

$$[X_i] = \mathrm{Trans}_{X_i}(r_{i,i+1})\,\mathrm{Rot}_{X_i}(\alpha_{i,i+1}).$$

Using this notation, each link can be described by a coordinate transformation from the previous coordinate system to the next coordinate system.

$${}^{n-1}T_n = \mathrm{Trans}_{z_{n-1}}(d_n) \cdot \mathrm{Rot}_{z_{n-1}}(\theta_n) \cdot \mathrm{Trans}_{x_n}(r_n) \cdot \mathrm{Rot}_{x_n}(\alpha_n)$$

Note that this is the product of two screw displacements, the matrices associated with these operations
are:

$$\operatorname{Trans}_{z_{n-1}}(d_n) = \left[\begin{array}{ccc|c} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_n \\ \hline 0 & 0 & 0 & 1 \end{array}\right]$$

$$\operatorname{Rot}_{z_{n-1}}(\theta_n) = \left[\begin{array}{ccc|c} \cos\theta_n & -\sin\theta_n & 0 & 0 \\ \sin\theta_n & \cos\theta_n & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \hline 0 & 0 & 0 & 1 \end{array}\right]$$

$$\operatorname{Trans}_{x_n}(r_n) = \left[\begin{array}{ccc|c} 1 & 0 & 0 & r_n \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \hline 0 & 0 & 0 & 1 \end{array}\right]$$

$$\operatorname{Rot}_{x_n}(\alpha_n) = \left[\begin{array}{ccc|c} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha_n & -\sin\alpha_n & 0 \\ 0 & \sin\alpha_n & \cos\alpha_n & 0 \\ \hline 0 & 0 & 0 & 1 \end{array}\right]$$

This gives:

$${}^{n-1}T_n = \left[\begin{array}{ccc|c} \cos\theta_n & -\sin\theta_n\cos\alpha_n & \sin\theta_n\sin\alpha_n & r_n\cos\theta_n \\ \sin\theta_n & \cos\theta_n\cos\alpha_n & -\cos\theta_n\sin\alpha_n & r_n\sin\theta_n \\ 0 & \sin\alpha_n & \cos\alpha_n & d_n \\ \hline 0 & 0 & 0 & 1 \end{array}\right] = \left[\begin{array}{ccc|c} & R & & T \\ \hline 0 & 0 & 0 & 1 \end{array}\right]$$

Where R is the 3×3 sub matrix describing rotation and T is the 3×1 sub matrix describing translation.

DENAVIT-HARTENBERG REPRESENTATION OF FORWARD KINEMATIC EQUATIONS OF ROBOT:

Denavit-Hartenberg Representation:

1. Simple way of modeling robot links and joints for any robot configuration, regardless of its sequence or complexity.
2. Transformations in any coordinates are possible.
3. Any possible combinations of joints and links and all-revolute articulated robots can be represented

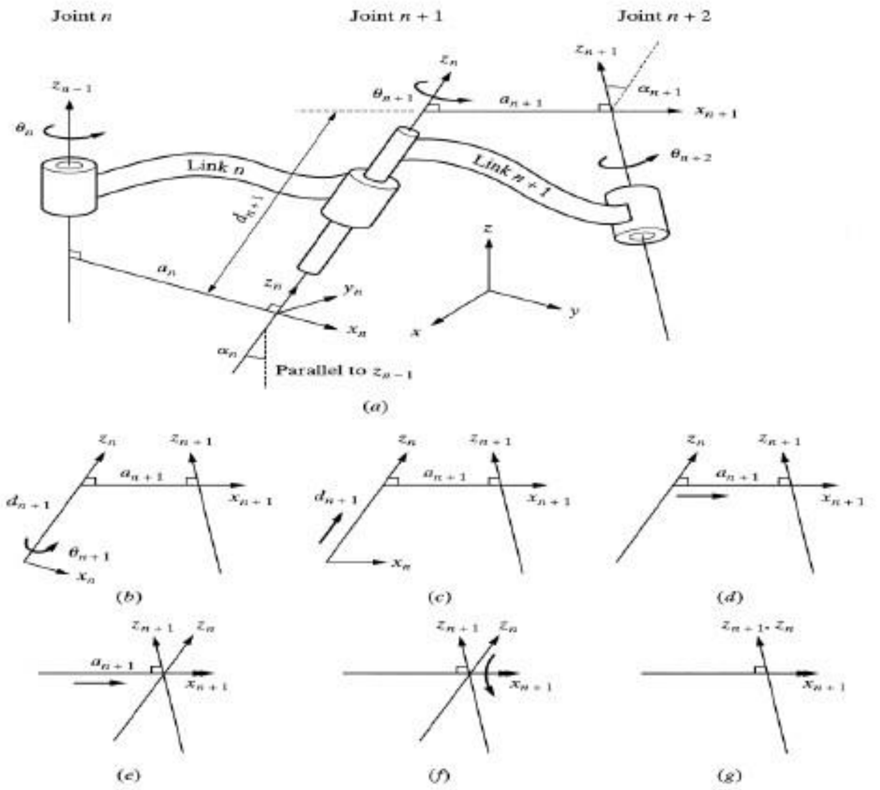


Fig 4.16 a D-H representation of a general-purpose joint-link combination

DENAVIT-HARTENBERG REPRESENTATION PROCEDURES:

Start point:

- Assign joint number n to the first shown joint.
- Assign a local reference frame for each and every joint before or after these joints.
- Y-axis does not used in D-H representation.

Procedures for assigning a local reference frame to each joint:

All joints are represented by a z-axis. (Right-hand rule for rotational joint, linear movement for prismatic joint)

- The common normal is one line mutually perpendicular to any two skew lines.
- Parallel z-axes joints make a infinite number of common normal.
- Intersecting z-axes of two successive joints make no common normal between them(Length is 0.).

Symbol Terminologies:

□ □ : A rotation about the z-axis.

□ d : The distance on the z-axis.

□ a : The length of each common normal (Joint offset).

□ □ : The angle between two successive z-axes (Joint twist)

Only □ and d are joint variables

The necessary motions to transform from one reference frame to the next.

I) Rotate about the zn-axis an able of □n+1.
(Coplanar)
II) Translate along zn-axis a distance of dn+1 to make xn and xn+1
colinear.
III) Translate along the xn-axis a distance of an+1 to bring the origins of xn+1
together.
IV) Rotate zn-axis about xn+1 axis an angle of □n+1 to align zn-axis with
zn+1-axis.

Determine the value of each joint to place the arm at a desired position and orientation.

R TH □ A1 A2 A3 A4
A5 A6

□C1 (C234C5C6 □ S
234S6)
□ □ S S C
□ 1 5 6
S (C C C □ S S)
□ □ 1 234 5 6 234 6
□ □ C S C
□ 1 5 6
□ S 234C5C6 □
C234S6
□0□

□nx ox a x px □
□n o a py □
□ □ y y y □
□nz oz a z pz □
□ □
□0 0 0 1□

C1 (□C234C5C6 □ S
234C6)
□

C23a3 □ C2 a2)□
□ S1S5C6

□
S1 (□C234C5C6 □ S 234C6)□

C23a3 □ C2 a2) □
□ C1S5C6

□
□

C1 (C234S5) □ S1C5 C1 (C234a4 □

S1 (C234S5) □ C1C5 S1 (C234a4 □

□ S 234C5C6 □ C234C6S 234S5

S 234a4 □ S
23a3 □ S 2 a2 □

□001□

~~THE INVERSE KINEMATIC SOLUTION~~ OF ROBOT:

 nx ox ax px
n oy ay py
1   A11[RHS] A2 A3 A4
A1   y oz az A5 A6
 nz 0 0 pz

0 1

C1 S1 0 0 n x ox ax px
0 0 1 0 n y oy ay py
  C1   A2 A3 A4 A5
 S1 0 0 n z oz az A6
  0   0 0 pz
0 0 1 0
1

 py
1 tan 1
 px

(C3a3 a2)(pz S 234a4) S3a3 (pxC1 p y S1 C234a4)
 2 tan 1
(C3a3 a2)(p xC1 p y S1 C234a4) S3a3 (Pz S 234a4)

 S3
 3 tan 1

 C3

 4   234   2 3

C234(C1ax S1a y) S 234az
5 tan 1
S1ax C1a y

 S 234 (C1 n x S1 n y) S 234n z
 6 tan 1
 S 234 (C1o x S1o y) C 234o z

~~INVERSE KINEMATIC PROGRAM~~ OF ROBOTS:

A robot has a predictable path on a straight line, or an unpredictable path on a straight line.

- A predictable path is necessary to recalculate joint variables. (Between 50 to 200 times a second)
- To make the robot follow a straight line, it is necessary to break the line into many small sections.
- All unnecessary computations should be eliminated.

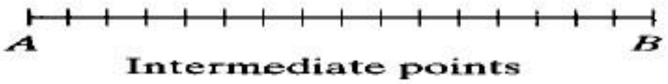


Fig. 4.17 Small sections of movement for straight-line motions

DEGENERACY AND DEXTERITY:

Degeneracy: The robot looses a degree of freedom and thus cannot perform as desired.

- When the robot's joints reach their physical limits, and as a result, cannot move any further.
- In the middle point of its workspace if the z-axes of two similar joints becomes co-linear.

Dexterity: The volume of points where one can position the robot as desired, but not orientate it.

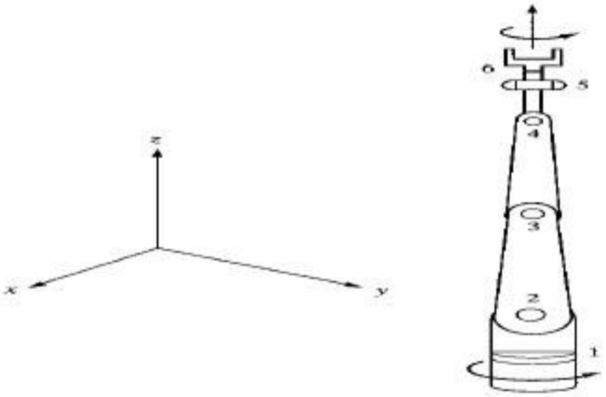


Fig. 4.18 An example of a robot in a degenerate position

THE FUNDAMENTAL PROBLEM WITH D-H REPRESENTATION:

Defect of D-H presentation: D-H cannot represent any motion about the y-axis, because all motions are about the x- and z-axis.

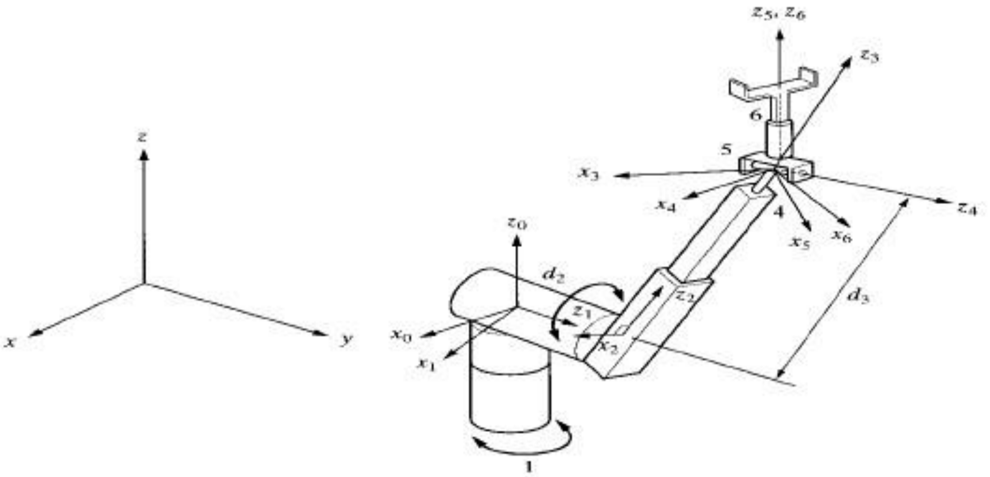


Fig. 4.19 the frames of the Stanford Arm.

#	□	d	a	□
1	□1	0	0	-90
2	□2	d1	0	90
3	0	d1	0	0
4	□4	0	0	-90
5	□5	0	0	90
6	□6	0	0	0

Table 4.1 Parameters Table for the Stanford Arm

INVERSE OF TRANSFORMATION MATIRICES

Inverse of a matrix calculation steps:

- □ Calculate the determinant of the matrix.
- □ Transpose the matrix.
- □ Replace each element of the transposed matrix by its own minor (ad-joint matrix).
- □ Divide the converted matrix by the determinant.

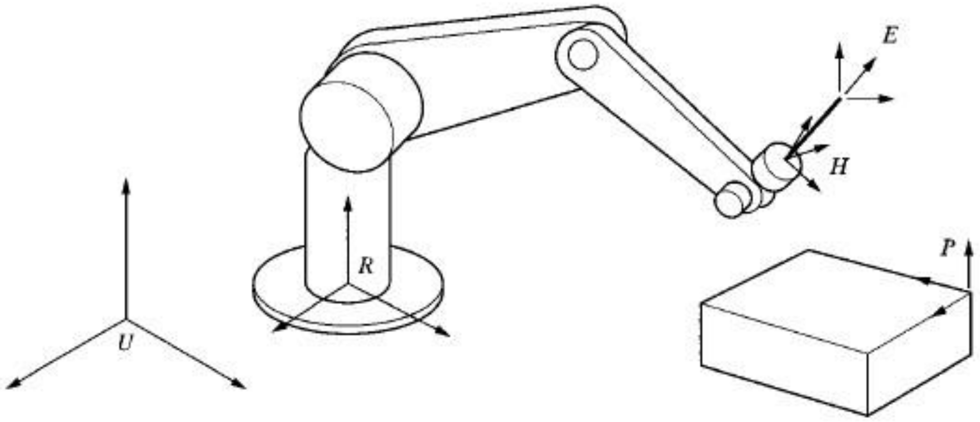


Fig 4.20 The Universe, robot, hand, part, and end effecter frames.

FORWARD AND INVERSE KINEMATICS OF ROBOTS:

Forward Kinematics Analysis:

- Calculating the position and orientation of the hand of the robot.
- If all robot joint variables are known, one can calculate where the robot is at any instant.

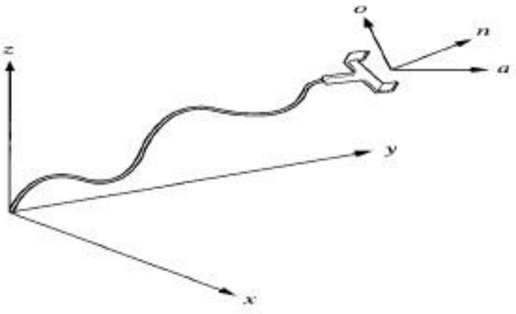


Fig. 4.21 The hand frame of the robot relative to the reference frame

Forward Kinematics and Inverse Kinematics equation for position analysis:

a) Cartesian (gantry, rectangular) coordinates.

b) Cylindrical coordinates.

c) Spherical coordinates.

d) Articulated (anthropomorphic, or all-revolute) coordinates

Forward and Inverse Kinematics Equations for Position

(a) Cartesian (Gantry, Rectangular) Coordinates: IBM 7565 robot

- All actuator is linear
- A gantry robot is a Cartesian robot

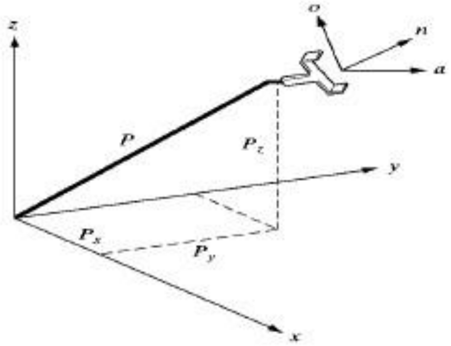


Fig. 4.22 Cartesian Coordinates

$$ {}^{R}T_{P} = T_{cart} = \begin{bmatrix} 1 & 0 & 0 & P_x \\ 0 & 1 & 0 & P_y \\ 0 & 0 & 1 & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

(b) Cylindrical Coordinates: 2 Linear translations and 1 rotation

□ translation of r along the x-axis

□ rotation of □ about the z-axis

□ translation of l along the z-axis

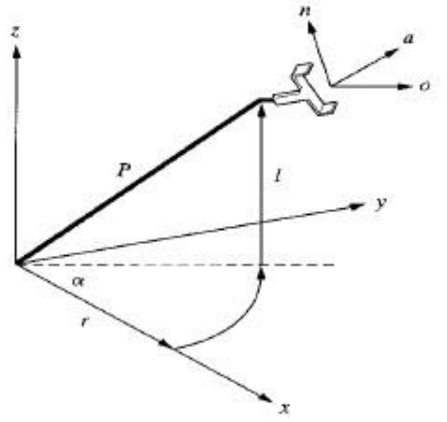


Fig. 4.23 Cylindrical Coordinates

R TP □ Tcyl (r , □ , l) □ Trans(0,0,l)Rot(z, □)Trans(r,0,0)

□C□ □ S□ 0 rC□ □
□ S□ C□ 0 rS□ □
R □
TP □ Tcyl □ □ 0 1l □
□ 0 0 □
□ 01 □
□ 0

(c) Spherical Coordinates: 1 linear translation and 2 rotations

□ translation of r along the z-axis

□ rotation of □ about the y-axis

□ rotation of □ along the z-axis

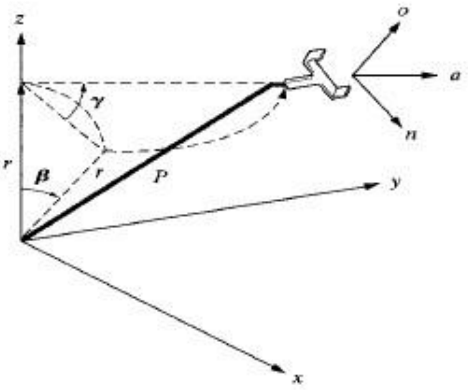


Fig. 4.24 Spherical Coordinates

R TP □ Tsph (r , □ , l) □ Rot(z, □)Rot(y, □)Trans(0,0, □)

□C□ □ C□ □ S□ S□ □ C□ rS□ □ C□ □
□ C□ □ S□ C□ S□ □ S□ rS□ □ S□ □
R □
TP □ Tsph □ □ 0 C□ rC□ □
□ □ S□ 0 0 □
□ 1 □
□ 0

(d) Articulated Coordinates: 3 rotations -> Denavit-Hartenberg representation

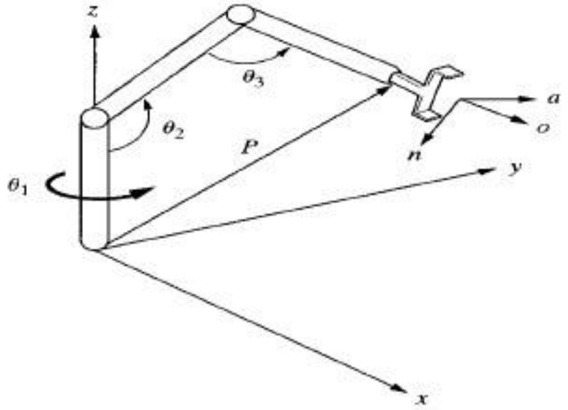


Fig. 4.25 Articulated Coordinates.

Forward and Inverse Kinematics Equations for Orientation

- Roll, Pitch, Yaw (RPY) angles
- Euler angles
- Articulated joints

(a) Roll, Pitch, Yaw (RPY) Angles

- Roll: Rotation of about - axis (z-axis of the moving frame)
- Pitch: Rotation of about - axis (y-axis of the moving frame)
- Yaw: Rotation of about - axis (x-axis of the moving frame)

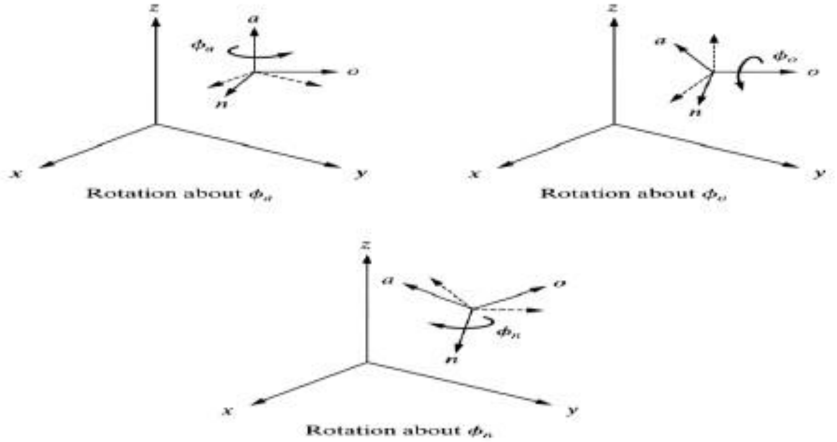


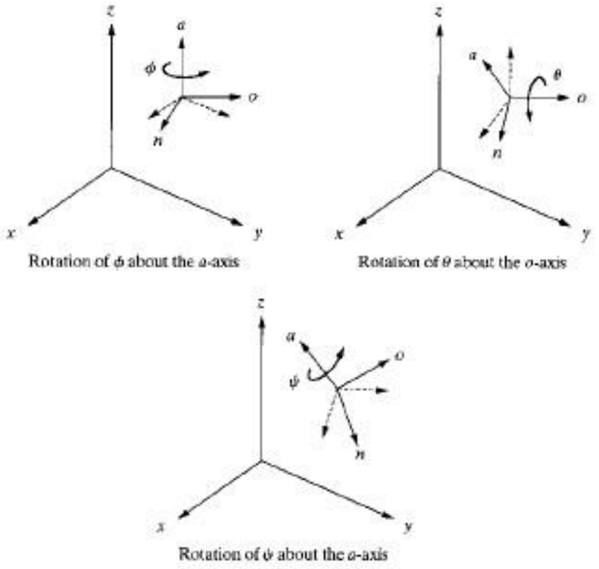
Fig. 4.26 RPY rotations about the current axes

(b) Euler Angles

□ Rotation of about - axis (z-axis of the moving frame) followed by

□ Rotation of about -axis (y-axis of the moving frame) followed by

□ Rotation of about -axis (z-axis of the moving frame)



Rotation of ϕ about the a-axis

Rotation of θ about the o-axis

Rotation of ψ about the a-axis

Fig. 4.27 Euler rotations about the current axes

Forward and Inverse Kinematics Equations for Orientation:

Assumption : Robot is made of a Cartesian and an RPY set of joints.

^RT_H □ Tcart (Px , Py , Pz) □ RPY (□a , □o , □n)

Assumption : Robot is made of a Spherical Coordinate and an Euler angle.

^RT_H □ Tsph (r , □ , □) □ Euler (□ , □ ,□)

UNIT V INDUSTRIAL ROBOT

Robot programming:

The primary objective of robot programming is to make the robot understand its work cycle. The program teaches the robot the following:

- The path it should take
- The points it should reach precisely How to interpret the sensor data
- How and when to actuate the end-effector
- How to move parts from one location to another, and so forth

Programming of conventional robots normally takes one of two forms:

(1) Teach-by-showing, which can be divided into:

- Powered leadthrough or discrete point programming
- Manual leadthrough or walk-through or continuous path programming

(2) Textual language programming

In teach-by-showing programming the programmer is required to move the robot arm through the desired motion path and the path is defined in the robot memory by the controller.

Control systems for this method operate in either:

Teach mode: is used to program the robot
Run mode: is used to run or execute the program

Powered lead through programming uses a teach pendant to instruct a robot to move in the working space. A teach pendant is a small handled control box equipped with toggle switches, dials, and buttons used to control the robot's movements to and from the desired points in the space.

These points are recorded in memory for subsequent playback. For playback robots, this is the most common programming method used. However, it has its limitations:

- It is largely limited to point-to-point motions rather than continuous movement, because of the difficulty in using a teach pendant to regulate complex geometric paths in space. In cases such as machine loading and unloading, transfer tasks, and spot welding, the movements of the manipulator are basically of a point-to-point nature and hence this programming method is suitable.

Manual lead through programming is for continuous-path playback robots. In walk-through programming, the programmer simply moves the robot physically through the required motion cycle. The robot controller records the position and speed as the programmer leads the robot through the operation.

If the robot is too big to handle physically, a replica of the robot that has basically the same geometry is substituted for the actual robot. It is easier to manipulate the replica during programming. A teach button connected to the wrist of the robot or replica acts as a special programming apparatus. When the button is pressed, the movements of the manipulator become part of the program. This permits the programmer to make moves of the arm that will not be part of the program. The programmer is able to define movements that are not included in the final program with the help of a special programming apparatus.

Teach-by-showing methods have their limitations:

1. Teach-by-showing methods take time for programming.

2. These methods are not suitable for certain complex functions, whereas with textual methods it is easy to accomplish the complex functions.

3. Teach-by-showing methods are not suitable for ongoing developments such as computer-integrated manufacturing (CIM) systems.

Thus, textual robot languages have found their way into robot technology.

Textual language programming methods use an English-like language to establish the logical sequence of a work cycle. A cathode ray tube (CRT) computer terminal is used to input the program instructions, and to augment this procedure a teach pendant might be used to define on line the location of various points in the workplace. Off-line programming is used when a textual language program is entered without a teach pendant defining locations in the program.

Programming Languages

Different languages can be used for robot programming, and their purpose is to instruct the robot in how to perform these actions. Most robot languages implemented today are a combination of textual and teach-pendant programming.

Some of the languages that have been developed are:

WAVE
AML
MCL
IRL
SINGLA
VAL
RAIL
TL- 10
PLAW
VAL II

VAL II

- It is one of the most commonly used and easily learned languages.
- It is a computer-based control system and language designed for the industrial robots at Unimation, Inc.
- The VAL II instructions are clear, concise, and generally self explanatory.
- The language is easily learned.
- VAL II computes a continuous trajectory that permits complex motions to be executed quickly, with efficient use of system memory and reduction in overall system complexity.
- The VAL if system continuously generates robot commands and can simultaneously interact with a human operator, permitting on-line program generation and modification.
- A convenient feature of VAL If is the ability to use libraries of manipulation routines. Thus, complex operations can be easily and quickly programmed by combining predefined subtasks.

Rules for the location name are as follows:

1. It is any string of letters, numbers, and periods.
2. The first character must be alphabetic.
3. There must be no intervening blank.
4. Every location name must be unique.
5. There may be a limit on the maximum number of characters that can be used.

The following example illustrates the general command format for VAL II:

100 APPRO P1 15

In this example, 100 is the label that refers to this instruction, APPRO is the instruction to the robot to approach the location named P1 by a distance of 15 mm.

In the following, we describe the most commonly used VAL II commands.

MOVE P1	This causes the robot to move in joint interpolation motion from its present location to location P1.
MOVES P1	Here, the suffix S stands for straight-line interpolation motion.
MOVE P1 VIA P2	This command instructs the robot to move from its present location to P1, passing through location P2.
APPRO P1 10	This command instructs the robot to move near to the location P1 but offset from the location along the tool z-axis in the negative direction (above the part) by a distance of 10
DEPART 15	Similar to APPRO, this instructs the robot to depart by a specified distance (15 mm) from its present position. The APPRO and DEPART commands can be modified to use straight-line interpolation by adding the suffix S.

DEFINE PATH 1= PATH(P1,P2,P3,P5) **MOVE PATH 1**	The first command (DEFTNE) defines a path that consists of series of locations P1, P2, P3, and P5 (all previously defined). The second command (MOVE) instructs the robot to move through these points in joint interpolation. A MOVES command can be used to get straight-line interpolation
ABOVE & BELOW	These commands instruct the elbow of the robot to point up and down, respectively.
SPEED 50 IPS	This indicates that the speed of the end- effector during program execution should be 50 inch per second (in./s).
SPEED 75	This instructs the robot to operate at 75% of normal speed.
OPEN	Instructs end effector to open during the execution of the next motion.
CLOSE	Instructs the end-effector to close during the execution of the next motion.
OPENI	Causes the action to occur immediately.
CLOSEI	Causes the action to occur immediately

If a gripper is controlled using a servo-mechanism, the following commands may also be available.	
CLOSE 40 MM	The width of finger opening should be 40 mm.
CLOSE 3.0 LB	This causes 3 lb of gripping force to be applied against the part.
GRASP 10, 100	This statement causes the gripper to close immediately and checks whether the final opening is less than the specified amount of 10 mm. If it is, the program branches to statement 100 in the program
SIGNAL 4 ON	This allows the signal from output port 4 to be turned on at one point in the program and
SIGNAL 4 OFF	Turned off at another point in the program.
WAIT10 ON	This command makes the robot wait to get the signal on line 10 so that the device is on there.

Logarithmic, exponential, and similar functions:

The following relational and logical operators are also available.

EQ	Equal to
NE	Not equal to
GT	Greater than
GE	Greater than or equal to
LT	Less than
LE	Less than or equal to
AND	Logical AND operator
OR	Logical OR
NOT	Logical complement

IF (Logical expression) THEN
(Group of instructions)
ELSE
(Group of instructions)
END
	If the logical expression is true, the group of statements between THEN and ELSE is executed. If the logical expression is false, the group of statements between ELSE and END is executed. The program continues after the END statement.
	The group of instructions after the DO statement makes a logical set whose variable value would affect the logical expression with the UNTIL

DO (Group of instructions) UNTIL(Logical expression)	statement. After every execution of the group of instructions, the logical expression is valuated. If the result is false, the DO loop is executed again; if the result is true, the program continues.

TYPE "text“ This statement displays the message given in the quotation marks. The statement is also used to display output information on the terminal.

PROMPT "text", INDEX This statement displays the message given in the quotation marks on the terminal. Then the system waits for the input value, which is to be assigned to the variable INDEX.

In most real-life problems, program sequence control is required. The following statements are used to control logic flow in the program.

GOTO 10This command causes an unconditional branch to statement 10.

SUBROUTINES can also be written and called in VAL II programs. Monitor mode commands are used for functions such as entering locations and systems supervision, data processing, and communications. Some of the commonly used monitor mode commands are as follows:

EDIT (Program name) This makes it possible to edit the existing program or to create a new program by the specified program name.

EXIT This command stores the program in controller memory and quits the edit mode.

STORE (Program name) This allows the program to be stored on a specified device.

READ (Program name) Reads a file from storage memory to robot controller.

LIST (Program name) Displays program on monitor.

PRINT (Program name) Provides hard copy.

DIRECTORYProvides a listing of the program names that are stored either in the controller memory or on the disk.

ERASE (Program name) Deletes the specified program from memory or storage.

EXECUTE (Program name) Makes the robot execute the specified program. It may be abbreviated as EX or EXEC.

ABORT Stops the robot motion during execution.

STOP The same as abort.

EXAMPLE 1:

Develop a program in VAL II to command a PUMA robot to unload a cylindrical part of 10 mm diameter from machine 1 positioned at point P1 and load the part on machine 2 positioned at P2. The speed of robot motion is 40 in./s. However, because of safety precautions, the speed is reduced to 10 in./s while moving to a machine for an unloading or loading operation.

Solution

1. **SIGNAL 5**
2. **SPEED 40 IPS**
3. **OPEN 100**
4. **APPRO PI, 50**
5. **SPEED 10 IPS**
6. **MOVE PI**
7. **GRASP 10, 100**
8. **DEPART P1, 50**
9. **SPEED 40 IPS**
10. **APPRO P2, 50**
11. **SPEED 10 IPS**
12. **MOVEP2**
13. **BELOW**
14. **OPENI 100**
15. **ABOVE**
16. **DEPART P2, 50**
17. **STOP**

EXAMPLE 2:

Suppose we want to drill 16 holes according to the pattern shown in the Figure. The pendant procedure can be used to teach the 16 locations, but this would be quite time-consuming and using the same program in different robot installations would require all points to be taught at each location. VAL II allows location adjustment under computer control.

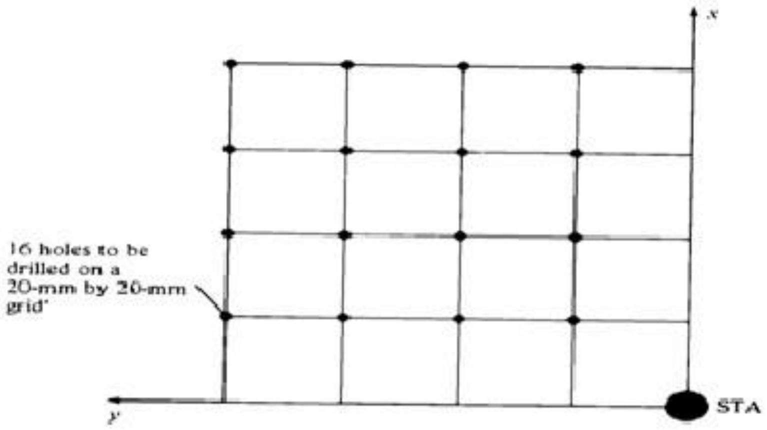
The program allows all holes to be drilled given just one location, called STA at the bottom right-hand corner of the diagram. Actually, two programs are required, since one will be a subroutine.

```
MAIN PROGRAM (MC)
1. K = 0
2. SPEED 20
3. FOR I = 1 TO 4
4. FOR J = 1 TO 4
5. K = K + 1
6. CALL DRILL
7. END
8. END
9. TYPE "DRILLING COMPLETE"
```

```
SUBROUTINE (DRILL)
1. XM = 20 * I
2. YM = 20 * J
3. MOVE SHIFT(STA BY XM.YM.0)
4. DEPART -20
5. SPEED 10
6. DEPART 20
7. TYPE/B."COMPLETED HOLE"./I2.K
8. SPEED 20
```

format

B = bfc 10



ROBOT SELECTION

This phenomenal growth in the variety of robots has made the robot selection process difficult for applications engineers. Once the application is selected, which is the primary objective, a suitable robot should be chosen from the many commercial robots available in the market.

The technical features are the prime considerations in the selection of a robot. These include features such as:

(1) degrees of freedom,
(2) control system to be adopted,
(3) work volume,
(4) load-carrying capacity, and
(5) Accuracy and repeatability.

The characteristics of robots generally considered in a selection process include:

1. Size of class
2. Degrees of freedom
3. Velocity
4. Actuator type
5. Control mode
6. Repeatability
7. Lift capacity
8. Right-Left-Traverse

9. Up-down-traverse
10. In-Out-Traverse
11. Yaw
12. Pitch
13. Roll
14. Weight of the robot

Robots for nuclear power plants

Once confined to the pages of science fiction, robots have dramatically captured the attention of the public and the industrial business community in recent years. Many observers view robots as a hall mark of neo industrialization, breathing renewed economic vigour and competitiveness into depressed industries through improved productivity and reduced labour costs. At the same time, however, workers often respond with apprehension to the mental image of a robot performing atask that formerly required a human. The social implications of the robotization of American industry will surely become of more concern to workers, managers, and policymakers alike as more robots enter the industrial workplace. According to the Robotics Industries Association, only f>3()() robots had been delivered in the United States by the end of 1983; most of those had been installed since 1976. But the force of technologic change and the pressure on international economic competition promise an accelerated pace of robot deployment in the years ahead. Someexperts predict that as many as 10(1 000 robots may be at work in this country by 1990—one-tenth of the total number projected worldwide. For most industries in which robots have been or are expected to be applied in significant numbers, such as automobile production, metalworking, and machinery manufacture, the incentives to robotize relate directly to preserving or recapturing competitive advantage through lowered unit costs of production and improved product quality. But for some industries, the attraction of robots is their potential to work in hazardous environments, thereby reducing the human risks associated with the work.

The electric utility industry is one such industry. Although utilities are not viewed by most industrial robot manufacturers as a significant potential market, special-application robots are under development for performing inspection and maintenance tasks inside nuclear power plants, where radiation levels, heat, and humidity either rule out the presence of human workers or severely limit their ability to work. For many of these tasks in a nuclear plant, robots would be a welcome additionto the workforce, freeing humans from some of the more onerous and discomforting jobs and, possibly, permitting certain tasks to be performed while a plant remains on-line, thus avoidingcostly plant downtime tor inspection or maintenance. Some of the robots under developmentfor utility applications represent the state of the art of robotics engineering, and the related research efforts could pioneer advances that have broad application to other industries.

Nuclear power and electronics has several current projects aimed at evaluating the technical and economic potential for robot applications in utility operations and at translating the understanding gained from these efforts to the utility professionals who have work aplenty waiting for robots that prove reliable and cost-effective. Such research is necessarily long range. The robotics industry, fewer than 20 years old by the broadest definition, remains in its infancy, awaiting substantial technical advances in vision systems, miniaturization, and computer controls before truly economic, versatile, and powerful robots are commonplace items of commerce. But R&D success with robots in recent years suggests that such machines will emerge from the laboratories and enter the commercial market before this decade is over. EPRl's research in robotic applications, at least in part, is intended to ensure that when that day arrives, utilities will have a clear understanding of the work robots can do for them and whether it makes economic sense to put them to work.

Robots for nuclear plants The use of remotely operated and robot like equipment to protect nuclear workers in high-radiation areas is not new. John Taylor, an EPRI vice president and director of the Nuclear Power Division, divides robotic equipment in nuclear applications into two broad categories: single-purpose devices with limited ability to perform different operations, and reprogrammable, multipurpose robots with some degree of computer-based artificial intelligence.

"I think the first category has reached a reasonable level of maturity," says Taylor At EPRI's Non-destructive Evaluation (NDE) Center and among reactor manufacturers, nuclear service contractors, and some utilities, these types of devices are in use today for such tasks as pipe cutting, welding, steam generator tube inspection and repair, and ultrasonic scanning of pipe sections for crack detection. "These devices have proved to be absolutely essential; we simply could not get some jobs done without them," adds Taylor. Robots in the second category, those with sufficient computer-based intelligence to support a variety of applications, "have a long way to go," in Taylor's words, before they can demonstrate significant practical benefit in nuclear plant operations. But, as Taylor adds, such robots are under development, and their initial trials are expected to provide valuable insight totheir ultimate potential. Soon after remote manipulator arms were developed for use in hot cells and fuel reprocessing activities, an arm mounted on a transporter with cameras and lights made its debut in the 1950s at the government's Hanford nuclear facility in Washington State.

Developedby Westinghouse Hanford Co., the remotely controlled transporter vehicle was dubbed Louie after a technician scrawled the nickname on the robot's arm. Louie has proved to be a versatile and long-lived workhorse and is still in use today. Some fundamental aspects of how this equipment is applied distinguish robotic equipment for nuclear plant applications from the more widely familiar industrial robots—those fixed devices that typically are employed for pick-and-place operations or other highly repetitive tasks. In many industrial applications of robots, the objective is to replace human workers with machines that are more productive, efficient, and accurate. Butfor nuclear applications, the objective is not so much to replace workers as it is to extend their presence—for example, to project their reach into areas of a nuclear plant where the thermal or radiation environment prohibits or limits a human presence.

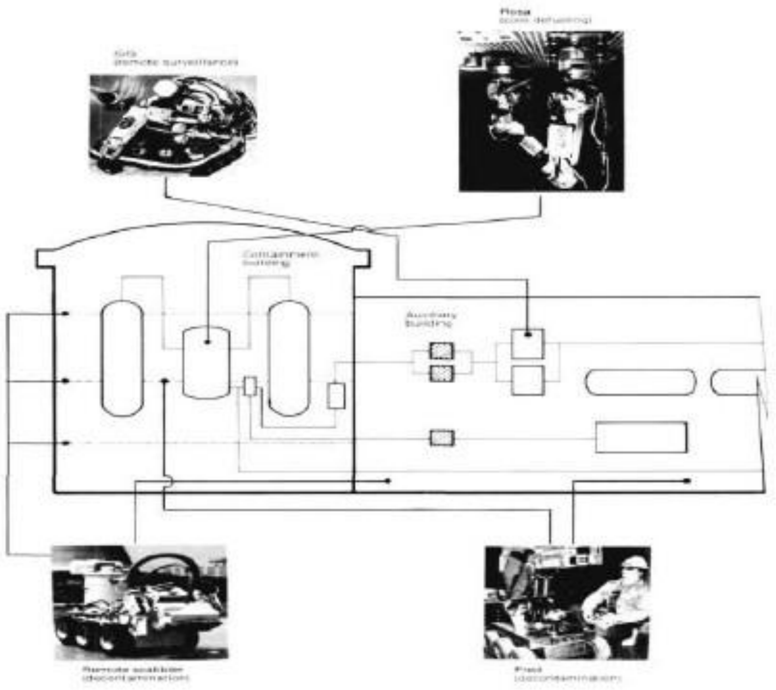
Utilities may face even tougher ORE limits in the future. In addition to guidelines that call on utilities to reduceOREs to levels "as low as reasonably achievable," NRC for several years has been studying proposals to reduce the ORE standards; such a development could have a multiplicative effect onutility costs for personnel exposure. Feasibility studied EPRI and NRC have both sponsored preliminary assessments of the potential for applying robotics in nuclear power plants. NRC, motivated primarily by the objective of reducing personnel radiation doses, looked mainly at surveillance and inspection tasks in a study performed by Remote Technology * In international usage, the rem has been replaced by the sievert in accordance with recommendations of the International Organization for Standardization. One sievert corresponds to 100 rem. Columbus Laboratories, focused on maintenance activities and attempted to identify potential availability improvements, as well as opportunities to reduce radiation exposure.

Each study attempted to quantify the cost in ORE and man-hours of a variety of jobs that a robot system might be capableof performing; the costs were then compared with those of the robot and its associated support systems and personnel Surveillance and inspection tasks evaluated in the NRC study range fromdetection of steam or water leaks, verification of valve positions, and reading of gages to measurement of radiation levels in components and various methods of sampling to detect contamination. The EPRI study surveyed 22 tasks that are performed routinely or during refuelling, including control rod drive maintenance, steam generator tube repair, and repair or replacement of various pumps and valves. Although the scope of activities analysed were different, both studies concluded there were potentially significant net positive economic benefits of applying robots in nuclear plants The NRC study, based on application of a cost-benefit methodology to two existingplants, concluded that commercially available robotic technology can be retrofitted into existing plants and will reduce both radiation exposure to workers and plant operating costs. The NRC study cautioned, however, that benefits can differ significantly among plants because of dissimilar design factors and operating histories. Some, on the other hand, may be less capable of doing demanding labor, but could be used as intelligent master robots, controlling the work of stronger drones. Several robot prototypes are making their debut in the recovery and cleanup of the damaged Three Mile Island Unit 2 nuclear plant in Pennsylvania, the site of a March 1979 loss-of-coolant accident that destroyed much of the reactor core and left large areas of the reactor containment building inaccessible to humans. Remote inspection has shown radiation fields as high as 3000 rad/h in some areas of the containment.* According to Adrian Roberts, a senior program manager in EPRI's Nuclear Power Division and manager of its TMI-2 information and examination program, the TMI cleanup effort has become a particularly strong spur to robotic equipment development. "At TMI we have a challenge for robotics that is here and now, some of the jobs simply can't be done other than remotely.

The venerable Louie from Westinghouse Hanford has been brought to TMI to perform radiologic characterizationduring decontamination of the water purification system. Officially known as the remotely controlled transporter vehicle, Louie will be used to monitor radiation levels as the demin- * In international usage, the rad has been replaced by the gray. One gray corresponds

Robots atTMI-2

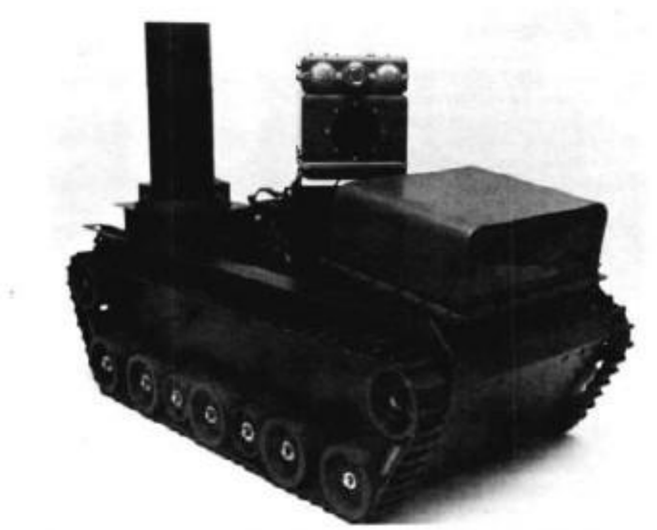
Cleanup and recovery work at the damaged TMI 2 reactor in Pennsylvania presents a unique challenge for the application of robotics technology. Two remotely operated manipulators called Fred and SISI have already seen service in surveillance and decontamination tasks. The RRV, nicknamed Rover, has been assigned the job of inspecting the contaminated basement of the reactor containment building. A remote scabbling machine has been developed to remove contaminated layers from concrete floors. Louie, specially modified for the TMI work, is slated to monitor radiation levels as the plant demineralizer tank is decontaminated. Rosa, a versatile remote manipulator arm, has been proposed to lend a hand in defueling the TMI 2 reactor core.



I hough the robot's nearly KXXl-lb (454-kg) lifting strength will not be needed in this operation, its radiation-hardened television cameras will get a workout near the demineralizer tank, which has a contact reading of 3000 rad/h. Perhaps the most ambitious effort to date to apply robotics in the I'Ml cleanup has been the EPRI-Supported development by Carnegie-Mellon University's (CMU's) Civil Engineering and Construction Robotics Laboratory of the remote reconnaissance vehicle (KRV) to probe the basement of the reactor containment building. The basement level, where no human has entered in over five years, remains highly contaminated with the radioactive sludge left trom some 600,000 gallons (2270 m1) of water, including primary cooling water, most ol which has since been pumped out. The RKV, nicknamed Rover by GI'U Nuclear Corp., the operating utility at I'M I. has been assigned the task of entering the dark and damp basement bv crane hoist, inspecting the scene with its three television cameras, and surveying the area radio logically with several on-board detection instruments. The six-wheel, 1000-lb KRV, developed in a cooperative effort involving EPRI, CMU, C,PU Nuclear, DOE, and the Hen l-'ranklin Partnership in Pennsylvania, was designed by CMU's William Whittaker, an assistant professor of civil engineering and director of the robotics laboratory.

The second RRV base vehicle, modified by 1'entek, Inc., HPKI's site contractor at TMI, is outfitted with a pneumatically powered scabbling machine and vacuum system for removing the contaminated top layer of concrete from floors in parts ot the reactor building. A third RRV remains at CMU's robotics laboratory for future development efforts. Other tasks proposed for future modifications of the prototype RRV include collection of liquid and sludge samples from the containment basement, collection of concrete core samples from the floor and walls, and some minor structural dismantling. "At TMI the interest is in working vehicles with high strength, reliability, and mobility," explains Whittaker, the RRV's designer.

The challenges at TMI are very physical and active, and the equipment that will meet those challengeswill be similarly physical and active. But there is certainly no one machine that will do it all, so we are looking at the evolution of a family of these things. One mode might be a fully configured RRV to supervise the activity of a drone that would earn' tools only. Another possibility is a miniatureversion of the RRV that would operate radio-remote from the mother ship." Clearly, robotic equipment is proving to be a valuable tool in the TMI recovery effort. Other applications of robotsat the site are also planned. A manipulator arm built by Westinghouse Electric Co. and known as Rosa (for remotely operated service arm) has been proposed for use in the defueling of the 1 Ml reactor core, tentatively planned for next year. Rosa, which can also operate underwater, is already known among some utilities operating pressurized water reactors for its ability to automatically inspect and repair steam generator tubes after it is mounted on the steam generator by service personnel. Waiting in the wings In addition to the robots that have been deployed at TMI, EPRI is evaluating two other prototype devices that could prove useful in nuclear plant environments. These machines could become cousins of the TMI machines in the ro



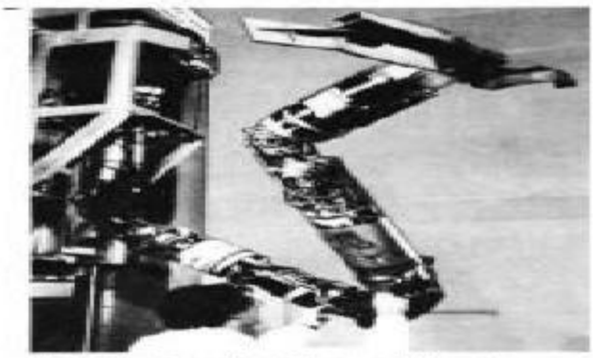
IRIS — for Industrial Remote Inspection system — is a general-purpose robot for hazardous environments. (Credit: EPRI)

One of these, produced by Advanced Resource Development (ARD) Corp., is known as an industrial remote inspectionsystem (IRIS). Designed as ageneral-purpose surveillance and inspectionrobot for hazardous environments,IRIS is a relatively small (compared withthe RRV) battery-powered, trackedtransporter that can be equipped withoptical, audio, and environmental sensors;manipulators; and communicationsand control subsystems.The 200-lb (91-kg) IRIS features aunique high-frequency wireless communicationsystem, specifically designedto operate in an environmentcluttered with physical barriers, as wellas with signal interference, which allowsit greater mobility and range thanmost robots developed to date.

Future development

Technologically, Odex may be close tothe fully autonomous, intelligent robotthat researchers say would representthe ultimate marriage between machineautomation and the developing field ofartificial intelligence Its ability to maneuver around or over obstacles underthe guidance of a remote operator approachesthe level of computer controlintegration that will be needed if a robotis to be capable of autonomously respondingto a programmed set of directionsby referencing a self-containeddata base for its location, destination,route, and tasks.Consummating the union betweenrobots and artificial intelligence is along-range research goal, however, becausethe challenges involve advancingthe frontiers of computer modelling of solid geometry, as well as the structuringof large amounts of computerdata for logical access by the robot.

Various military and non-military research programs around the country are now focusing on the mathematicaland computer science aspects that willeventually be brought to bear on thischallenge. The military programs arelargely funded by the Office of Naval Research and the Defence Advanced Research Projects Agency. Others, includingprograms at Stanford University,Purdue University, the Universityof Michigan, the Massachusetts Instituteof Technology, and CMU, involve non-military as well as military-relatedR&D.Irving Oppenheim, an associate professorof civil engineering at CMU, isworking with EPRI on some aspects ofthe problem in a research project to assessthe potential for applying artificialintelligence in robots for constructionand maintenance work. The Japanesealready make significant use of auto made devices for various tasks in construction,but, in general, these devicesare not the smart type. Two elementsthat are needed to make robots autonomous, according to Oppenheim, are theability to logically detect and avoidobstacles and a way of modeling the three-dimensional work environment of the robot so that its "world map" canbe referenced as it proceeds on an assigned task."There" are some attempts at themathematics that will permit a robot tofind a configuration that avoids an obstacle,and we are working with the existingones, testing them out, findingtheir shortcomings, and modifyingthem to accomplish some of the objectivesthat these obstacle avoidancecapabilities are going to have," saysOppenheim.



ISIS, developed by Hispano Suiza, is being used at France's Chinon A3 reactor for repairs. (Credit: Hispano Suiza)

OC Robotics: Nuclear remote handling

Remote handling in radioactive environments often requires dextrous manipulators that can access a radioactive space through a small opening and avoid obstacles between the entry point and work site. OC Robotics is the world leader in snake-arm robots: remote tele-operated manipulators that can ‘follow-their-nose’ into confined spaces.

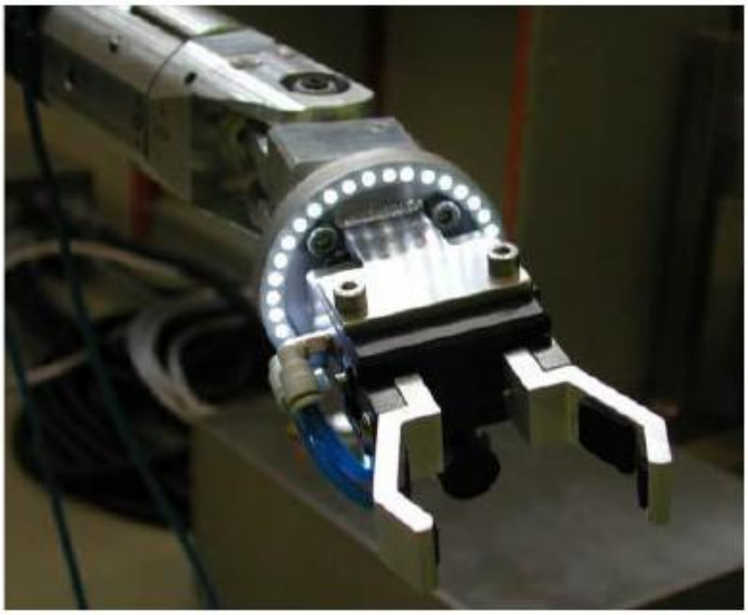
OC Robotics snake-arm robots

To date OC Robotics has focused on life extension projects for power generating plant. Customers around the world, including Ontario Power Generation, Areva and Ringhals AB (Sweden) have used OC Robotics’ systems to conduct ‘minimally invasive’ maintenance and repair operations through small (typically pre-existing) access holes. Focusing on profit-generating plant has enabled OC Robotics to grow and develop nuclear capabilities. This experience can also be applied to decommissioning tasks. This document provides an overview of OC Robotics’ snake-arm robot technology and previous nuclear experience. Whilst OC Robotics’ core technology is snake-arm robots, a turn-key solution would be tailored to the demands of the specific application. OC Robotics products include a mobile vehicle, vision systems, sensors and tooling, user interface, software and electronics infrastructure that allow remote control.

- **Tooling:** Confined spaces often require specialist tools which are small enough to be manoeuvred in the space available. OC Robotics has designed tools for visual and UT inspection, manipulation (gripper), cutting/cropping, welding and fastening (below).

- **Tool services:** Snake-arm robots all have a hollow bore, which means that services are routed inside the arm to the base avoiding the risk of snagging and maintaining a smooth external surface. Snake-arm robots can also be used a guide for delivering active or passive tools, e.g. another snake-arm robot or a video probe.

- Contamination: Snake-arm manipulators can be designed without prominent ‘elbows’ making them straightforward to seal against contamination or water. OC Robotics has also delivered systems that are fully sealed and air-tight to prevent air-borne contamination being taken up into the mechanisms.



Example tooling

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- **Materials:** OC Robotics has delivered systems with specific material requirements. Systems can be designed without any prohibited materials so that they are suitable for use in the nuclear industry.

- **Electronics:** A design principle of snake-arm robots is that the motors and related electronics are located in the base of the arm. There are three reasons for this: first, a lighter arm can be a longer arm; second, motors are bulky so an arm can be either smaller in diameter or have more space internally for services; third, main systems, including electronics, can be kept in an accessible area. This final point is critical for high radiation dose and wet environments.

- **Control:** The OC Robotics user interface is intuitive and easy tounderstand. It can be tailored to each application to ensure that theuser has all the information required without being overloaded.

- **Data collection and management:** OC Robotics’ user interface is ableto record video and images alongside text or audio.

- **Technology integration:** The customer’s own capabilities can beintegrated with a solution. For example a solution may combine asnake-arm manipulator with in-house UT inspection developments.

- **Quality Assurance:** OC Robotics has worked as prime contractor to the nuclear sector and operates to a Quality Management System certified to ISO 9001

Explorer range of Snake-Arm Robots

Explorer range snake-arm robots vary in size from 40mm to 150mm in diameter and from 1m to 3.25m in length. These dimensions represent the mid-range of our capabilities. The strength of the Explorer design is that is scalable, so both smaller diameters and longer reach versions are possible.

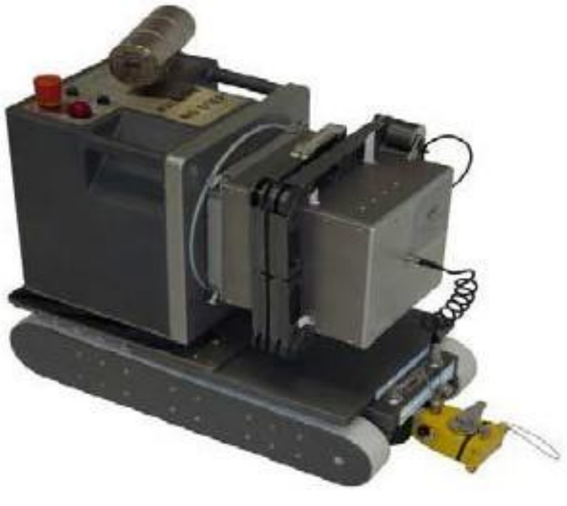
Options include “quick release” mechanisms between the arm and the actuators, 1 or 2 degree of freedom wrists, and a variety of different tools. Snake-arms can be integrated with an introduction axis – a linear rail, industrial robot or vehicle – to enable controlled ‘nose-following’ motion.

The Explorer range of snake-arm robots is designed to operate as a standalone unit or with an OC Robotics introduction axis. Alternatively it can be integrated with a standard industrial robot, a crane or a mobile vehicle. Using industrial robots as an example, the Explorer range can be considered as a tool on the end of the industrial robot or as a flexible fore-arm for the robot. Our proprietary software controls both the industrial robot and the snake-arm to coordinate their motion.

OC Robotics completed its first commercial nuclear contract in the summer of 2004. Working with Areva, two types of snake-arm robot were supplied to Ringhals AB to complete an urgent pipe replacement in an extremely awkward area below Ringhals 1. The Inspection Arm, the more flexible of the two snake-arms, was 1000mm long and 35mm in diameter and was used to get the ideal camera location to monitor the process. The Manipulation Arm, which was 800mm long and 60mm in diameter, was used to deliver the processing tools and fixtures, remove the old pipe, introduce the new pipe and conduct tasks such as welding and inspection. Replacing the leaking section of pipe involved more than 30 distinct procedures with the majority being conducted by the robots working cooperatively

Ringhals Inspection Arm

Ontario Power Generation, Pickering, Canada

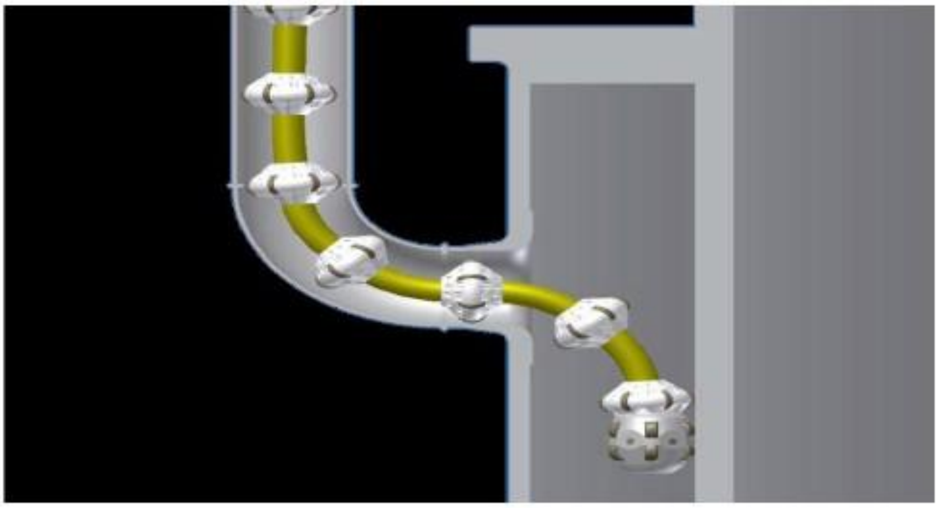


OC Robotics’ SAFIRE (Snake-Arm Feeder Inspection Robotic Equipment) was designed to conduct inspections within the Upper Feeder Cabinet (UFC) of CANDU nuclear reactors in Ontario, Canada. The 2.2m long, 25mm wide snake-arm is mounted on a tracked mobile vehicle which is driven along walkways in the UFC. The snake-arm is stowed coiled for compactness and is deployed by unwinding and ‘nose-following’ between pipes. The snake-arm can be deployed at any angle to reach below or above the walkway, and can reach 100% of the UFC. Side and forward facing tool-mounted cameras are used for navigation and image capture. Pan-tilt-zoom cameras on the mobile and base units provide scene views and additional inspection capability.

OC Robotics investigated the design of a snake-arm to reach in excess of 10m down a multi-curved pipe in order to measure vessel wall thickness from within a vessel cooling jacket, see image below. Working within pipework requires a device which is compliant and will adapt to the bends in the pipe. However, to reach deep into a pipework system an endoscope will not suffice – friction will simply stop it going round more than a few bends. A snake-arm robot, on the other hand, is controllable along its length which means that the body of the device can be biased around each of the bends, not just at the tip.

The OC Robotics Pipe Snake™ needs some structure to support its weight, such as a pipe, yet it is steerable and can be guided around bends. The biggest benefit of a snake-arm robot over an endoscope is that a snake-arm robot can be designed to include shape measurement which means that the user can know the shape of the arm and therefore the location of the tip. Users can record where defects are found and then return to the same spot during subsequent inspections to check defects over time.

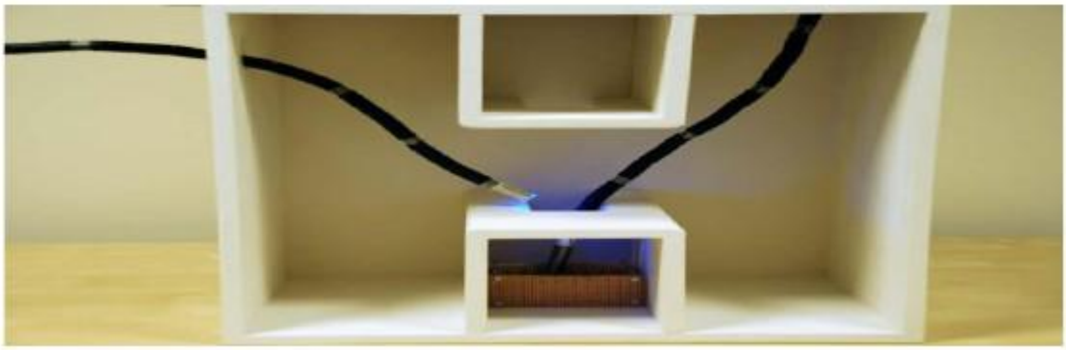
The OC Robotics Pipe SnakeTM Sellafield



OC Robotics portable snake-arm tools

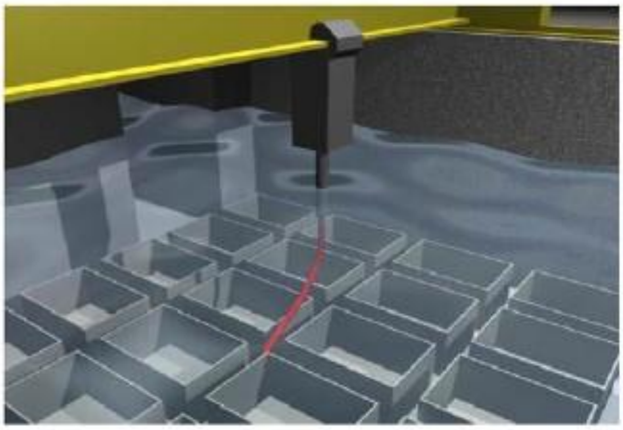
Standard flexible endoscopes - also known as borescopes or video scopes - have a long flexible body with a steerable tip. They are useful for inspection in confined spaces but they suffer from a lack of control and a reliance on the environment to support the body of the device. This means that flexible scopes cannot bridge large horizontal gaps and cannot advance around multiple corners. Snake-arm robots do not need support from the environment, they are self-supporting, and are steerable along their entire length.

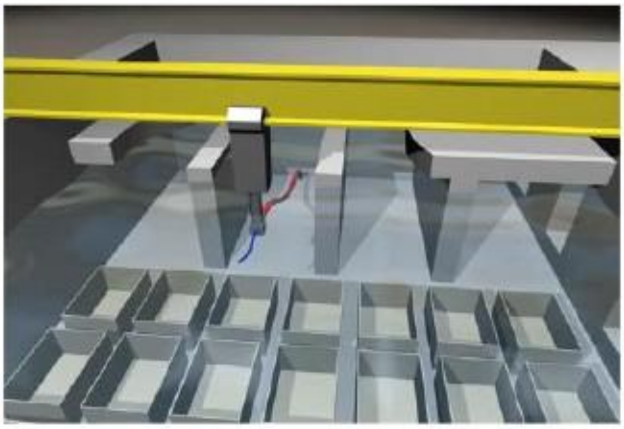
The smallest fully self-supporting arm to date is 12.5mm in diameter and 400mm in length (below). It is stored in a self-contained portable unit and can be battery or mains powered.



When the environment can be used for support then snake-arms can be much more slender. This is also true when gravity is no longer an issue, for example if the arm is hanging vertically or operating underwater. We have designed a neutrally buoyant arm for underwater operations.

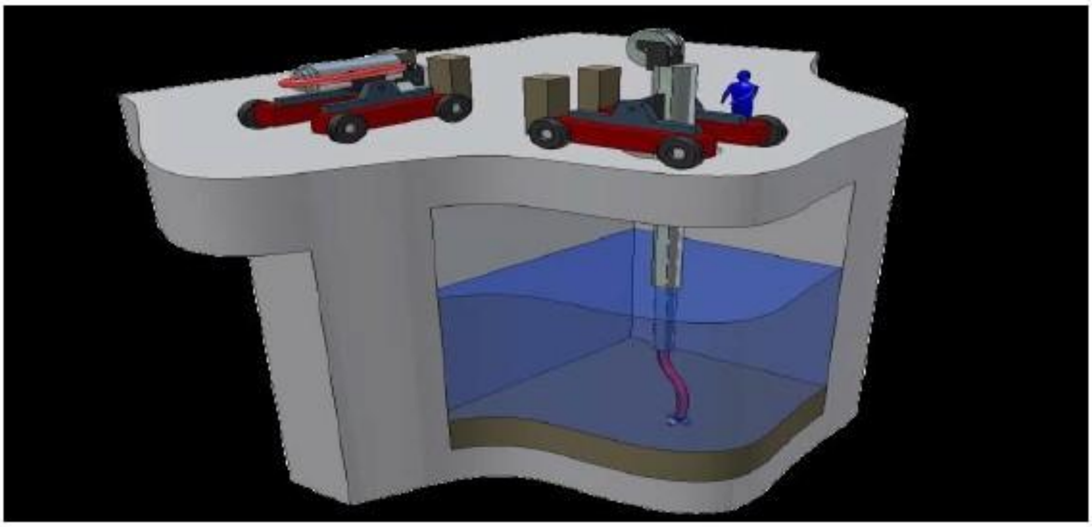
Snake-arm robots can have smooth, continuous external surfaces with all services running internally, which greatly reduces the likelihood of snagging and makes sealing and resealing easier. The combination of an easy-to-seal smooth arm and an actuator pack within an air tight container means that snake-arms are the ideal platform for washable, wet or fully submerged applications.





Long reach and high payload manipulators

The general snake-arm robot design is very scalable and OC Robotics has talked to customers about manipulators up to 15m in length to carry significant payloads. While very slender snake-arm robots will inevitably be unable to move large tools, a shorter, thicker arm can carry significant payloads. These arms will likely have fewer segments and are ideally suited to glove box work as an alternative to master-slave manipulators.



Introduction - Industrial Applications of Robots

Robots are widely used in Industries for automation purposes.

- Automation –

(a) Fixed

(b) Flexible

(c) Programmable.

They remove human labors and can be used for continuous or Batch processing purposes. By use of these robots Productivity, quality both increases. Time for production reduces.

Major applications of robots in industries can be classified as follows.

(a) Material Handling Applications

(b) Processing Operations

(c) Assembly and Inspection Applications

GENERAL CONSIDERATIONS FOR ROBOT'S IN MATERIAL HANDLING APPLICATIONS

- Part Positioning and Orientation.
- Gripper Design.
- Minimum Distances Moved. ⍰Robot Work Volume.
- Robot Weight Capacity.
- Accuracy and Repeatability. ⍰Robot Configuration.
- Machine Utilization Problems.
- Material Handling Applications

This is the major application area of Robots inIndustry & most widely used. This application can be classified into

- Material Transfer Applications.
- Material Loading/Unloading Applications.

MATERIAL TRANSFER APPLICATIONS

Divided into: Pick and place robots, Palletizing, Depalletizing and Related Robots.

PICK AND PLACE ROBOTS

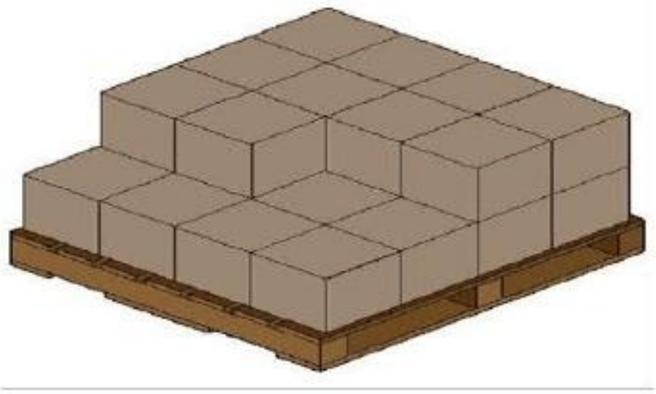
- Picks a part Job piece from one location and moves it to another location.
- Part may be presented by mechanical feeding device or conveyor.
- For simple case, robot needs only 2 degree of freedom. One to lift and drop, other is to move between the pickup point and drop point.
- Has to track a moving pickup point or drop onto a moving conveyor. Either case requires sophisticated system inter-locks system.
- When different objects are handled, the robot must distinguish between them.
- To handle this issue, sensor system which executes the respective module must be used.

PALLETIZING AND RELATED OPERATIONS

Large amount of containers (cartons) are placed on a pallet (wooden platform) and then it is handled by fork-lift trucks or conveyors.

- These are very convenient method for shipping large quantity of products.
- Computer controlled robot, using high-level programming language is suitable for this operation.

Other Operations are:



Depalletizing Operations [Reversal of palletizing operations].

- Inserting parts into cartons / conveyor.
- Stacking and un-stacking operations.

The robot maybe called to load/unload different pallets differently like (which may): vary in size. Different products loaded onto pallets. Differences in numbers and combinations of cartons to different customers.Bar codes are used to solve the identification problem for depalletizing the optical reader system can be used. Differences in loading and unloading can be accomplished by loading the respective subordinate in to controller. Usually the palletizing operation is much complex then Depalletizing because of customer's orders (different boxes of different sizes has to be delivered to different customers.

MACHINE LOADING / UNLOADING

It is used to service a production machine by transferring parts to/from the machine.

There are 2 cases: **Machine load/Unload** : Loads raw material and unloads finished part.

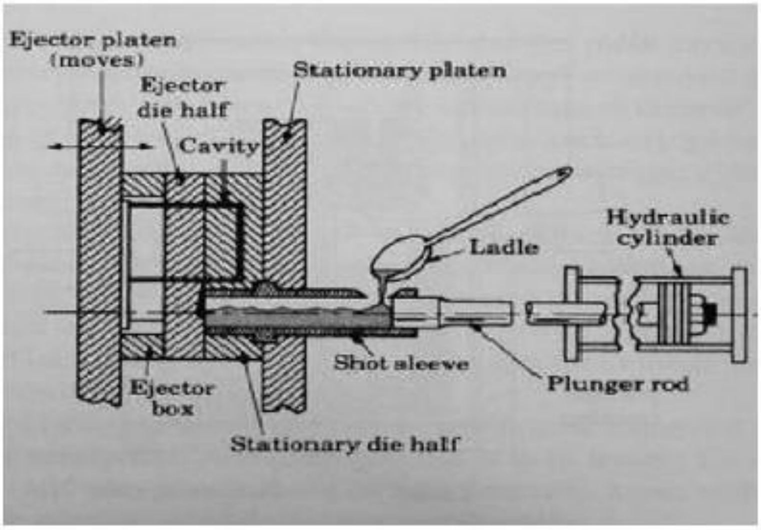
Machine Loading: Load the raw material but the finished part is ejected by other mechanism. Example: Presswork

Machine Unloading: Raw materials automatically loaded and the machine produces finished product. The robot unloads the finished product.

Successful Operations in which robots are used:

- Die Casting
- Plastic Molding
- Forging and related operations
- Machining operations
- Stamping press operations

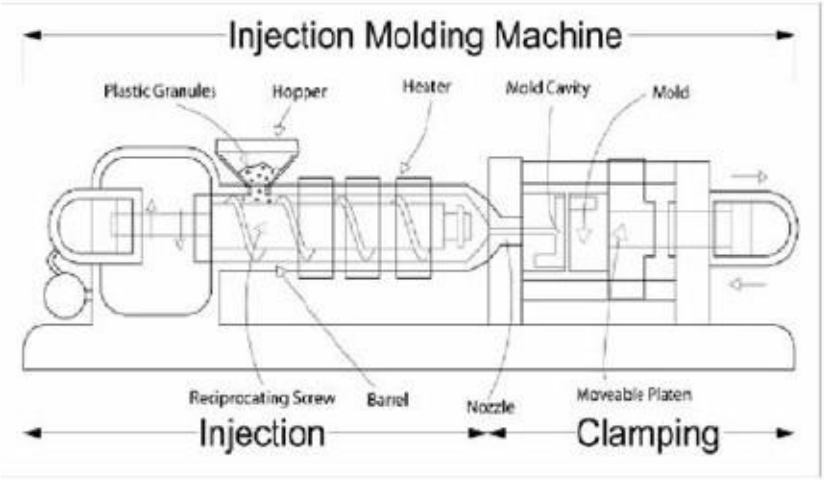
DIE CASTING



Molten metal forced into cavity of a mold under high pressure. Mold is called die hence named die casting. Common metals include alloys of zinc, tin, lead, aluminium, magnesium and copper. The die is closed and molten metal is force in using pump. To ensure cavity is filled enough metal is forced in that causes overflow and flash in the space between die halves. When metal has solidified it is ejected by using pins (usually) and quenched in water bath. The flash is removed using trimming operation. It's a straight forward approach & limit switches are used for providing Interlocks. Thus die casting involves the following Casting Removing the part from the machine Quenching, Trimming

Range: 100 to 700 openings of the die per hour depending upon the machine. Problems encountered here are in Programming side , Design of Grippers, Transporting the molten metal to the injection Chamber etc.

PLASTIC MOLDING



Batch-volume or high volume process used to make plastic parts to finite shape and size.

Covers Number of process:

- Compression molding
- Injection Molding (Most common)
- Thermoforming
- Blow Molding
- Extrusion etc.,

A thermoplastic material is introduced in form of small pellets from storage hopper. Heated in heating chamber to 200-300 C and injected in to mold cavity under pressure. If much is injected flash is created, if little is inserted sink holes are created rendering unacceptable. Highly sophisticated production machine capable of maintaining temperature, pressure, amount of material injected called "INJECTION MOLDING MACHINE" is used. If the part struck in the mold then we can use Gravity to cause the product to drop, directing an air stream to force the part out etc. Based on the molding job the method of part removal is done.

Disadvantage:

Production time is larger than the Die castingmethod. Robot is idle for most time till the processing finishes. Part inspection & Flash removal is difficult.

FORGING AND RELATED OPERATIONS

Metalworking process where metal is pressed or hammered into desired shape. It is of two types:

(1) Hot forging here the metal is heated to high temperature before forging.

(2) Cold forging it adds strength to the metal and used for high quality products.

The operations include: Die Forging and Upset Forging. Die Forging: Accomplished on a machine tool called drop hammer where raw billet is hit 1 or more times between upper and lower portions of forging die. Upset Forging: Also known as upsetting, where size of a portion of work path is increased by squeezing the material into the shape of die.

Some technical and economic problems include:

- Production runs are typically older machines.
- Short production runs.
- Parts occasionally stick in the dies. Can be readily detected by humans but posses problem for robots.
- Design of gripper is significant engg. problem because it must withstand shock from hammer blows.

Some of technical & Economical Problems are: Machines are older ones (designed for manual operations) which can't be easily interfaced with Robots.

- Due to short forging cycles its not economical for robots to be installed.
- Parts occasionally stick in dies. Humans can easily bring it out but it's a difficult job for Robots.
- Design of Grippers is another problem.

MACHINING OPERATIONS

Machining is metalworking in which the shape of the part is changed by removing excess material with a cutting tool. Principal types : Turning , Milling, Shaping, Planning, Grinding. Robots utilized to perform the loading and unloading functions in machining operations. The following robot features contribute to success:

- Dual Gripper.
- Up to six joint motions.
- Good Repeatability.
- Palletizing and Depalletizing capabilities.
- Programming Features.

STAMPING PRESS OPERATIONS

Used to cut and form sheet metal parts. Performed by means of a die set held in a machine tool called a PRESS. Raw material in the form of coils, sheets and individual flat blanks. One limiting factor is the cycle time of the press. These are too fast for currently available commercial robots.

SPOT WELDING

Process in which 2 sheet metal parts are fused together by passing a large electric current through the part where the weld is to be made.

ROBOTS FOR SPOT WELDING

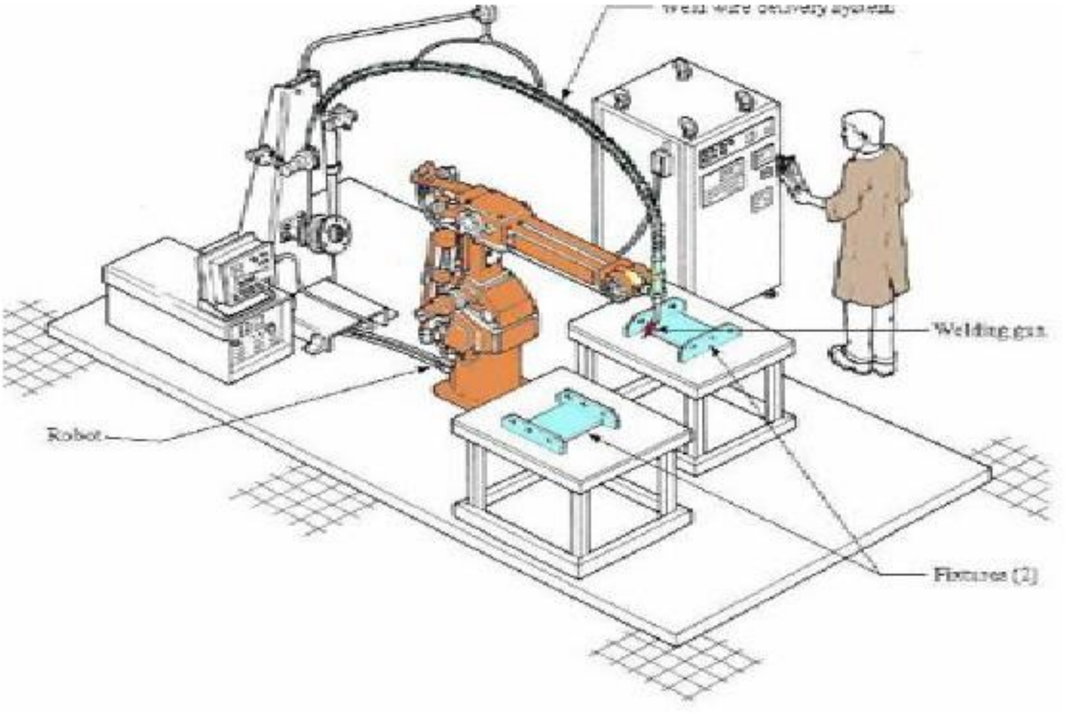
A welding gun is attached as the end effector to the robot's wrist.

Advantages of robots use in spot welding: Improved quality, Operator safety, Better control over production operation.Features of robots for spot welding: Relatively large. Sufficient payload to manipulate the welding gun. Work volume must be adequate for the size of product. Position and orient the weld gun in places difficult to access. Controller memory should have enough capacity.

Operation - Spot Welding

Two Electrodes are in the shape of Pincer. When this pincer opens the electrodes are positioned at the point where the metal part has to be fused. Prior clamping or fixing of the part is must. Electrodes are squeezed together and current is applied so a large heat is produced at that point. This heat fuses the metal parts together.

ARC (Continuous) WELDING



- It's a continuous welding process.

- Used to make long welded joints in which airtight seal is required between the two metal pieces which are to be joined together.

- Electrode in the form of rod or metal wire is used.

- 100 to 300 Ampere current with 10 to 30 voltage is used.

- High temperature is used to create pool of molten metal to fuse the two pieces together.

Problems faced by Human operatorUnpleasant and Hazardous Environment. • The Arc creates ultraviolet radiation which is harmful to human eyes.

- For this they use Dark window/Glass. It effectively filters these radiations but the welder is virtually blind while wearing it except when there is arc.

- High temperatures, sparks, Smoke are also potential threat.

ARC (Continuous) WELDINGProblems in Robot arc welding: Variations in the components to be welded. To compensate these variations and irregularities correct the upstream production operation so that the variations are reduced to a point where they do not create problem in arc welding.

Provide the robot with sensors to monitor the variations and control logics to compensate for part variations.There are a variety of arc welding process. For robot arc welding Gas Metal Arc Welding (GMAW) and Gas Tungsten Arc Welding (GTAW) are used. GMAW also known as MIG welding (Metal Inert Gas Welding) involves the use of a welding wire made of same or similar metals as the parts being joined. The weld wire acts as a welding electrode. In GTA welding (also known as Tungsten Inert Gas Welding) a tungsten rod is used as electrode to establish the arc. Tungsten had high melting point so the electrode doesn't melt during the fusion process.

The filler materials have to be added separately. GTA is used for welding aluminium, copper, stainless steel, etc.. In both these types inert gases such as helium and argon are used to surround the welding arc to protect the fused surfaces from oxidation. In GMA the electrode is continuously supplied from a coil and contributes to the molten metal pool, used in the fusion process.

Features of welding robots:

Work volume and degree of freedom.
Motion control system
Precision of motion
Interface with other system Programming

SENSORS IN ROBOT ARC WELDING: Contacting type and Non Contacting type Vision Based Systems.

ADVANTAGES OF Robot ARC WELDING:

Higher productivity,
Improves safety & quality of work cycle
Greater quality of product,
Process rationalization

SPRAY PAINTING AND ASSEMBLY :

Immersion and floor coating methods [bath type]. low technology methods. Here the part is dipped into the paint tank of liquid paint. when object removed the excess paint drains back to the tank. in flow type, part is positioned above the tank & stream of paint flow over the object. Spray Coating method.A new technique used is electro deposition Method: The part to be painted is given Negative charge and dipped into water containing suspended particles of paint. Paint particles are given Positive charge, and consequently they are attracted towards negative charged part.The next major industrial painting is Spray Coating.

- It comes with air spray, airless spray & electrostatic Spray.
- This involves use of spray guns to apply paint on the part or object.
- Air spray uses compressed air mixed with paint to atomize it into high velocity stream, which is directed out towards the object through the nozzle.
- Air less spray uses liquid paint to flow through the nozzle under high pressure instead of pressurized air.

This makes the liquid to break up into fine droplets. Electrostatic spray method uses either air spray or airless spray guns.

- Here the object is electrically grounded and the paint droplets are given Negative charge.
- This makes the paint to get fixed on the object evenly.
- Problems faced by human operators:
  - (a) Fumes & Mist in air
  - (b) Noise in the nozzle
  - (c) Fire Hazards
  - (d) potential cancer Hazards

FEATURES OF SPRAY COATING ROBOTS:

Continuous path control.Manual lead through programming.Multiple program storage.Benefits / Advantages: It saves human operators from hazardous environments. Low energy consumption, Consistency of finish. Reduced usage of coating material. Greater productivity. Other processing operations where robots can be used:- Drilling, Routing, Grinding, Polishing, Reverting, Water jet cutting, Laser drilling and cutting etc.Robots in Assembly operationsAssembly -fitting together of two or more parts to form new thing.

- Traditionally automation is done in high volume productions.
- By using robots low & medium volume productions can also be automated effectively.
- Main areas in which we can use robots are: Parts presentation methods, Assembly Tasks

Parts Presentation methods: When the robot has to perform assembly task operation, the parts has to be presented to it.

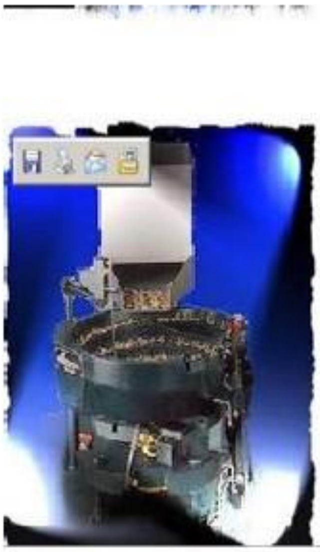
For this several ways can be used as given below:

(1) Parts located in a specific area. [Parts not positioned or oriented]
(2) Parts located at a known position [parts not oriented]
(3) Parts located at a known position & orientation.

There are lot of methods used to present part which is in a known position & orientation such as

(1) Bowl Feeders
(2) Magazine Feeders
(3) Trays & Pallets etc.,

Bowl feeders



Used to feed & orient small parts in automated assembly operations.

(a) Bowl

(b)Vibrating base

A track rising in a spiral up the side of bowls is used to feed the parts as shown in the diagram.Base contains leaf spring & oscillatingelectromagnet which causes the Track & Bowl to vibrate. To orient the parts in right way we use two methods.

(1) Selection- taking parts that are not properly oriented & rejecting them. (sent back to bowl to reorient themselves)

(2) Orientation - Physically reorienting the parts. Both methods use series of obstacles through which the parts are allowed to travel.

- Obstacles physically change the orientation of the parts when they move over it.

- Exiting parts travel down to some holding fixture (located @ outlet point of bowl feeder ,so gravity is used to deliver the part.)

Disadvantages:

BACK PRESSURE Due to parts lying along the track leading to holding fixture.

- Result of two forces (a) force due to vibration in track and (2) force due to weight of all parts present in the track.

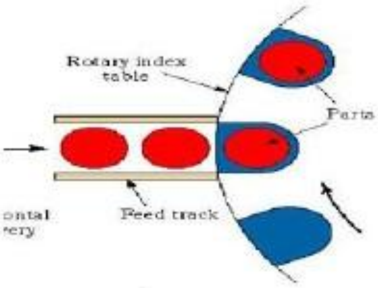
- It doesn't allow the robot to move the part successfully.
- Mainly used to reduce the back pressure.
- Other ways are to reduce the back pressure by(1) making the angle to holding fixture relatively small and (2) to turn off the vibrator when enough no of parts present in the track.

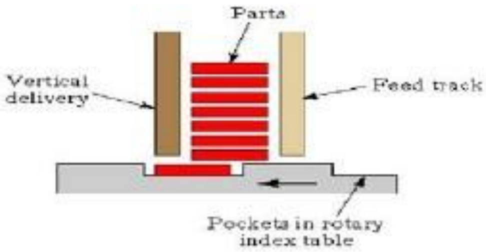
VARIOUS ESCAPEMENT &PLACEMENT DEVICES

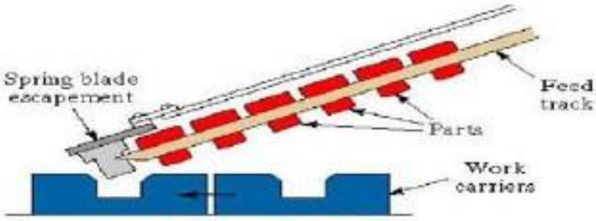
Magazine Feeders

Bowl feeders - used for bulk parts received at work station, but when doing this orientation gets changed. This is a major disadv of bowl feeders. Alternative method is using Magazine Feeders. This method transfers the pblm of orientation from the work station. Parts are feed in an orderly pre oriented way. Parts are loaded in a tube like arrangement or container, in a oriented way. (Usually any o/p from production process will have a orientation.)

- This container is known as Magazine.
- An Escapement device is used to remove the parts from the magazine.







- If the parts can't be loaded directly to the magazine then it has to be done manually.but then there is no use for magazine feeder in this case. Trays & Pallets Main Advantage is they can be used for variety of different part geometries.

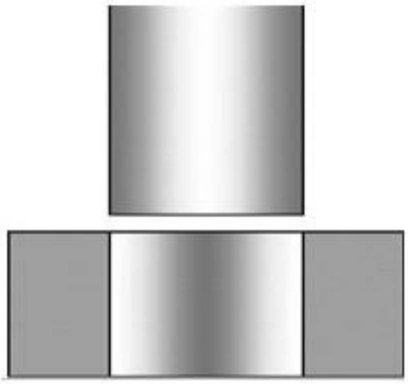
- Conditions to be satisfied to use pallet & tray are part should be in known location & orientation. If cycle time is large & tray size is also large then manual presentation is required. If cycle time is very fast then an automated operation of part presenting is needed.

Bin picking is an alternative procedure. Robots in Assembly Operations (tasks)Divided into two categories:

(1) Part mating - Two or more parts are brought into contact.

(2) Part joining - Parts mated & then additional steps used to make the parts to be together with each other. Part mating: Peg-in-hole. Hole-on-peg. Multiple peg-in-hole. Stacking.

Peg-in-hole



It involves the insertion of onepart into another. It's a common assembly task. Can be of two ways

(1) **Square peg in hole** - where base object is rectangle or square in shape and inserting object is square type. [Hole is square in shape]

(2) **Round peg in hole** - base part is rectangle & the part to be mated is circular [Hole is circular/round in shape].

Hole-on-peg: inverse of peg -in-hole method.

- Need better DOF for putting the peg into the hole.
- Needs better compliance.
- Example: Placing of a gear onto the shaftMultiple peg-in-holeAnother version of peg-in-hole.
- One part has multiple pegs & the other corresponding part has multiple holes.
- Example: mounting of microelectronic chip into a circuit. multiple pin chip is joined on circuit board with appropriate holes.

Stacking

Several components are placed one on top of the other with no pins or devices for locating the parts relative to each other Example: motor armature or transformer in which individual laminations are stacked over the other.Parts joining tasksIncludes Mating & fastening (holding) procedures.

(1) Fastening screws: common method, self tapping screws are used. uses rotation & simultaneous advancing (drilling). Power screw drivers are used.

(2) Retainers: Pins inserted through several parts in order to retain the mated parts together.

(3) Press fits: here peg is slightly larger than the hole. Extra force is needed to accomplish the task.

(4) Snap fit: Has both benefits of retainers & Press fitting techniques. Involves joining of parts where one part elastically deforms to accommodate the other part.

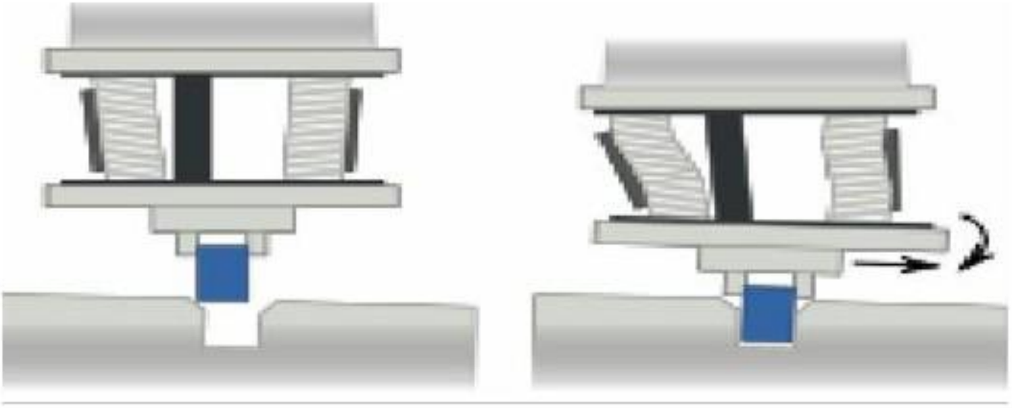
(5) Welding & related joining methods: Continuous & Spot welding are used.

(6) Adhesives: Glue or other adhesives can be applied to join parts by making adhesive bed on a part, along a path where second part is to be placed or applying glue at selected points & joining the parts together.

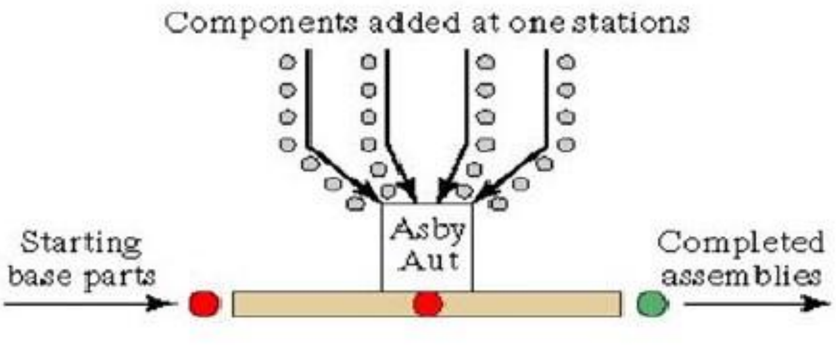
(7) Crimping: Deforming a portion of one part to fasten it with other part.

(8) Sewing: used only in soft, & flexible parts.

REMOTE CANTERED COMPLIANCE(RCC)



Compliance - is a measure of the amount in angle or distance that a robot axis or end effectors will move when a force is applied to it. Remote centred compliance(RCC) is a mechanical device that facilitates automated assembly by preventing peg-like objects from jamming when they are inserted into a holeAssembly system configurationsDefinition The use of mechanized and automated devices to perform various assembly tasks in an assembly line or cell .When to use Automated Assembly System High product demand Stable product design A limited number of components in the assembly Product designed for automated assembly Types Single workstation Series workstation parallel workstation etc., Assembly configuration - Single work station All the parts are presented to the robot @ a single work station. • All the tasks are accomplished at the single workstation. Generally used for low volume products with limited no of assembly tasks. Needs only less capital expense **Disadvantage:** not very fast, less reliable if more parts to be assembled, gripper or tool design is complex.



Most common configuration

- Used in medium & high production situations.
- Assembly line consists of series of workstations, with each station performing few operations on the product.
- Product gradually builds up as they move down the line.
- Continuous, synchronous or asynchronous transfer systems can be used with the in-line configuration Series or in line assembly

Dial type assembly machine –

- Series Operations
- Parallel operations

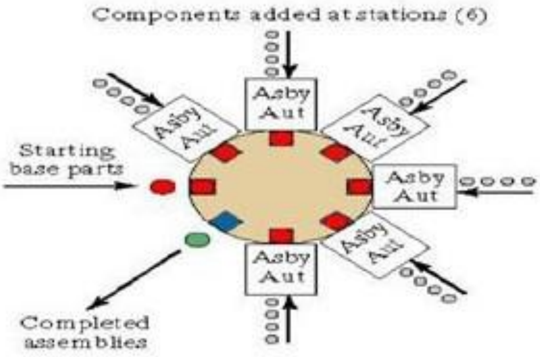
Same operations are performed in two or more routes.

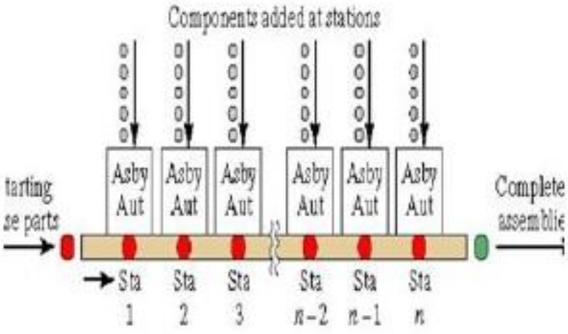
- Based on Two conditions parallel operations can be considered.

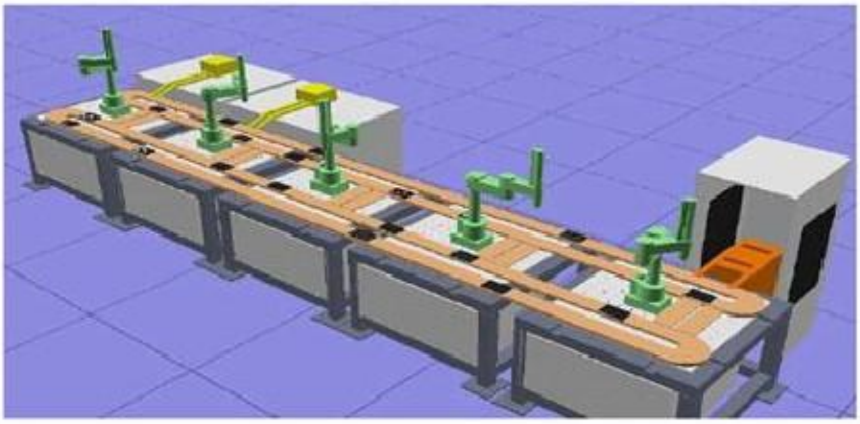
(1) When production cycle time is too long in one line when compared with other sections.

(2) Reliability - when break down occurs in one line then other parallel line can be used to perform the task without actually shutting the process Inspection Systems Why?

- Used for quality inspections of products.
- Used to Identify the part position & Orientation of parts.
- Testing of Equipments or parts
- Performance Analysis
- Interfacing with other hardware's etc.







VISION INSPECTION SYSTEM

Acts as a sensor, which is used for inspection purpose. Capable of 2D scene analysis applications

- Part location
- Part identification
- Bin picking etc.,

Vision Inspection System Robot Role

(1) To present the part to the vision system in proper position & orientation

(2) To manipulate (movement) the vision system

Factors/Requirements of machine vision system

- Resolution.
- Field of view (focusing)
- Special Lightning.
- Throughput etc.,

There are two types/methods. They are

(1) Robot Manipulated Inspection or Test Equipment. The robot moves the inspection or testing device around the part. Example: car body dimension measurement by moving electronic or LASER probe over the edges/corners of car.

(2) Robot Loaded Test Equipment used mainly in machine loading / unloading process. Mechanical, electrical, pneumatic gauges, functional testing devices can be connected to the robot end effecter for testing purposes.

Robot unloads a finished part & gives it to testing equipment where the product is tested. If the part is within tolerable limit its accepted and sent to next step for further processing otherwise part is rejected.This testing process acts as a feedback control system such that the tools can be adjusted based on test result. Functional test is widely used in electronics Industry. Quality & performance cannot be determined by the visual inspection process alone. So functional or performance test are used.