SRINIX COLLEGE OF ENGINEERING, BALASORE

DEPARTMENT OF MECHANICAL ENGINEERING

NAME OF THE SUBJECT-ROBOTICS

BRANCH-MECHANICAL ENGINEERING

SEMESTER-7^{TH}

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COURSE OUTLINES OF MODULE-I

1. **Fundamentals of Robotics: Evolution of Robots and Robotics.**
2. **Laws of Robotics and Definition of Industrial Robot.**
3. **Robot Anatomy with Robot Configuration.**
4. **Human Arm Characteristics.**
5. **Design and Control Issues.**
6. **Manipulation and Control.**
7. **Classification of Robot.**
8. **Workspace of Manipulator.**
9. **Resolution, Accuracy and Repeatability.**
10. **Economic and Social Issues.**
11. **Joints Used in Robot and its Representation.**
12. **Specification of Robot.**
13. **Present and Future Application.**
14. **Robot Teaching.**
15. **Economic Analysis with Case Studies.**
16. **Robot Controls.**
17. **Robot Kinematics and Direct Kinematic Model.**

References-1. Robotics and Control-R K Mittal & I J Nagrath-TMH Publication.
2. Robotics Technology-S R Deb & S Deb-TMH Publication.
3. Prof. D K Pratihar-IIT Kharagpur.

Introduction to Robotics :-

- Mankind has always strived to give life-like qualities to its artifacts in an attempt to find substitutes for himself to carry out his orders and also to work in a hostile environment.
- The popular concept of a robot is of a machine that looks and works like a human being. This humanoid concept has been inspired by science fiction stories and films in the twentieth century.
- The industrial robots of today may not look the least bit a human being although all the research is directed to provide more and more anthropomorphic and human-like features and super-human capabilities in these.
- To sum up, machines that can replace human beings as regards to physical work and decision making are categorized as robots and their study as robotics.
- The robot technology is advancing rapidly. The industry is moving from the current state of automation to robotization, to increase productivity and to deliver uniform quality.

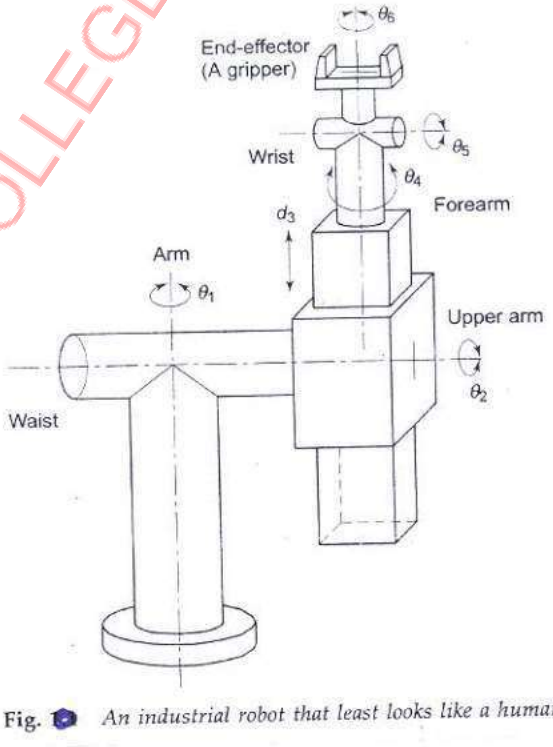


Fig. An industrial robot that least looks like a human

→ Robotics is a science, which deals with the issues related to design, manufacturing, usages of robots.

→ In robotics, we use the fundamentals of physics, mathematics, mechanical Engineering, Electronics Engineering, Electrical Engineering, computer sciences and others.

Motivation behind robot

To cope with increasing demands of a dynamic and competitive market modern manufacturing methods should satisfy the following requirements :

(1) Reduced production cost
(2) Increased productivity
(3) Improved product quality

Note - ① Automation can help to fulfill the above requirements

② Automation : Either Hard or Flexible automation

③ Robotics is an example of flexible automation.

- Production
  - Piece Production (No Automation)
  - Batch Production (Flexible Automation)
  - Mass Production (Hard Automation)

Interdisciplinary Areas in Robotics

Mechanical Engineering

① Kinematics - Motion of robot arm without considering the forces and/or moments.

② Dynamics - Study of the forces and/or moments.

③ Sensing - collecting information of the environment

Evolution of Robots and Robotics

- Czech writer, Karel Capek, in his drama, introduced the word robot to the world in 1921. It is derived from Czech (Chechoslovakian) word robota meaning "forced labourer".
- Isaac Asimov the well-known Russian science fiction writer, coined the word robotics in his story "Runaround" published in 1942, to denote the science devoted to study of robots.
- Joseph Jacquard's use of punched cards in mechanical looms, which laid the foundations for NC, CNC and automats, in addition to robotics.
- Numerical control (NC) works on control actions based on stored information that may include start and stop operations, coordinate points, actions, logic for branching and control sequences.
- Need of systems to work in hostile environments that human workers cannot easily or safely access (for example radioactive material handling) led to the development of teleoperated manipulator in 1940s.
- The field of "telecherics" deals with the use of remote manipulators controlled by a human being in a "master-slave" configuration. Here, the actual machine (slave) is operated from a distance by a control "joystick" of a geometrically similar machine (master) as shown in fig. (a)

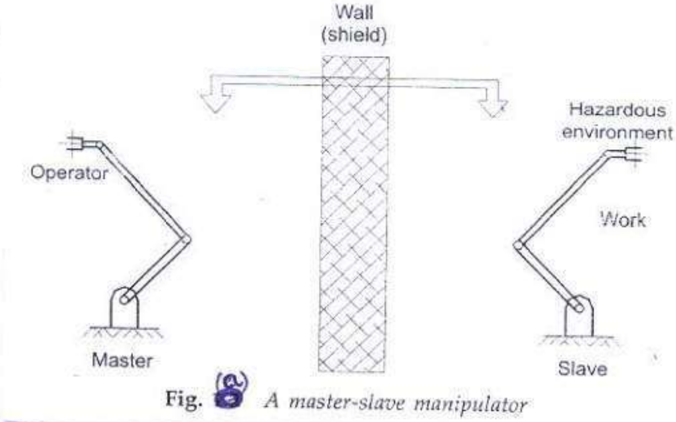


Fig. (a) A master-slave manipulator

* Father of robot - George Devol - 1954 (First patent on manipulator)

- The combination of Numerical control and telecherics have evolved the basic concepts of modern industrial robots with human operator and master manipulator of fig.(a) replaced by a programmable controller. This merging created a new field of engineering referred to as robotics and with it a number of engineering and scientific issues in design, control and programming have emerged, which are substantially different from those of the existing techniques.
- In 1938-39, a jointed mechanical arm was invented for use in spray painting.
- A process controller that could be used as a general-purpose playback device for operating machines was developed in 1946, the year in which first large-scale electronic computer ENIAC was built.
- The first numerically controlled machine tool was developed in 1952.
- The patenting of the first manipulator, with the basic concept of teaching/playback, in 1954, set rolling the exponential growth in robotics.
- The unmatched quality, reliability and productivity offered by these robots, although in very limited applications was recognized by the industry and sparked the formation of several world-wide centres of research in this area by the mid-1960s.
- The new field of robotics received support from simultaneously developing fields of artificial intelligence (AI), artificial vision and developments in digital microcomputers.
- In 1967-1968, the first legged and wheeled walking m/cs using vision and other sensors, were reported. The servomotors were used in place of hydraulic devices in 1970 to power the robots.

- In 1974, the first servomotor actuated and microcomputer controlled robots were commercially launched and in 1976, they were used by NASA Viking lander to collect samples from the surface of Mars.

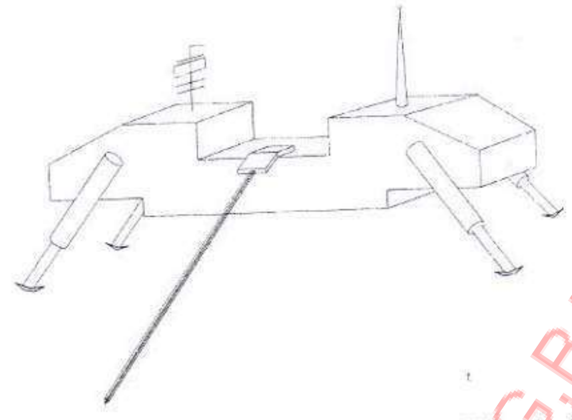


Fig. Sketch of a mobile robot, the kind used as Viking lander

- In 1975 saw the largest worldwide growth of university based laboratories, research centres, curricula and publications in robotics.
- The growth, thereafter in robotics has been closely associated with developments in microcomputers, micro-controllers, sensor technology, vision technology and artificial intelligence. The year 1997 saw the amalgamation of all these in the success of the Mars mission through "Pathfinder" and "Sojourner"
- Industrial robots are increasingly used in manufacturing plants, medical surgery and rescue efforts. These require more difficult technology as much higher degree of accuracy, repeatability, flexibility and reliability is needed for industrial robots.
- Robotics today is dealing with research and development in a number of interdisciplinary areas, including kinematics, dynamics, control, motion planning, sensing, programming and machine intelligence.

Laws of Robotics

Robots were required to perform according to three principles known as "three laws of robotics", which are as valid for real robots as they were for Asimov's robots and they are ÷

(1) A robot should not injure a human being or through inaction, allow a human to be harmed.

(2) A robot must obey orders given by humans except when that conflicts with the first law.

(3) A robot must protect its own existence unless that conflicts with the first or second law.

These are very general laws and apply even to other machines and appliances. They are always taken care of in any robot design.

Definition of Industrial robot

The British Robot Association (BRA) has defined the industrial robot as :

"A reprogrammable device with min^{m} of four degrees of freedom designed to both manipulate and transport parts, tools or specialized manufacturing implements through variable programmed motions for performance of specific manufacturing task".

The Robotics Industries Association (RIA) of USA defines the robot as :

"A reprogrammable, multifunctional manipulator designed to move material through variable programmed motions for the performance of a variety of tasks".

The definition adopted by International Standards organisation (ISO) ~~and~~

"An industrial robot is an automatic, servo-controlled, freely programmable, multipurpose manipulator with several areas for the handling of w/ps, tools or special devices.

Robot classification

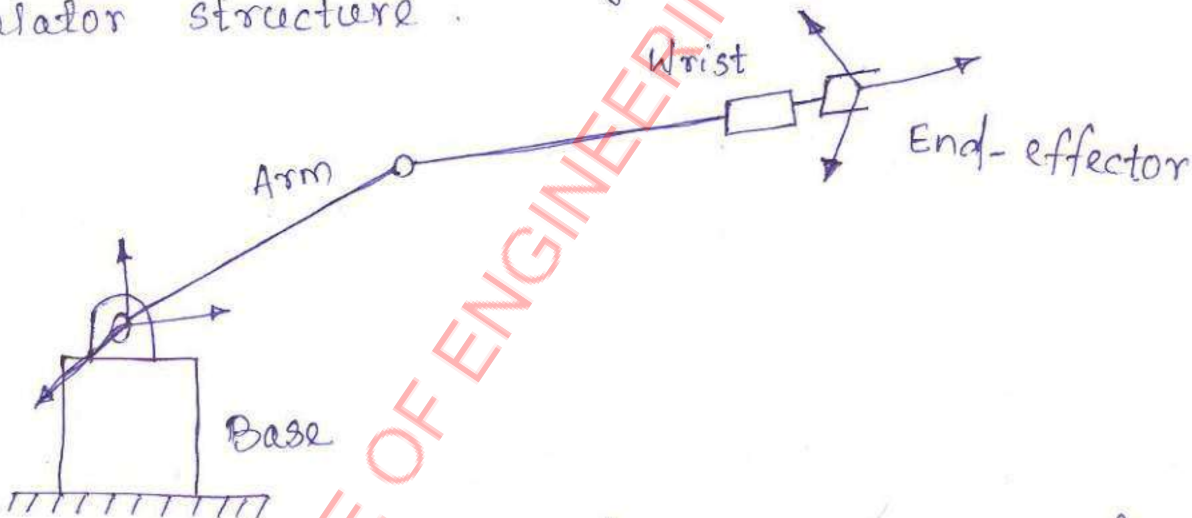
① Arm configuration
- cartesian coordinate
- cylindrical coordinate
- spherical coordinate
- scara coordinate
- Revolute coordinate

② Drive system
- Electrical
- Hydraulic
- Pneumatic

③ Drive gear system
- Direct Drive Robot
- Geared Robot.

Robot Anatomy

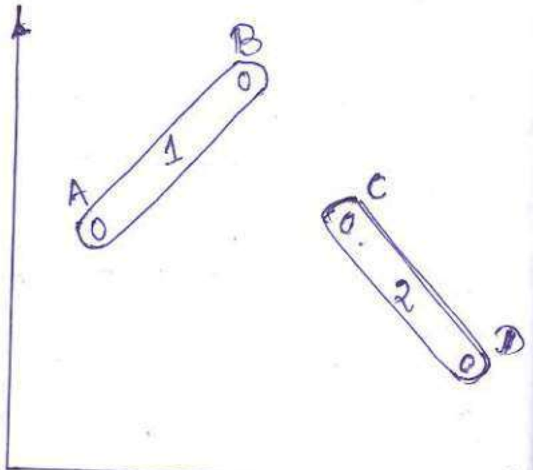
- The study of structure of robot is called robot anatomy. The mechanical structure of a robot is like the skeleton in the human body. The robot anatomy is the study of skeleton of robot i.e the physical construction of the manipulator structure.



The base, arm, wrist and end-effector forming the mechanical structure of a manipulator.

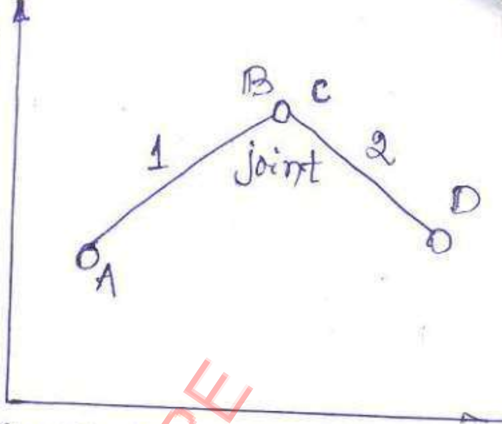
① Links :-

- The mechanical structure of a robotic manipulator is a mechanism, whose members are rigid links or bars. A rigid link that can be connected at most with two other links is referred to as a binary link.
- Fig.(a) shows two rigid binary links 1 & 2 each with two holes



[Two rigid binary links in free space [Fig.(a)] at the ends A, B & C, D respectively to connect with each other or to other links.

- Two links are connected together by a joint. By putting a pin through holes B and C of links 1 & 2 an open kinematic chain is formed as shown in fig.(b).
- The joint formed is called a pin joint also known as a revolute or rotory joint.



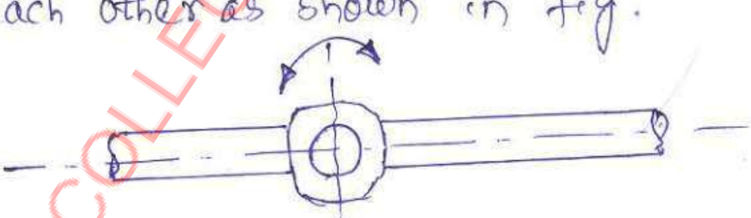
[fig.(b) An open kinematic chain formed by joining two links]

② Joints and Joint Notation Scheme:-

- Many types of joints can be made betn two links. However, only two basic types are commonly used in industrial robots. These are
  (i) Revolute (R) (ii) Prismatic (P)

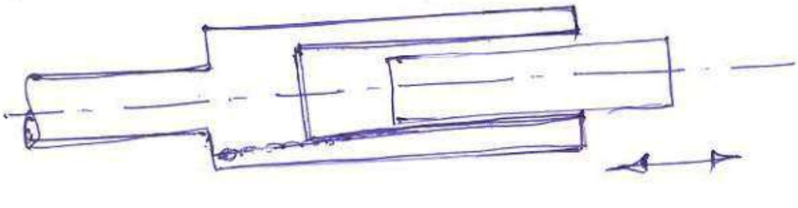
- The relative motion of the adjoining links of a joint is either rotory or linear depending on the type of joint.

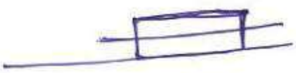
Revolute joint:- The two links are jointed by a pin (pivot) about the axis of which the links can rotate with respect to each other as shown in fig.



Revolute (R)

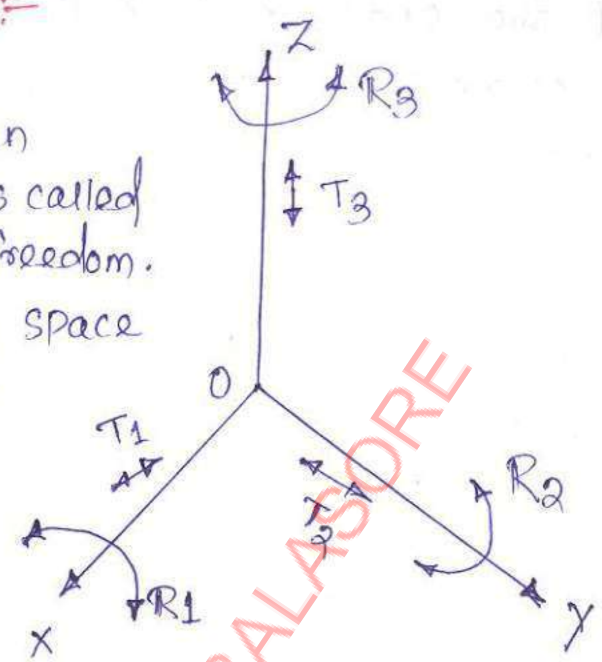
Prismatic joint:- The two links are so jointed that these can slide (linearly move) w.r. to each other. Screw & nut (slow linear motion of the nut), rack & pinion are ways to implement prismatic joints.





Prismatic (R)

③ Degrees of Freedom (DOF):-



- The number of independent movements that an object can perform in a 3-D space is called the number of degrees of freedom.
- Thus, a rigid body free in space has six degrees of freedom - three for position & three for orientation. The six independent movements shown in fig. are

[Representation of six degrees of freedom w.r.to a coordinate frame]

(i) three translations (T_1, T_2 & T_3) representing linear motions along three ⊥lar axes, specify the position of the body in space.

(ii) three rotations (R_1, R_2 & R_3) which represent angular motions about the three axes, specify the orientation of the body in space.

④ Required DOF in a manipulator :-

- It is concluded that to position and orient a body freely in 3-D space, a manipulator with 6-DOF is required. Such a manipulator is called a spatial manipulator. It has three joints for positioning and three for orienting the end-effector.
- spatial manipulators with more than 6-DOF have surplus joints and are known as redundant manipulators.
- The extra DOF may enhance the performance by adding to its dexterity. Dexterity implies that the manipulator can reach a subspace, which is obstructed by objects by the capability of going around these.

(5) Arm Configuration :-

- The mechanics of the arm with 3-DOF depends on the type of three joints employed and their arrangement. The purpose of the arm is to position the wrist in the 3-D space and the arm has following characteristic requirements

(i) Links are long enough to provide for max^m reach in the space.

(ii) The design is mechanically robust because the arm has to bear not only the load of o/p but also has to carry the wrist and the end-effector.

The four basic configurations are

(i) cartesian (rectangular) configuration - all three P joints (PPP)

(ii) cylindrical configuration - one R & two P joints (RPP)

(iii) Polar (spherical) configuration - two R & one P joint. (RRP)

(iv) Articulated (Revolute or Jointed-arm) configuration - all three R joints (RRR)

(v) other configurations (SCARA configurations) - Selective compliance Assembly Robot Arm

(i) Cartesian configuration

- This is the simplest configuration with all three Prismatic joints as shown in fig. It is constructed by three lar slides, giving only Linear motions along the three principal axes. There is an upper and lower limit for movement of each link.

- The endpoint of the arm is capable of operating in a cuboidal space called workspace.

- The workspace represents the portion of space around the base of the manipulator that can be accessed by the arm end point.

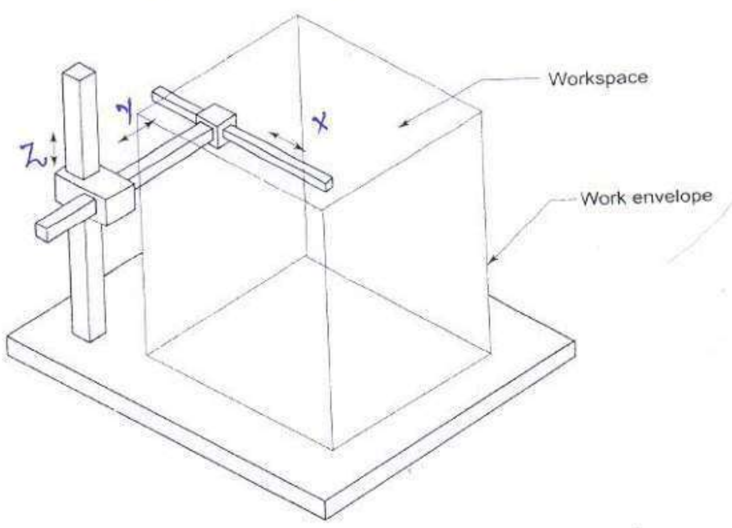


Fig. 6 A 3-DOF Cartesian arm configuration and its workspace

- The shape and size of the workspace depends on the arm configuration, structure, degrees of freedom, size of links and design of joints.
- The physical space that can be swept by a manipulator may be more or less than the arm endpoint workspace.
- The volume of the space swept is called work volume, the surface of the workspace describes the work envelope.

(ii) <u>cylindrical configuration:-</u>

- The cylindrical configuration pictured in fig. uses two lar prismatic joints and a revolute joint.
- The difference from the cartesian one is that one of the prismatic joint is replaced with a revolute joint.

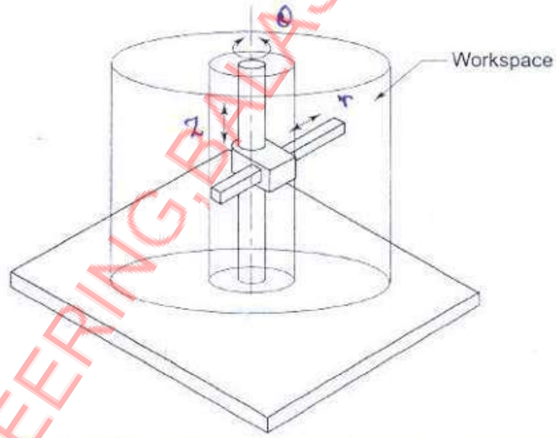


Fig. [illegible] A 3-DOF cylindrical arm configuration and its workspace

- The vertical column carries a slide that can be moved up or down along the column. The horizontal link is attached to the slide such that it can move linearly in or out w.r.to the column. This results in a RPP configuration.
- The arm endpoint is thus capable of sweeping a cylindrical space. To be precise, the workspace is a hollow cylinder as shown in fig. usually a full 360° rotation of the vertical column is not permitted due to mechanical restrictions imposed by actuators & transmission elements.
- The cylindrical configuration offers good mechanical stiffness and the wrist positioning accuracy decreases as the horizontal stroke increases. It is suitable to access narrow horizontal cavities and, hence, is useful for machine loading operations.

(iii) Polar (Spherical) Configuration :-

- The polar configuration as shown in fig. It consists of a telescopic link (prismatic joint) that can be raised or lowered about a horizontal revolute joint.
- These two links are mounted on a rotating base. This arrangement of joints known as RRP configuration, gives the capability of moving the arm end-point within a partial spherical shell space as work volume as shown in fig.

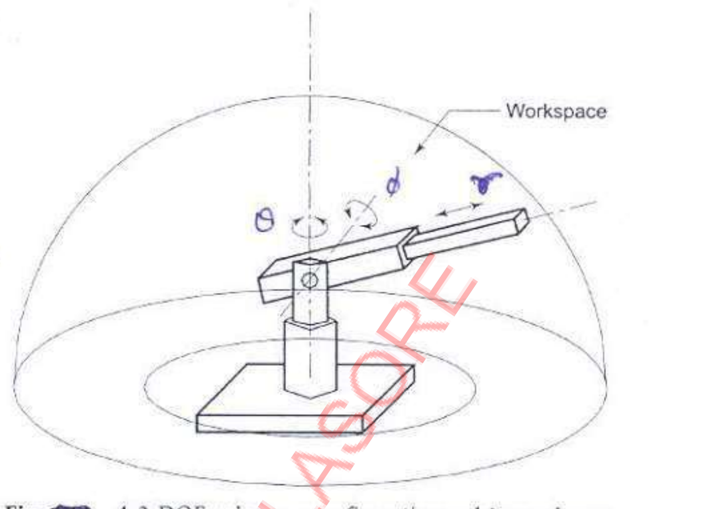


Fig. A 3-DOF polar arm configuration and its workspace

- This configuration allows manipulation of objects on the floor because its shoulder joint allows its end-effector to go below the base.
- Its mechanical stiffness is lower than cartesian and cylindrical configurations and the wrist positioning accuracy decreases with the increasing radial stroke.
- The construction is more complex. Polar arms are mainly employed for industrial applications such as machining, spray painting.

(iv) Articulated (Revolute or jointed-arm) configuration:-

- The articulated arm is the type that best simulates a human arm and a manipulator with this type of an arm is often referred as an anthropomorphic manipulator.
- It consists of two straight links, corresponding to the human forearm and upper arm with two rotary joints corresponding to the 'elbow' & "shoulder" joints.

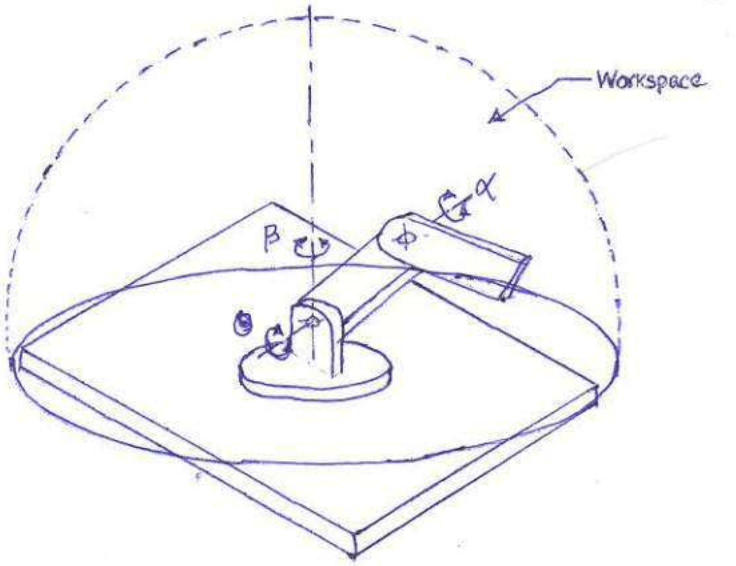


Fig. A 3-DOF articulated arm configuration and its workspace

- These two links are mounted on a vertical rotary table corresponding to the human waist joint. fig. shows the joint-link arrangement for the articulated arm.
- This configuration (RRR) is also called revolute because three revolute joints are employed. The work volume of this configuration is spherical shaped and with proper sizing of links and design of joints, the arm endpoint can sweep a full spherical space.
- The arm endpoint can reach the base point and below the base, as shown in fig. This anthropomorphic structure is the most dexterous one, because all the joints are revolute and the positioning accuracy varies with arm endpoint location in the workspace. The range of industrial applications of this arm is wide.

(v) Other configurations:-

- If the characteristics of articulated and cylindrical configurations are combined, the result will be another type of manipulator with revolute motions, confined to the horizontal plane. Such a configuration is called SCARA, which stands for Selective Compliance Assembly Robot Arm.

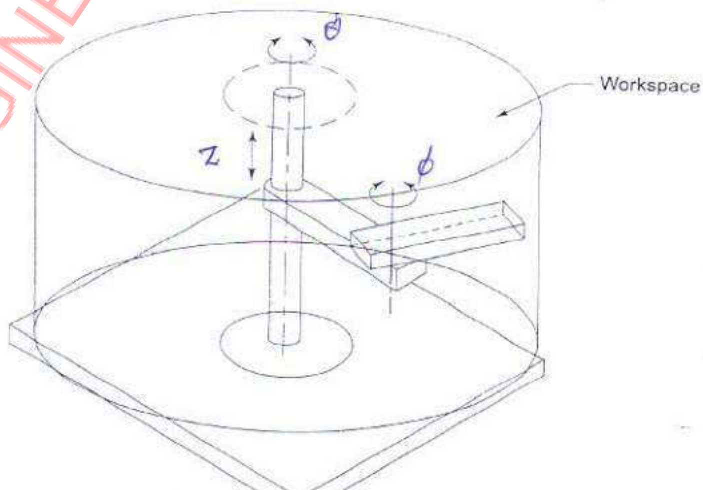


Fig. The SCARA configuration and its workspace

- This configuration provides high stiffness to the arm in the vertical direction and high compliance in the horizontal plane, thus making SCARA congenial for many assembly tasks.

⑥ Wrist configuration:-

- Wrist is the second part of a manipulator that is attached to the endpoint of the arm. The wrist subassembly movements enable the manipulator to orient the end-effector to perform the task properly, for example, the gripper (an end-effector) must be oriented at an appropriate angle to pick & grasp a w/p.

- For arbitrary orientation in 3-D space, the wrist must possess at least 3-DOF to give three rotations about the three principal axes.
- The wrist requires only rotary joints because its sole purpose is to orient the end-effector. A 3-DOF wrist permitting rotation about three perpendicular axes provides for roll (motion in a plane perpendicular to the end of the arm), pitch (motion in vertical plane passing through the arm) and yaw (motion in a horizontal plane that also passes through the arm) motions. This type of wrist is called roll-pitch-yaw or RPY wrist.

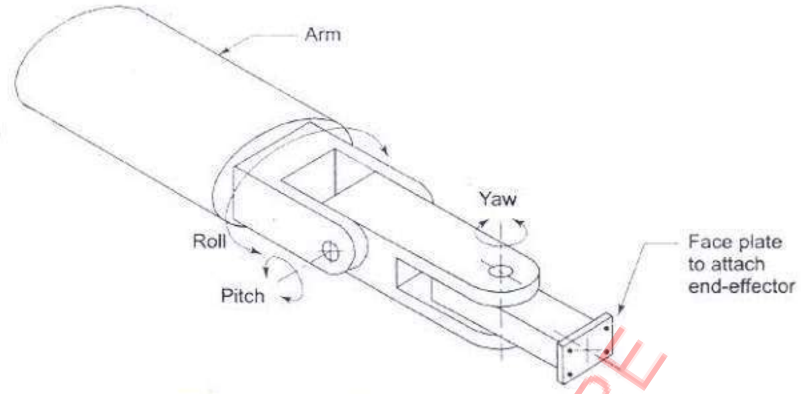


Fig. A 3-DOF RPY wrist with three revolute joints

⑦ The End-effector :-

- End effector is a device that is attached to the end of the wrist arm to perform specific task.
- A robot performs a variety of tasks for which various tooling and special grippers are required to be designed. A robot manipulator is flexible and adaptable, but its end-effector is task-specific.

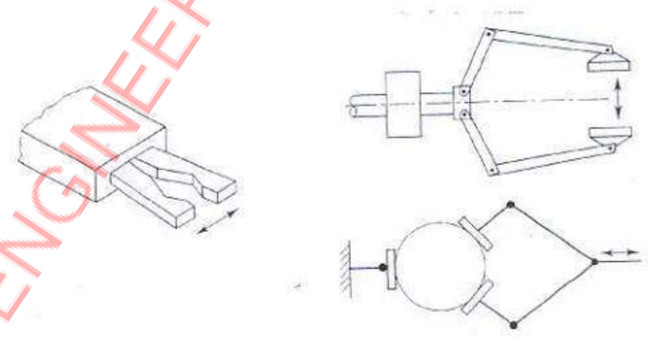


Fig. Some fingered grippers for holding different types of jobs

- A gripper designed for picking up a tool to be fitted to a CNC machine tool is not suitable for welding a railway wagon.
- The wide range of gripping methods include
  - Mechanical clamping
  - Magnetic gripping
  - Vacuum (Suction) gripping
- Mechanical type of grippers may simply use mechanical clamping with vice-type mechanism, it may use hooking or lifting mechanisms and mechanisms for scooping or ladling powders, molten metal or plastics.

- Mechanical type of grippers find wide applications in forging and metal working industry.
- Magnetic grippers may be employed for transfer of steel sheets or chips.
- Vacuum cups may be used for transfer of sheets of glass, plastic or thin sheets of papers.

Robot Anatomy with neat sketch :-

Robot anatomy is concerned with the physical construction and characteristics of the body, arm & wrist, which are the component of the robot manipulator. which consists of a number of component that allowed be oriented in a variety of position movements betn the various components of the body, arm and wrist are provided by a series of joints. These joint movements usually involve either rotation or sliding motions.

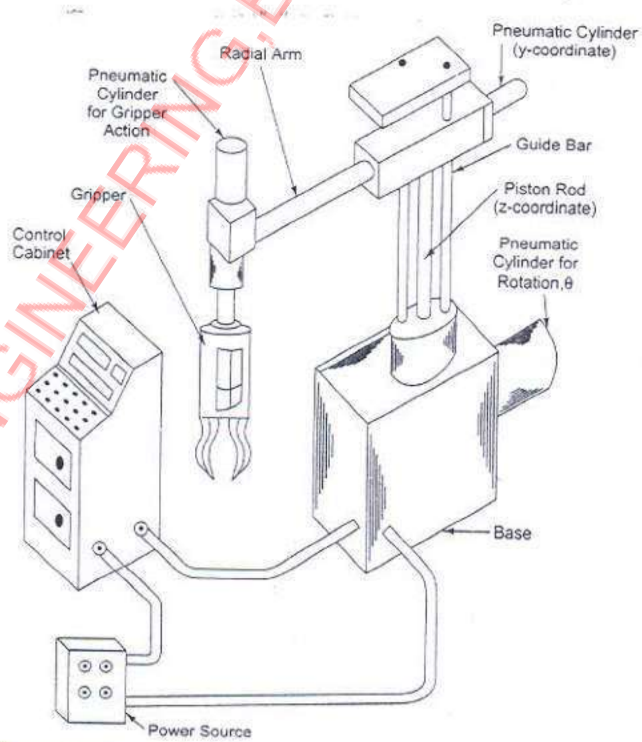


FIG. A robotic system

① Base - Fixed or mobile
② The manipulator - arm which several DOF.
③ The end-effector or gripper - holding a part or tool.
④ Drives or Actuators - causing the manipulator arm or end effector to move in a space.
⑤ controller - with hardware & software support for giving commands to the drives.
⑥ sensors - To feed back the information for subsequent action of the arm or grippers as well as to interact with the environment in which the robot is working.
⑦ Interface - connecting the robot subsystem to the external world.

Human arm characteristics

- The human arm and its capabilities make the human race class apart from other animals. The design of the human arm structure is a unique marvel and is still a challenge to replicate. Certain characteristics of the human arm are a far cry for today's manipulators.
- It is, therefore, worth considering briefly human arm's most important characteristics as these serve as a benchmark for the manipulators.
- The human arm's basic performance specifications are defined from the zero reference position which is the stretched right arm and straight out and horizontal with the palm in downward direction.
- The three motions to orient the hand, which is the first part of human arm are approximately in the following range.

$$-180^\circ \le \text{Roll} \le +90^\circ$$

$$-90^\circ \le \text{Pitch} \le +50^\circ$$

$$-45^\circ \le \text{Yaw} \le +15^\circ$$

- Note that to provide the roll motion to the hand, forearm and upper-arm, both undergo a twist, while pitch & yaw are provided by the wrist joint. The second part of the human arm consists of upper arm and forearm with shoulder and elbow joints. It has 2-DOF in the shoulder with a ball and socket joint, 1-DOF in the elbow betn forearm and upper-arm with two bones in the forearm and one in upper arm.
- The 2-DOF shoulder joint provides an approximately hemispherical sweep to the elbow joint. The elbow joint moves the forearm by approximately 170° (from −5° to 165°) in different planes, depending on the orientation of two forearm bones & the elbow joint.

- Another important feature of the human arm is the ratio of the length of the upper arm to that of the forearm, which is around 1.2.
- A mechanical structure identical to the human arm, with 2-DOF shoulder joint, three-bones elbow joint, eight-bones wrist joint with complicated geometry of each bone and joint, is yet to be designed & constructed.
- The technology has to go a long way to replicate human arm's bone shapes, joint mechanisms, mechanism to power and move joints, motion control, safety & above all, self repair.

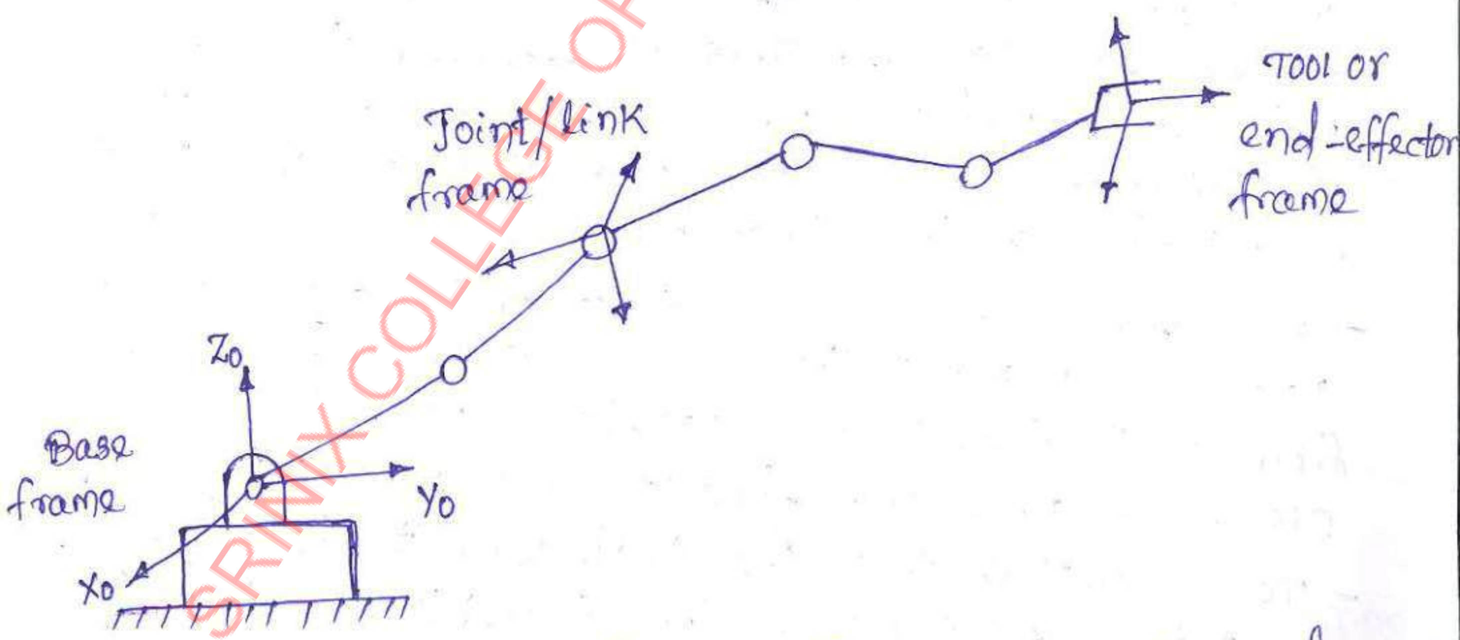
Design and control Issues

- Robots are driven to perform more and more variety of highly skilled jobs with minimum human assistance or intervention. This requires them to have much higher mobility, manipulatability and dexterity than conventional machine tools.
- The mechanical structure of a robot, which consists of rigid cantilever beams connected by hinged joints forming spatial mechanism is inherently poor in stiffness, accuracy and load carrying capacity.
- The errors accumulate because joints are in a serial sequence. These difficulties are overcome by advanced design and control techniques.
- The weight and inertial load of each link is carried by the previous link. The links undergo rotary motion about the joints, making centrifugal and coriolis effects significant.
- All these make the dynamic behaviour of the robot manipulator complex, highly coupled and nonlinear.
- The kinematic and dynamic complexities create unique control problems that make control of a robot a very challenging task and effective control system

design a critical issue. The robot control problem has added a new dimension in control research.

Manipulation and control

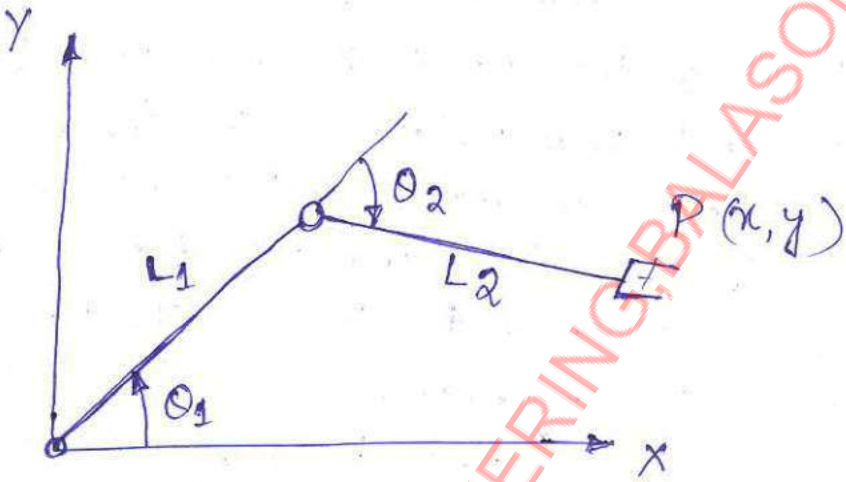
- In the analysis of spatial mechanisms (manipulators), the location of links, joints and end-effector in 3-D space is continuously required. Mathematical description of the position and orientation of links in space and manipulation of these is, naturally, one topic of immediate importance.
- To describe position and orientation of a body in space, a frame is attached to the body. The position and orientation of this frame w.r.to some reference coordinate frame, called base frame; mathematically describes the location of the body.
- Frames are attached to joints, links, end-effector and workpieces in the environment of the robot to mathematically describe them as shown in fig.



(Attachment of frames for manipulator modelling)

- consider the simplest nontrivial two-link planar manipulator as shown in fig. with link lengths (L_1, L_2) and assume that the joint angles are (θ_1, θ_2) and

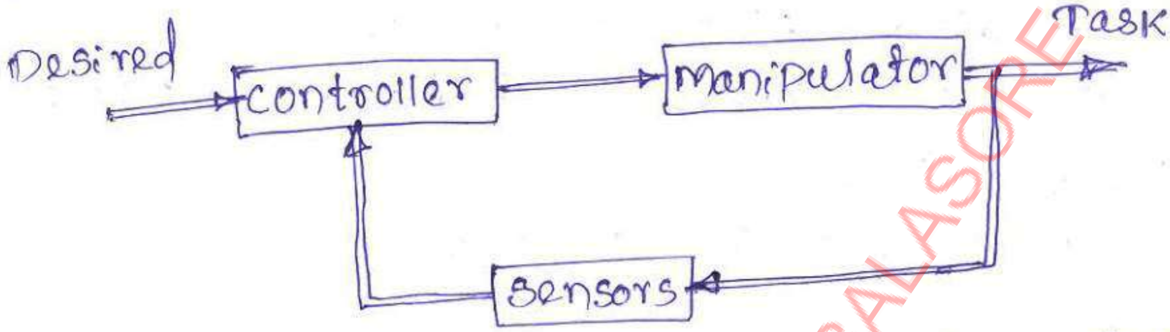
the coordinates of end-effector point P are (x, y)
- from simple geometrical analysis for this manipulator, it is possible to compute coordinates (x, y) from the given joint angles (θ_1, θ_2) and for a given location of point P (x, y), joint angles (θ_1, θ_2) can be computed.



(The 2-DOF two-link planar manipulator)

- The basic problem in the study of mechanical manipulation is of computing the position and orientation of end-effector of the manipulator when the joint angles are known. This is referred to as forward kinematics problem. The inverse kinematics problem is to determine the joint angles, given the position & orientation of the end-effector.
- To perform an assigned task or to attain a desired position, a manipulator is required to accelerate from rest, travel at specified velocity, traverse a specified path and finally decelerate to stop.
- To accomplish this, the trajectory to be followed is computed. To traverse this trajectory, controlling torques are applied by the actuators at the manipulator joints.
- These torques are computed from the equations of motion of the manipulator, which describe the dynamics of the manipulator.

- The dynamic model is very useful for mechanical design of the structure, choice of actuators, computer simulation of performance, determination of control strategies and design of control system.



(A Schematic sketch of a manipulator control system)

- The tasks to be performed by the manipulators are (i) to move the end-effector along a desired trajectory and (ii) to exert a force on the environment to carry out the desired task.
- The controller of manipulator has to control both tasks, the former is called position control (trajectory control) and the latter force control.
- A schematic sketch of a typical controller is shown in fig. above. The position, velocities, forces and torques are measured by sensors and based on these measurements and the desired behaviour, the controller determines the inputs to the actuators on the robot so that the end-effector carries out the desired task as closely as possible.

Interdisciplinary Areas in Robotics

Mechanical Engineering

① Kinematics - Motion of robot arm without considering the forces and moments.

② Dynamics - study of forces or moments.

③ Sensing - collecting information of the environment.

Computer Science.

① Motion Planning : Planning the course of action

② Artificial intelligence : to design & develop suitable brain for the robots

Electrical and electronics Engg.

① control schemes & hardware implementations

General Sciences

① Physics ② Mathematics

Degrees of Freedom of a System

It is defined as the minimum number of independent parameters/ variables/ coordinates needed to describe a system completely.

Notes ① A point in 2-D: 2 dof, in 3-D space : 3 dof

② A rigid body in 3-D : 6 dof

③ Spatial Manipulator : 6 dof

④ Planar Manipulator : 3 dof

Classification of Robots

Based on the type of Tasks Performed

① Point-to-point Robots

Ex:- Unimate 2000

T^3 (The Tomorrow Tool)

② Continuous Path Robots

Ex:- PUMA (Programmable Universal Machine for Assembly)

CRS (Common Robotic System)

② Based on the Type of controllers

(i) Non-servo-controlled Robots

– open-loop control system

Ex- Seiko PN-100

Less accurate & less expensive

(ii) closed-loop control system

ex- unimate 2000, PUMA, T^3

more accurate and more expensive

③ Based on configuration of the Robot

(i) cartesian coordinate robots

(ii) cylindrical coordinate robots

(iii) spherical or Polar coordinate robots

(iv) Revolute or Articulated coordinate robots

④ Based on mobility levels

(i) Robots with fixed base (also known as manipulators)

Manipulators
- serial, PUMA, CRS
- parallel, stewart platform

(ii) Mobile robots
- wheeled robots
- Tracked robots
- Multi-legged robots

Workspace of Manipulators

It is the volume of space that the end-effector of a manipulator can reach.

① Dextrous workspace :- It is the volume of space, which the robot's end-effector can reach with various orientations.

② Reachable workspace :- It is the volume of space that the end-effector can reach with one orientation.

- The work envelop is described by the surface of the work space.
- The volume of the space swept by the robot arm is called work volume.

Resolution

It is defined as the smallest allowable position increment of a robot.

① Programming resolution - Smallest allowable position increment in robot programme. Basic Resolution unit (BRU) = 0.01 inch/0.1 degree

② control resolution - smallest change in position that the feedback device can measure say 0.36°/Pulse

Accuracy

It is the precision with which a computed point can be reached.

The accuracy of a measurement system is the degree of closeness of measurements of a quantity to that quantity's true value.

Repeatability

It is defined as the precision with which a robot re-position itself to a previous tought point.

Economics Issue

- Robot economics is the study of the market for robots.
- The following are a variety of ways that robots affect the economy.

① The Rise of the Machines:- Technology has played a role in making work more efficient for thousands of years, from simple farming tools to current-day assembly-line robots in factories. while it is certainly true that robots are replacing jobs and are a significant threat to low-skilled workers & somewhat of a threat to middle-skilled workers, there are many positive effects that robots have on the economy.

② Productivity Growth:- Higher living standards can come about through higher wages, lower pricing of goods and services and an overall greater variety of products and services. Labour productivity growth as measured as o/p per hour is what leads these things to occur.

Growth results from one or a mixture of three things:- increases in the quality of labour, increases in capital and total factory productivity (TFP), also known as multi-factor productivity.

③ Gross Domestic Product Growth:-

④ Job creation:- Many people fail to realize that robots are actually creating new, high-paying jobs that require skilled workers. While it is true that robots are replacing low-skilled workers and automating the tasks that they perform, robots and automation are requiring jobs that focus workers on higher-value work.

Social Issues

The different sets of issues are given below

① productivity and capital formation labour
- unemployment, displacement, or job shifting

② positive and negative effects on the quality of working environment
- Exposure to hazards, job boredom and employer/employee relations.

③ Education and training
- Need for technological specialists
- Need for a technologically literate workforce
- Need for retraining workers

④ International impacts
- Import/Export of robotics technology
- contribution to economic competitiveness

⑤ other applications
- military, space, oceans

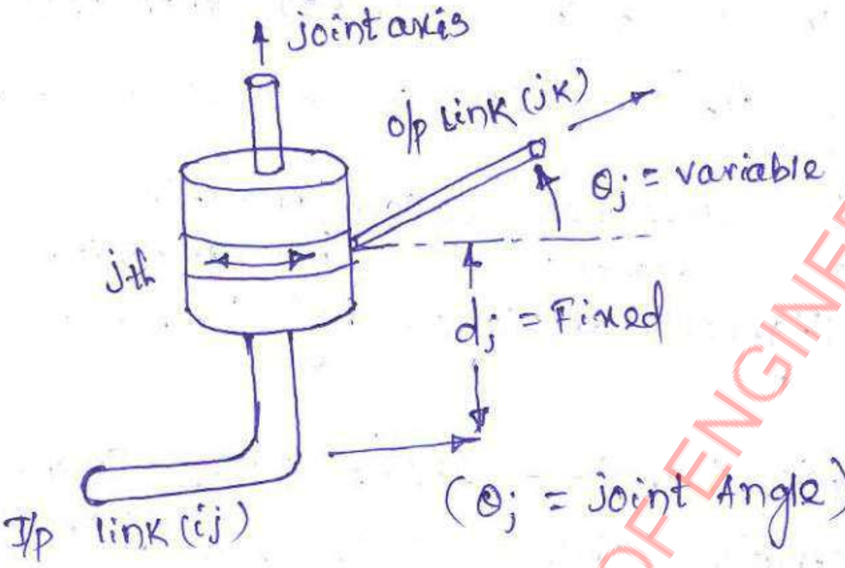
Joints used in Robot

① Linear joint [Prismatic / Sliding

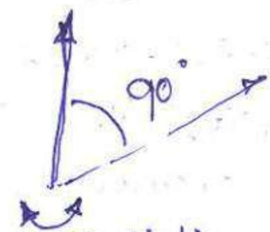
② Rotary joint [Revolute / Twisting

* Degree of freedom or connectivity – How many rigid link can be connected to one fixed link through that particular joint.

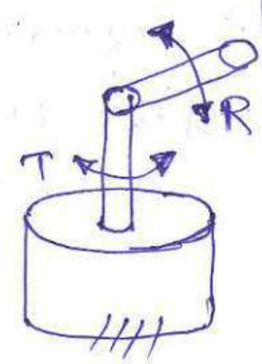
– It indicates the number of rigid bodies that can be connected to a fixed rigid body through the said joint.



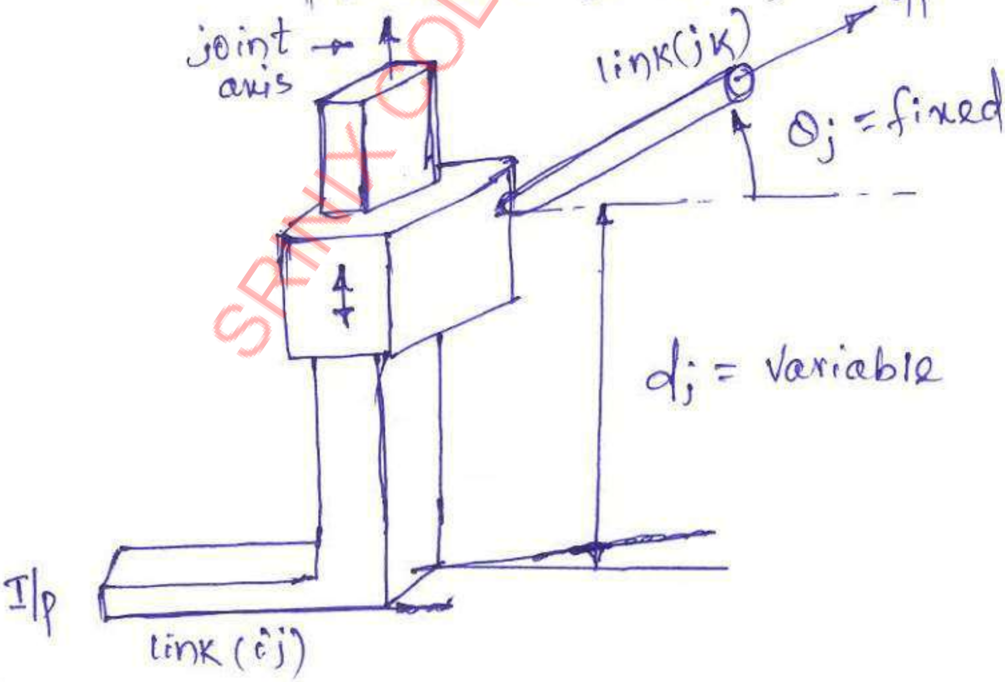
Joints with one DOF
Revolute joint (R)



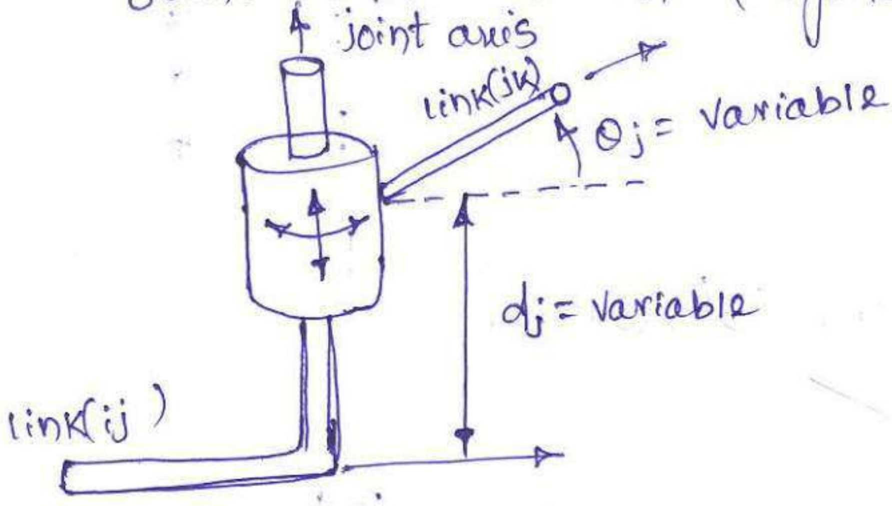
Twisting joint



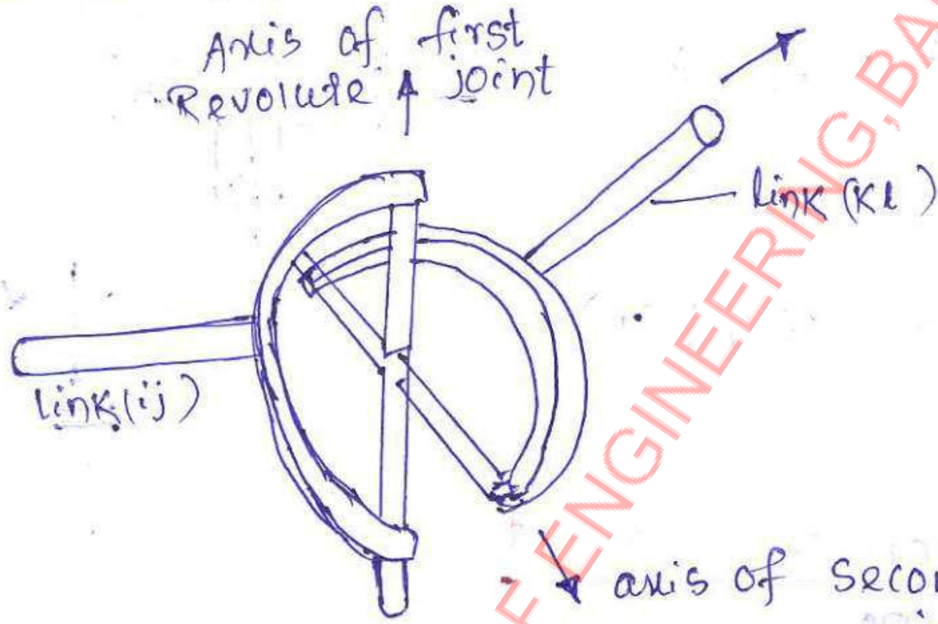
Joints with one DOF
prismatic joint (P)



Joints with two DOF (cylindrical joint(C))



Joints with two dOF
Hooke joint or universal joint

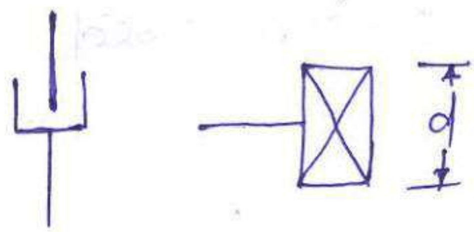


* Joints with three DOF - Ball Socket Joint
Spherical Joint

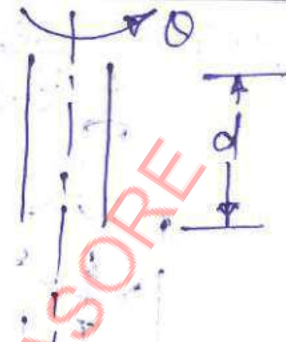
Representation of the Joints

(1) Revolute Joint (R)

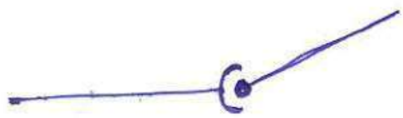
(2) Prismatic Joint (P)



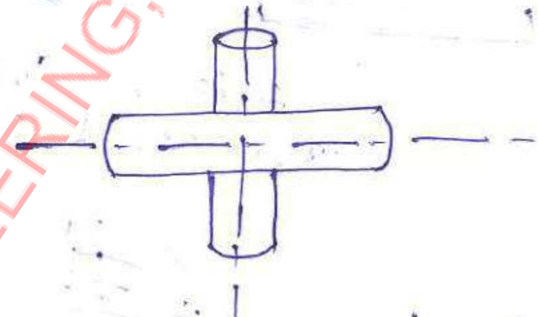
(3) Cylindrical Joint (C)



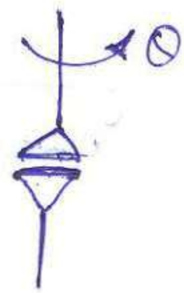
(4) Spherical Joint (S')(S-prime)



(5) Hookes Joint (U)



(6) Twisting Joint (T)



Specification of a Robot

(1) control type
(2) Drive system
(3) coordinate system
(4) Teaching/programming methods
(5) Accuracy, Repeatability, Resolution
(6) Pay-load capacity
(7) Weight of the manipulator
(8) Applications
(9) Range and speed of arms and wrist
(10) Sensors used.

Present Applications of Robot

The potential manufacturing applications of industrial robots are :

(1) Material handling – (i) Depalletizing / Palletizing
(ii) Transporting components
(iii) Bottle loading / parts loading

(2) Machine loading/unloading components
(i) loading a punch press
(ii) loading a die casting machine
(iii) Loading electron beam welding and laser beam welding machines.
(iv) Loading parts on the test machine

(3) Spray painting – (i) painting of trucks/automobiles
(ii) Painting of agricultural equipment.

(4) welding – (i) spot welding
(ii) Arc welding
(iii) Seam welding of variable width

(5) Machining – (i) Drilling
(ii) Deburring
(iii) Grinding
(iv) cutting
(v) Forming

(6) Assembly – (i) Mating components
(ii) Riveting small assemblies

(7) Inspection – (i) In-process measuring and quality control, searching the missing parts.

(8) others – (i) Heat-treatment, applications of adhesives.

The non-manufacturing areas of robotic applications are.

(A) Hazardous Environments –

(1) Under-water Applications
(i) To explore various resources (valuable stones, gems) oil/mineral exploration.
(ii) To carry out drilling, pipe-line survey, inspection and repair of ships.
(iii) salvage operation (The recovery, evacuation & reclamation of damaged, discarded material, ships and floating equipment for reuse, repair, refabrication or scrapping.

(2) Space Applications
(i) For carrying out on-orbit services, assembly job and interplanetary missions.
(ii) Spacecraft deployment and retrieval, survey of outside space shuttle; assembly, testing, maintenance of space stations; transport of astronauts to various locations.

(iii) Robo-nauts
(iv) Free-flying robots
(v) Planetary exploration rovers

(3) Mining – (i) Exploration
(ii) Search and rescue
(iii) Tunnelling for main roadways
(iv) Operation is short passages

(4) Nuclear - Maintenance of atomic reactors

(5) Municipal Services – (i) Fire fighting
(ii) Underground (dangerious gas filled) sewer clearing
(iii) Garbage collection

Ⓑ <u>Medical</u>
(i) Telesurgery
(ii) Micro-capsule multi-legged robots
(iii) Prosthetic devices (Rehabilitation engineering for handicapped).

Ⓒ <u>Distribution</u> – (i) Warehousing
(ii) Retailing (for food industry or for retail industry)

Ⓓ <u>Agriculture</u> – (i) For spraying pesticides
(ii) for spraying fertilizers in liquid form
(iii) cleaning weeds
(iv) Sowing seeds
(v) Inspection of plants

→ Military applications of robots may be in both manufacturing and non-manufacturing areas.

Future Applications of Robot

(1) Adoption of industrial Internet of Things (IIOT) Technology-

- Robots will increasingly deploy smart sensors at the edge of production to collect data previously inaccessible to manufacturers. This trend is currently underway and will lead to new levels of productivity and efficiency.

(2) Industrial cybersecurity as a Priority-

- As robots become more connected to internal systems for data collection, the cybersecurity risks increase.
- Manufacturers will be forced to address vulnerabilities in their processes and invest heavily in cybersecurity to ensure safe, reliable production.

(3) Big data analysis becomes a competitive differential

- Robots will become a key source of information on the factory floor. The collection of data, however is just one piece of the puzzle.
- Manufacturers will have to implement systems to organize and analyze all of this information in order to act on it.

(4) open Automation Architectures will be implemented-

- As robotic automation gains widespread adoption, the need for open automation architectures grows.
- Large industry players will work with industry organizations to produce standards and open documentation that make robotic integration easier while improving product compatibility.

(5) Virtual Solutions will invade physical processes-

- Virtual Solutions will become an integral part of industrial robotics. one current growing application is the virtual representation of robotic systems for proof of concept and offline programming.

(6) Collaborative robots will continue to grow in popularity -

- Collaborative robots can work safely alongside humans and are often far cheaper than their industrial counterparts.
- As collaborative robots become more capable in tough industrial settings, they will see greater adoption by manufacturers with strict ROI requirements.

Robot Teaching

* To provide necessary instructions to the robot.

*

Teaching Methods

- Online Methods
  - Manual teaching (Point to point task)
    - Control handle/Joystick
    - Push buttons
    - Teach-Pendant
  - Lead-through teaching (continuous path task)
    - Robot Simulator
- Off-line Methods (Programming Language)

Off-line Method

VAL Programming for PUMA (Programmable Universal Machine for Assembly)

VAL — Versatile Assembly language / Variable Assembly language

→ Task - Pick and place operation

VAL Program

```
APPRO PART, 100
MOVES PART
CLOSEI
DEPARTS 200
APPROS BIN, 300
MOVE BIN
OPENI
DEPART 100
```

Other VAL commands

```
SPEED 40
EXECUTE
ABORT
Edit filename
LISTF
STORE
DELETE
LOAD filename
```

Economic Analysis

Let F = capital investment to purchase a robot which includes its purchasing cost and installation cost.

B = Savings in terms of material and labour cost

C = operating and maintenance cost

D = Depreciation of the robot

A = Net savings

$$\boxed{A = B - C - D}$$

G = Tax to be paid on the net savings

pay-Back period, $E = \frac{(\text{capital investment}, F)}{(B - C - G)}$

Let I = Modified net Savings after the payment of tax

Rate of return on investment

$$H = \left(\frac{I}{F}\right) \times 100\%$$

A company decides to purchase the robot, if

(1) pay-back period < techno-economic life

(2) rate of return on investment > rate of bank interest

Numerical Example

The costs and savings associated with a robot installation are given below.

costs of a robot including accessories : Rs. 12,00,000

Installation cost : Rs. 3,00,000

Maintenance and operating cost : Rs. 20 per hour

Labour Saving : Rs. 100 per hour

Material saving : Rs. 15 per hour

The shop runs 24 hours in a day (in 3 shifts) and the effective workdays in a year are 200. The tax rate of the company is 30% and techno-economic life of the robot is expected to be equal to six years. Determine

(a) pay-back period of the robot

(b) rate of return on investment

<u>Ans</u> :-

capital investment (F) = cost of the robot including accessories + Installation cost = Rs. 15,00,000

Total hours of running of the robot per year

$= 24 \times 200 = 4800$ hrs

Saving per year (B) = Labour Saving + Material Saving

$= (100 \times 4800) + (15 \times 4800)$

$=$ Rs. 5,52,000

Maintenance and operating cost per year (C)

$= 20 \times 4800 =$ Rs. 96,000

Techno-economic life of the robot = 6 years

constant depreciation per year $= \frac{12,00,000}{6}$

$=$ Rs. 2,00,000

Net savings (A) = Savings - operating cost - Depreciation

$= 5,52,000 - 96,000 - 2,00,000$

$=$ Rs. 2,56,000

Tax to be paid to the government by the company (G) = 30% of Net Savings (A)

$$= \frac{30}{100} \times 2,56,000$$

$$= \text{Rs. } 76,800$$

Pay-Back period of the robot

$$E = \frac{F}{B-C-G} = \frac{15,00,000}{5,52,000 - 96,000 - 76,800}$$

$$= 3.9 \text{ years} < \text{techno-economic life}$$

Net Savings after the payment of tax (I)

$$= 0.7 \times 2,56,000$$

$$= \text{Rs. } 1,79,200$$

Rate of return on investment

$$(H) = \frac{I}{F} \times 100$$

$$= \frac{1,79,200}{15,00,000} \times 100$$

$$= 11.95\% > \text{rate of bank interest}$$

Therefore, the purchase of the robot is justified by taking loan from the bank.

Types of Robot controls

There are different types of controllers used in robotics. They are

(1) Drum controller
(2) Air logic controller
(3) Programmable controller
(4) Microprocessor - based controller
(5) Minicomputer - based controller

* Drum controller

(i) In drum controller, as the drum rotates, it actuates those switches which are wired to hydraulic or pneumatic valves.

(ii) Thus, the manipulator movements are controlled by the rotational advancement of the drum. It is now obsolete.

* Air-logic controller

(i) Air logic controller employs a number of pneumatic valves which in turn control the opening and closing of the main valves of the robot manipulator in close synchronization with the timers.

* Programmable controller

(i) In a programmable controller, the sequential order in which the swithes are to be operated is kept in the memory.

(ii) It can be entered into the controller with the help of a keyboard.

(iii) The programme can also be displayed on the CRT screen.

(iv) A programmable controller may be used to control and coordinate various tasks to be done by the peripheral equipment including robots.

* Microprocessor-Based Controller

(i) The microprocessor-based control is the most popular robot control system.

(ii) Microcomputers of various types may be employed to program the sequential tasks or motions and store them in its memory.

(iii) It contains special circuitry to interpret the programs kept in its memory and at the same time it sends drive signals to various actuators of the robot manipulator.

(iv) It can also count the number of sequential events or tasks accomplished.

(v) It is versatile, programmable and has good memory.

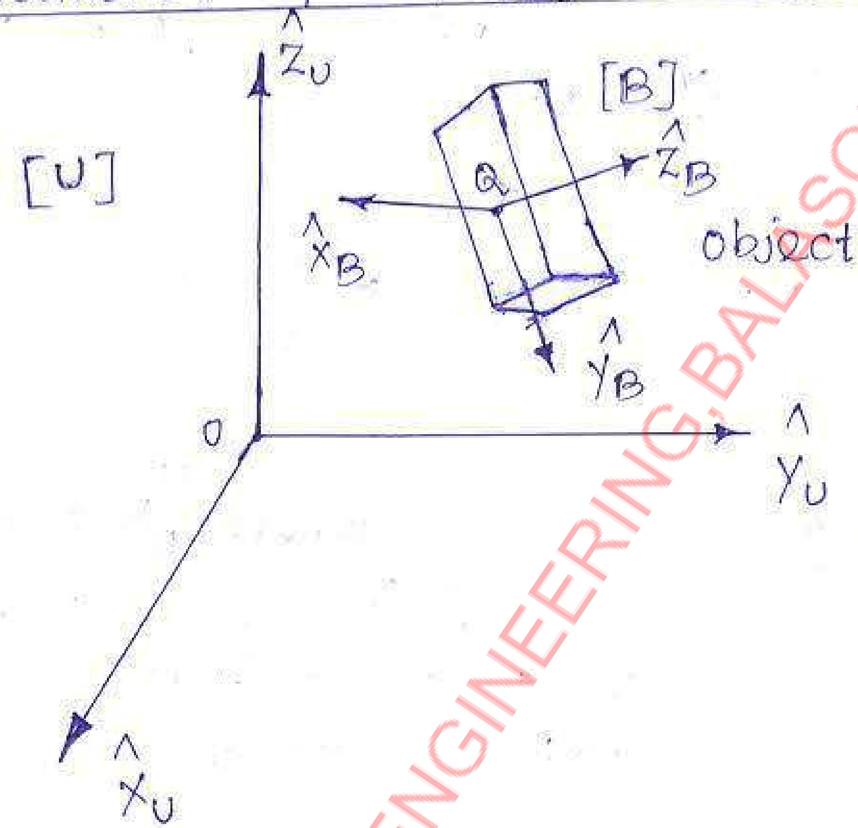
(vi) point-to-point, continuous path and controlled path motions can be easily programmed in microprocessor-based robotic systems.

* Minicomputer-Based Controller

Robots having higher payload are manipulated through a minicomputer-based controller.

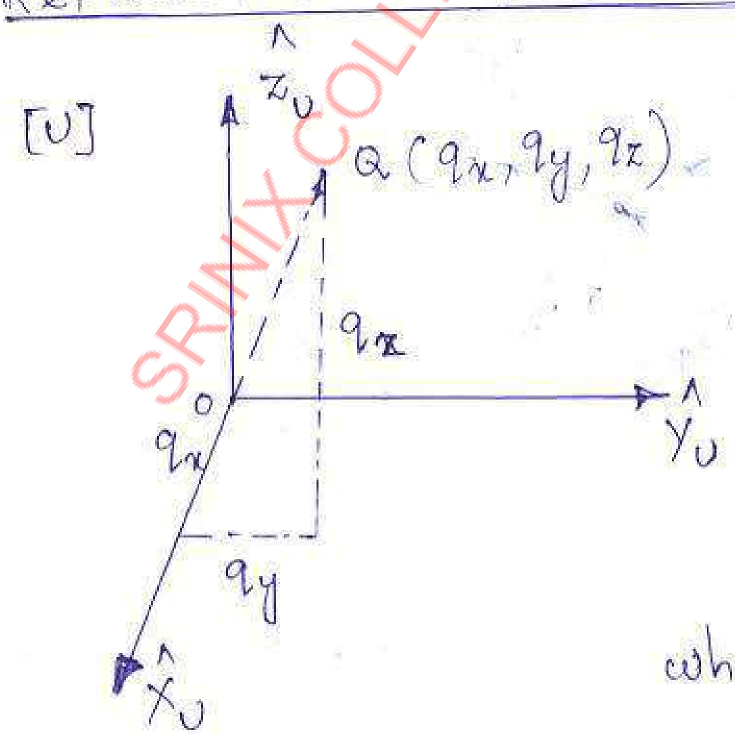
Robot Kinematics

Representation of an object in 3-D space



[U] = universal coordinate system

Representation of the Position

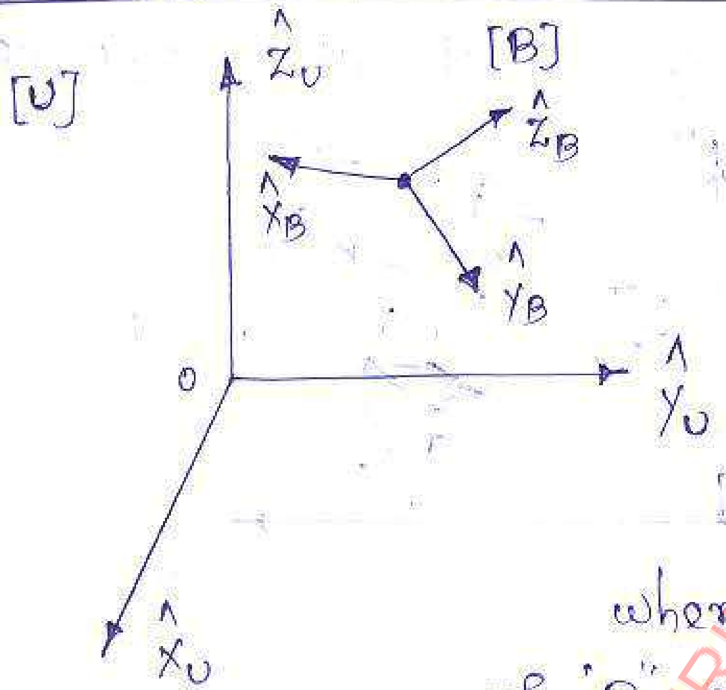


$$^{U}\bar{Q} = \begin{bmatrix} q_x \\ q_y \\ q_z \end{bmatrix}; \quad 3 \times 1 \text{ matrix}$$

1 vector

where $^{U}\bar{Q}$ = Position vector

Representation of the orientation



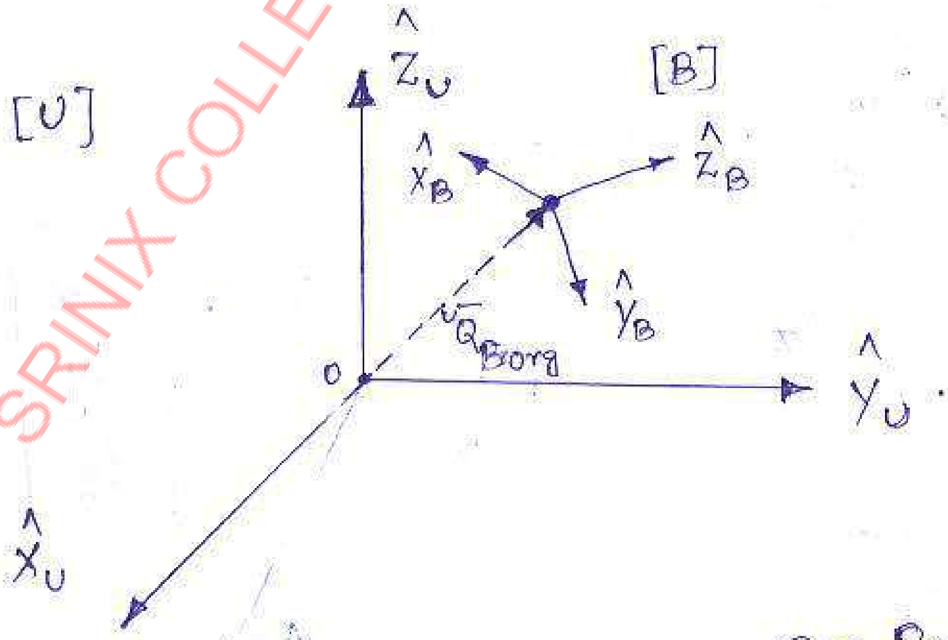
$${}^{U}_{B}R = \left[{}^{U}\hat{X}_B \;\; {}^{U}\hat{Y}_B \;\; {}^{U}\hat{Z}_B\right]_{3\times3}$$ matrix

a set of 3 vector

where ${}^{U}_{B}R$ = The rotation of "B" w.r. to "U". The rotation of body coordinate system w.r. to universal coordinate system.

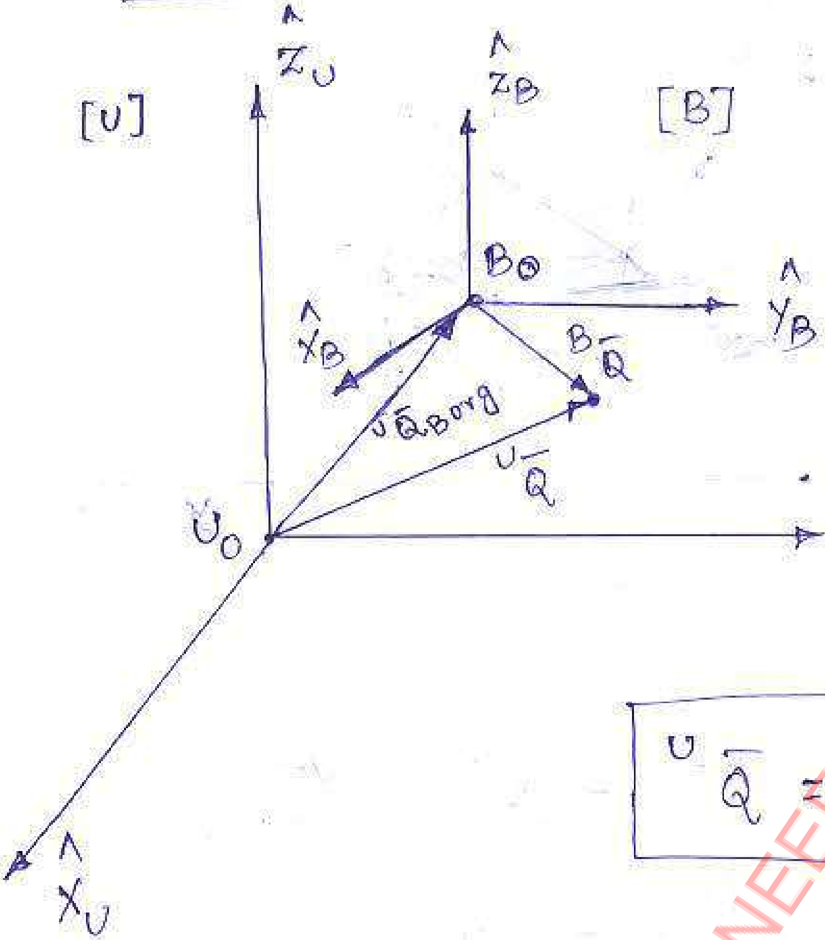
Frame Transformation

Frame : A set of four vectors carrying position and orientation information.



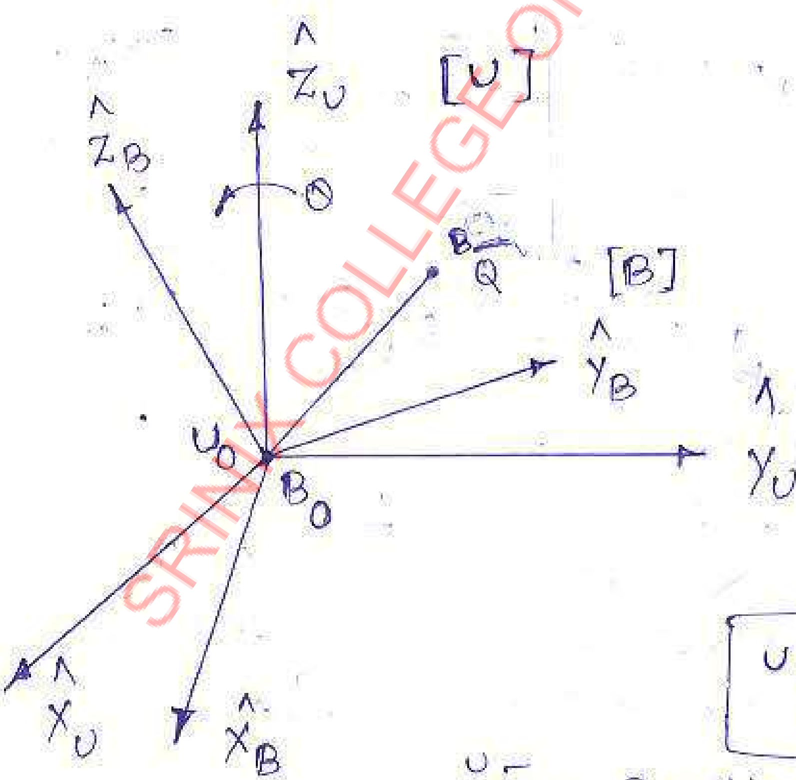
B = Body coordinate frame

Translation of a Frame



$$\boxed{{}^{U}\bar{Q} = {}^{U}\bar{Q}_{Borg} + {}^{B}\bar{Q}}$$

Rotation of a frame



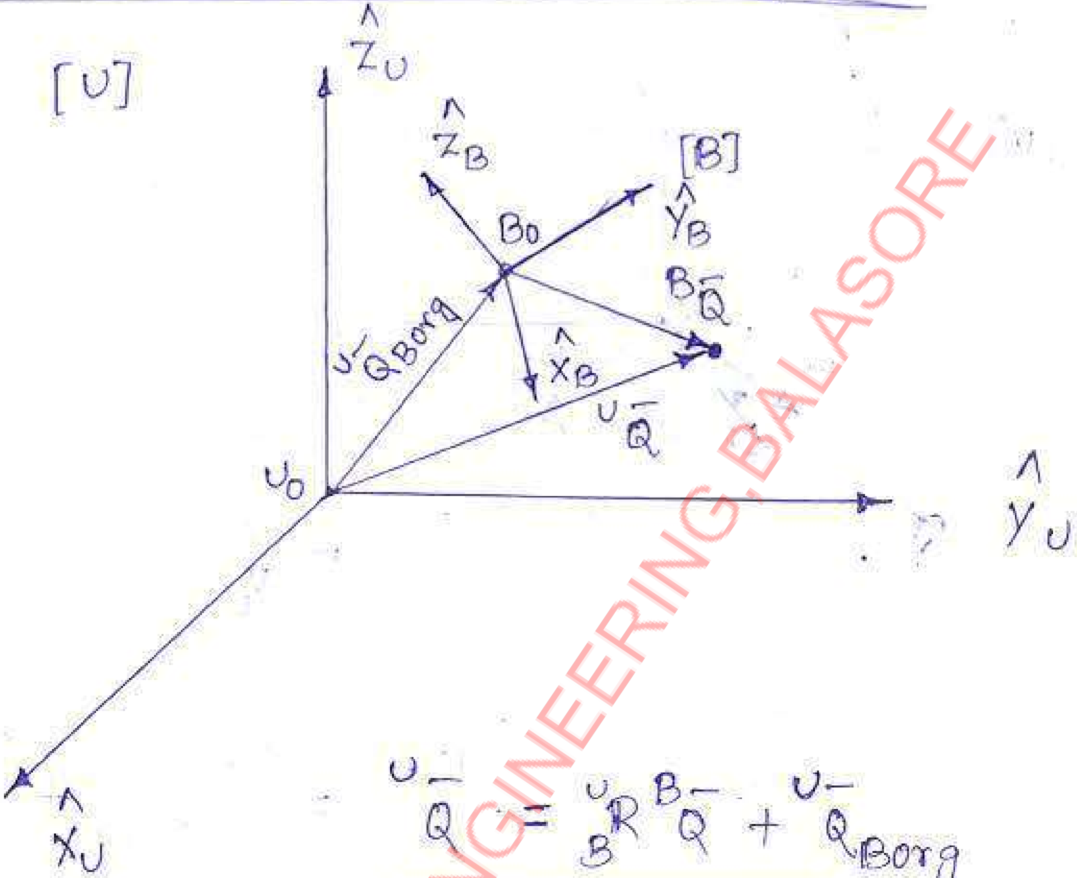
${}^{B}\bar{Q}$ = Position of a point w.r.to rotated frame 'B'.

$$\boxed{{}^{U}\bar{Q} = {}^{U}_{B}R\,{}^{B}\bar{Q}}$$

${}^{U}\bar{Q}$ = Position w.r.to universal coordinate system

${}^{U}_{B}R$ = Rotation of 'B' w.r.to 'U'

Translation and Rotation of a frame



$${}^U\bar{Q} = {}^U_BR\,{}^B\bar{Q} + {}^U\bar{Q}_{Borg}$$

$$\Rightarrow \boxed{{}^U\bar{Q} = {}^U_BT\,{}^B\bar{Q}}$$

where T = Transformation = (Translation & Rotation)

$$\Rightarrow \left[\begin{array}{c} {}^U\bar{Q}(3\times1) \\ \hline \end{array}\right] = \left[\begin{array}{c|c} {}^U_BR(3\times3) & {}^U\bar{Q}_{Borg}(3\times1) \\ \hline & \end{array}\right] \left[\begin{array}{c} {}^B\bar{Q}(3\times1) \\ \hline \end{array}\right]$$

$$\Rightarrow \left[\begin{array}{c} {}^U\bar{Q}(3\times1) \\ \hline 1 \end{array}\right] = \left[\begin{array}{c|c} {}^U_BR(3\times3) & {}^U\bar{Q}_{Borg}(3\times1) \\ \hline 0\ \ 0\ \ 0 & 1 \end{array}\right] \left[\begin{array}{c} {}^B\bar{Q}(3\times1) \\ \hline 1 \end{array}\right]$$

perspective transformation   Scaling factor

Let $[T]$ = Homogeneous transformation matrix

$$[T] = \left[\begin{array}{c|c} {}^{U}_{B}R\,(3\times3) & {}^{U}\bar{Q}_{Borg}\,(3\times1) \\ \hline 0 \quad 0 \quad 0 & 1 \end{array}\right]$$

$$[T] = \begin{bmatrix} \boxed{\begin{matrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{matrix}} & \boxed{\begin{matrix} q_x \\ q_y \\ q_z \end{matrix}} \\ \begin{matrix} 0 & 0 & 0 \end{matrix} & 1 \end{bmatrix}$$

Rotation

Position/Translation

4x4 Homogeneous transformation matrix.

Translation operator

$Trans(\hat{X}, q)$: Translation of q units along x-direction

$$Trans(\hat{X}, q) = \begin{bmatrix} 1 & 0 & 0 & q \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Rotational operator

$Rot(\hat{Z}, \theta)$: Rotation about $\hat{Z}$ axis by an angle 'θ'.

$$Rot(\hat{Z}, \theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$Rot(\hat{X}, \theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}$$

$$Rot(\hat{Y}, \theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$$

Numerical Example (Homogeneous Transformation)

(Q1) A frame {B} is rotated about $\hat{X}_U$ axis of the universal coordinate system by 45° and translated along $\hat{X}_U$, $\hat{Y}_U$ and $\hat{Z}_U$ by 1, 2 and 3 units respectively. Let the position of a point Q in {B} is given by $[3.0, 2.0, 1.0]^T$. Determine ${}^U\bar{Q}$.

Ans :-

$$\boxed{{}^U\bar{Q} = {}^U_BR\,{}^B\bar{Q} + {}^U\bar{Q}_{Borg}} \qquad \boxed{{}^U\bar{Q} = {}^U_BR \times {}^B\bar{Q}}$$

$$\boxed{{}^U\bar{Q} = {}^U_BT\,{}^B\bar{Q}}$$

Rotation Term   Translation Term   position Term

$$\underbrace{\begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & \cos45^\circ & -\sin45^\circ & 2 \\ 0 & \sin45^\circ & \cos45^\circ & 3 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{4\times4} \underbrace{\begin{bmatrix} 3 \\ 2 \\ 1 \\ 1 \end{bmatrix}}_{4\times1}$$

$$\boxed{{}^U\bar{Q} = {}^A_BT\,{}^B\bar{Q}} = \begin{bmatrix} 4 \\ 2\cos45^\circ - \sin45^\circ + 2 \\ 2\sin45^\circ + \cos45^\circ + 3 \\ 1 \end{bmatrix} = \underbrace{\begin{bmatrix} 4 \\ 2.707 \\ 5.121 \\ 1 \end{bmatrix}}_{4\times1}$$

NOTE :- (1) The coordinate of the object is always represented in homogeneous form to produce the accurate position of the object after transformation.

(2) $\{B\}$ = Body coordinate matrix = Homogeneous matrix of the object.

(3) ${}^{u}\bar{Q}$ = coordinate of the translated object

(02) (Use of Transformation)

The coordinates of point 'P' in frame $\{1\}$ are $[3.0 \;\; 2.0 \;\; 1.0]^T$. The position vector P is rotated about z-axis by 45°. Find the coordinates of point Q, the new position of point P.

Ans :- The 45° rotation of 'P' about the z-axis of frame $\{1\}$ is

$$R_z(45^\circ) = \begin{bmatrix} \cos 45^\circ & -\sin 45^\circ & 0 \\ \sin 45^\circ & \cos 45^\circ & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 0.707 & -0.707 & 0 \\ 0.707 & 0.707 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The rotation vectors

$${}^{1}Q = R_z(45^\circ)\,{}^{1}P$$

$$= \begin{bmatrix} 0.707 & -0.707 & 0 \\ 0.707 & 0.707 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 3.0 \\ 2.0 \\ 1.0 \end{bmatrix}$$

$$
= \begin{bmatrix} (0.707 \times 3) + (-0.707 \times 2) + 0 \\ (0.707 \times 3) + (0.707 \times 2) + 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0.707 \\ 3.535 \\ 1 \end{bmatrix}
$$

Thus the coordinates of the new point 'Q' relative to frame $\{1\}$ are $[0.707 \;\; 3.535 \;\; 1]^T$

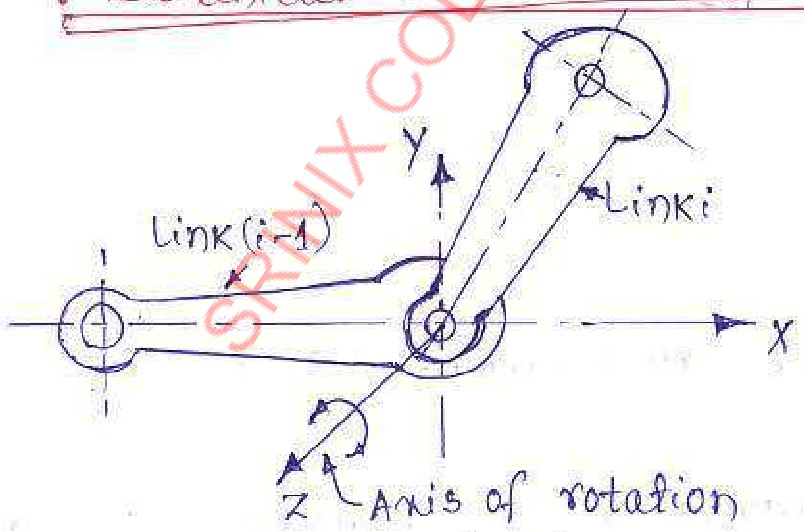
or the new position vector is

$$
Q = [0.707 \;\; 3.535 \;\; 1.0]^T
$$

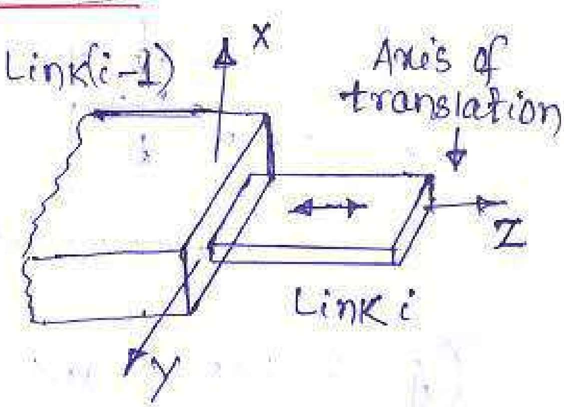
Symbolic Modeling of Robots - Direct Kinematic Model

- A robotic manipulator is designed to perform a task in the 3-D space.
- The tool or end-effector is required to follow a planned trajectory to manipulate objects or carry out the task in the workspace.
- This requires control of position of each link and joint of the manipulator to control both the position and orientation of the tool.
- To program the tool motion and joint-link motions, a mathematical model of the manipulator is required to refer to all geometrical and/or time-based properties of the motion.
- Kinematic model describes the spatial position of joints and links and position and orientation of the end-effector.
- The differential kinematics of manipulators refers to differential motion i.e velocity, acceleration and all higher order derivatives of position variables.

Mechanical structure and Notations



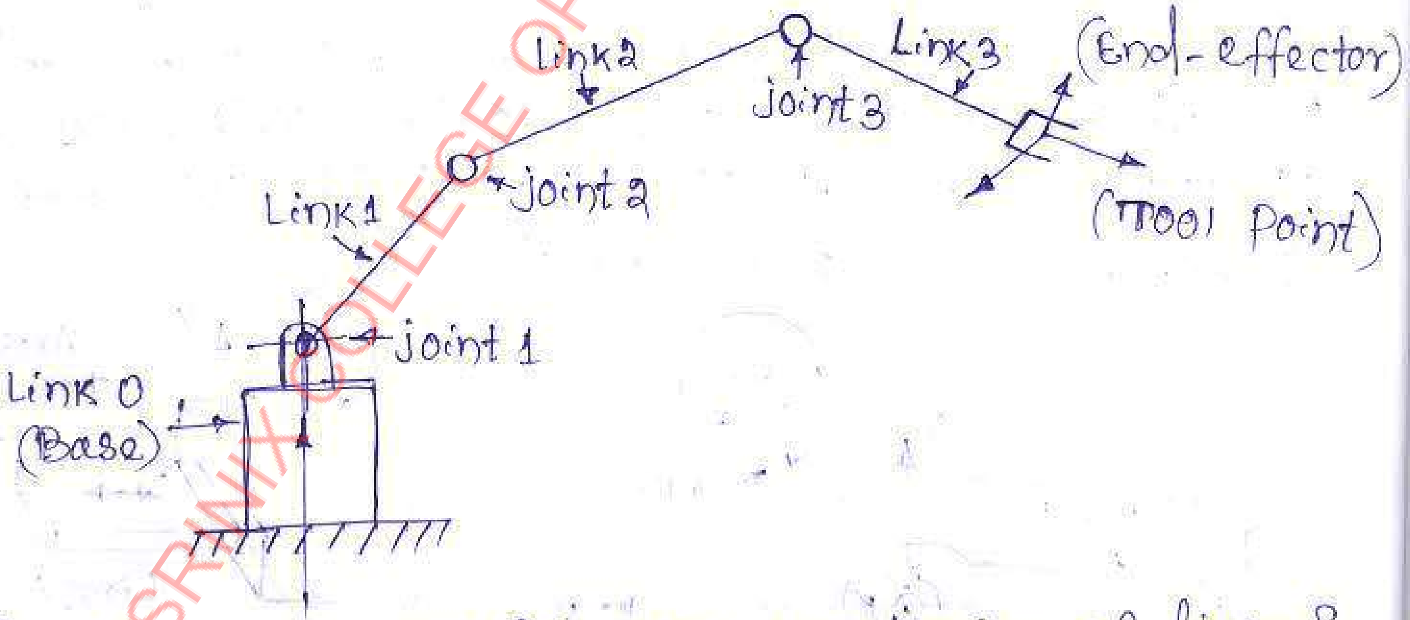
(a) Revolute joint



(b) Prismatic (Sliding) joint

Two common types of joints and axis of motion (Joint axis)

- A manipulator consists of a chain of rigid bodies called links connected to each other by joints, which allow linear or revolute motion betn connected links each of which exhibits just one DOF.
- A joint with 'm' DOF can be modeled as 'm' joints with one DOF each connected with (m-1) links of zero length.
- Single DOF joints betn links of a manipulator can be classified as revolute or prismatic. A revolute joint, denoted as R-joint, allows rotational motion betn connected links.
- A prismatic joint, denoted as P-joint, also known as sliding or rectilinear joint, permits translational motion betn the connected links. Each joint has a joint axis w.r.to which, the motion of joint is described as shown in fig.
- In the case of revolute joints, the axis of relative rotation is the joint axis. For the prismatic joint, the axis of relative translational motion is the joint axis.



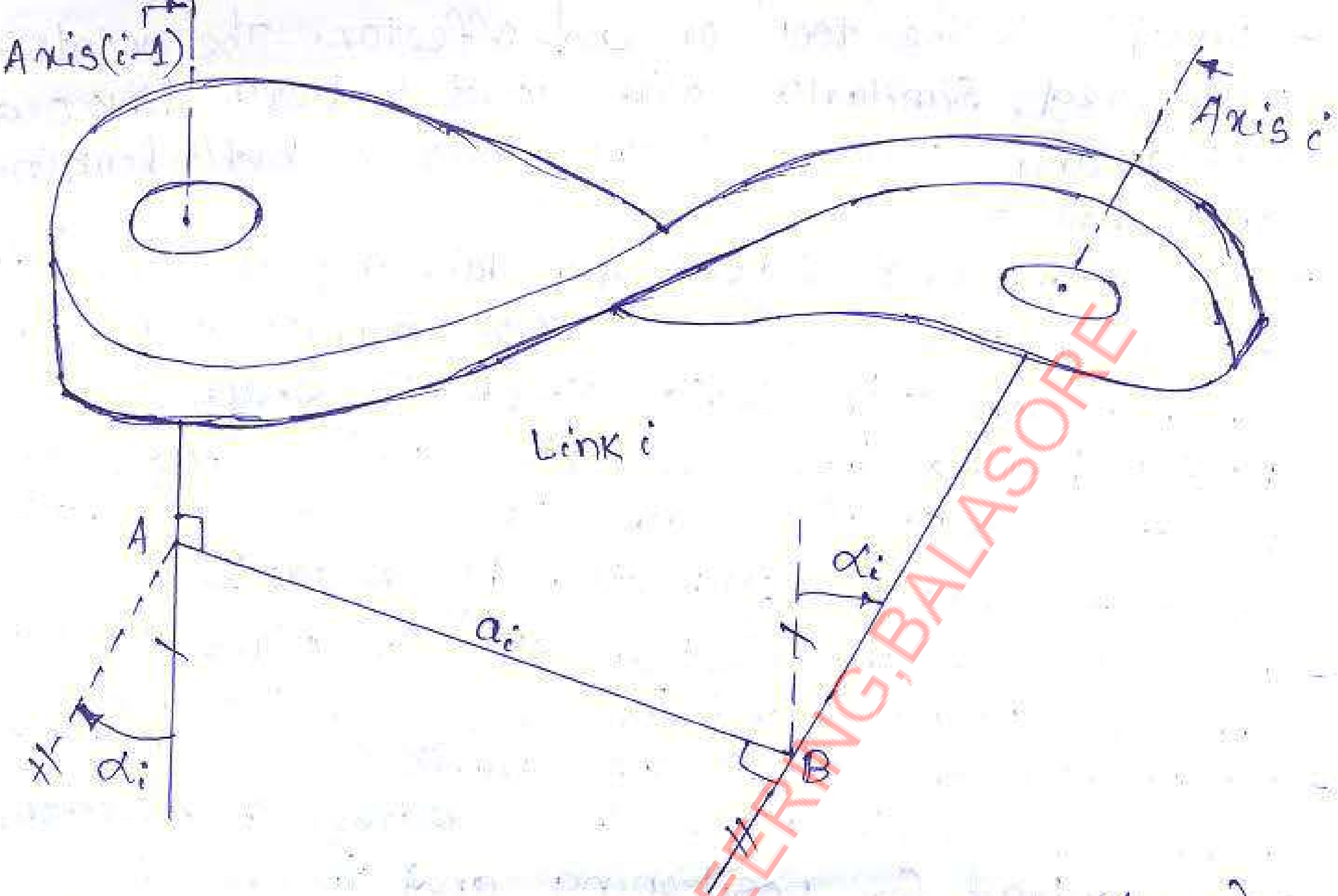
(A 3-DOF manipulator arm - numbering of links & joints)

- The links of a manipulator are numbered outwardly starting from the immobile base as link 0, first moving body as link 1, to the last link out to free end as link 'n'.

- Link 'n' is the "tool" or end-effector. The joints are numbered, similarly, with joint 1 betn link 0 and link 1 and so on, out to the joint 'n' betn link (n-1) and link 'n'.
- The numbering scheme for labelling links and joints is shown in fig. for a 3-DOF manipulator arm which is an open serial kinematic chain of rigid bodies having three revolute joints. Thus, an n-DOF manipulator arm consists of (n+1) links (including link 0) connected by 'n' joints.
- Description of an object in space requires six parameters three for position and three for orientation.
- To position and orient the end-effector in 3-D space, therefore, a minimum of three degrees of freedom are required for positioning and three degrees of freedom for orientation.
- Typical robotic manipulators have five or six DOF.
- A manipulator is considered to be consisting of an arm with typically first three links from the base and a wrist with the remaining 2 or 3 links.
- The arm accomplishes the task of reaching the desired position, whereas the wrist helps to orient the end-effector.

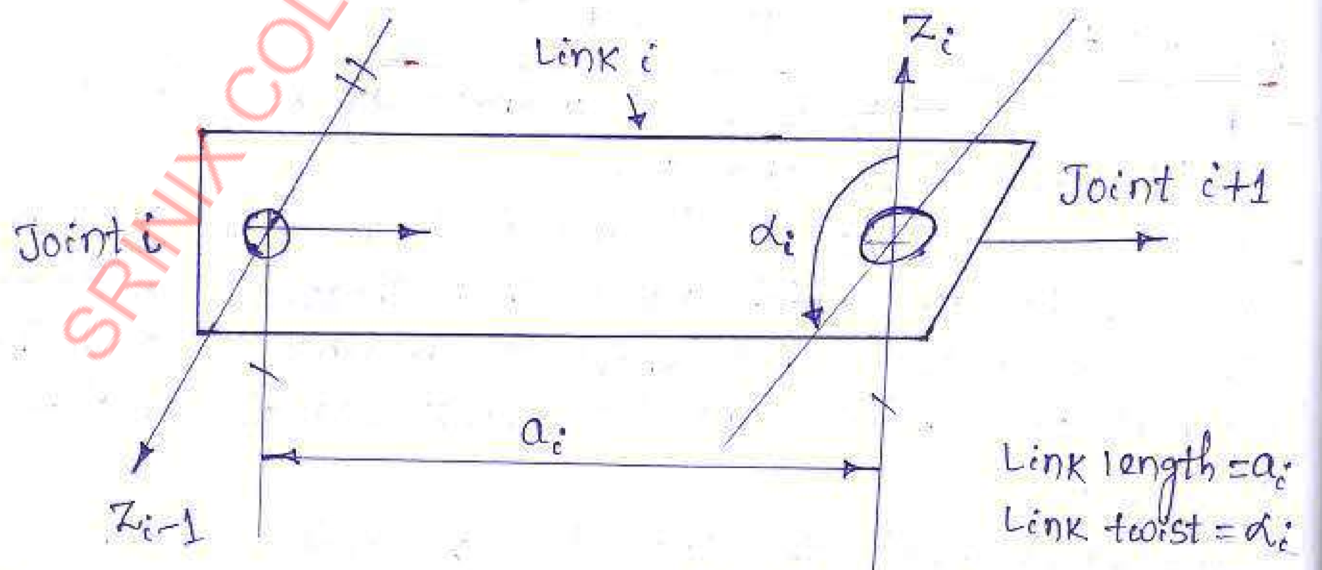
Description of links and Joints

- Fig. shows link i of a manipulator with associated joint axes (i-1) and i.
- For the two axes (i-1) and i, there exist a mutual perpendicular, which gives the shortest distance betn the two axes. This shortest distance along the common normal is defined as the link length and is denoted as a_i.
- The angle betn the projection of axis (i-1) and axis i, on a plane perpendicular to the common normal AB, is known as the link twist and is denoted by α_i.



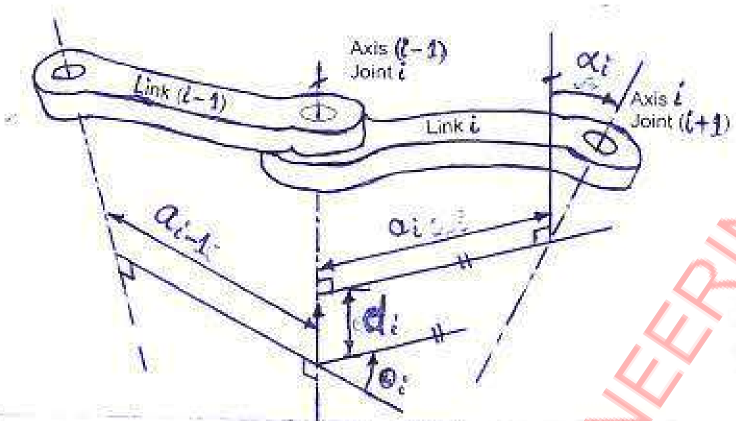
(Description of link parameters a_i and α_i)

- The link twist α_i is measured from axis(i-1) to axis i in the right hand sense about AB as shown in above fig.
- These two parameters a_i and α_i are known as link parameters and are constant for a given link.



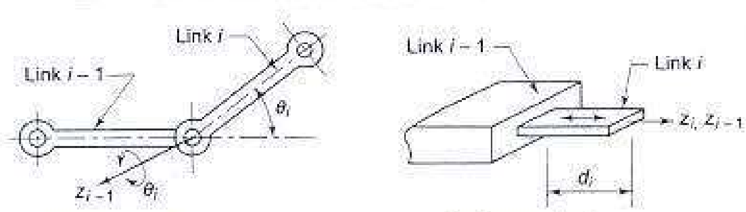
(Link parameters for a straight link with a twist of 90°)

- Another common link geometry is straight link with link twist angle as multiple of $\pi/2$ radians.
- Sometimes, the link may have a bend such that the axis of joint $(i-1)$ and joint i intersect and in this case the link length of link i is zero although physical link dimension is not zero. The above fig. shows a straight link with link twist of $\pi/2$ radians.



(Description of joint-link parameters for joint i & link i)

- Joint distance (d_i) is the perpendicular distance between the two adjacent common normals a_{i-1} and a_i measured along axis $(i-1)$
- Joint angle (θ_i) is the angle betn the two adjacent common normals a_{i-1} and a_i measured in right-handed direction about the axis $(i-1)$.
- It is the rotation about joint axis $(i-1)$ needed to make a_{i-1} parallel to a_i. These two parameters are called joint parameters as shown in above fig.



d_i = 0 or constant
(a) For revolute joint

θ_i = 0 or constant
(b) For prismatic joint

(Joint parameters θ_i and d_i for two types of joints)

- For a revolute joint, d_i is zero or constant and θ_i varies, while for a prismatic joint θ_i is zero or constant and d_i varies, describing the relative position of links.
- The varying parameter is known as joint variable and a generalized parameter (q) is used to denote the joint displacement (variable) of either type of joint.
- The generalized joint displacement variable is defined as

$$q_i = \begin{cases} \theta_i, & \text{if joint } i \text{ is revolute} \\ d_i, & \text{if joint } i \text{ is prismatic} \end{cases}$$

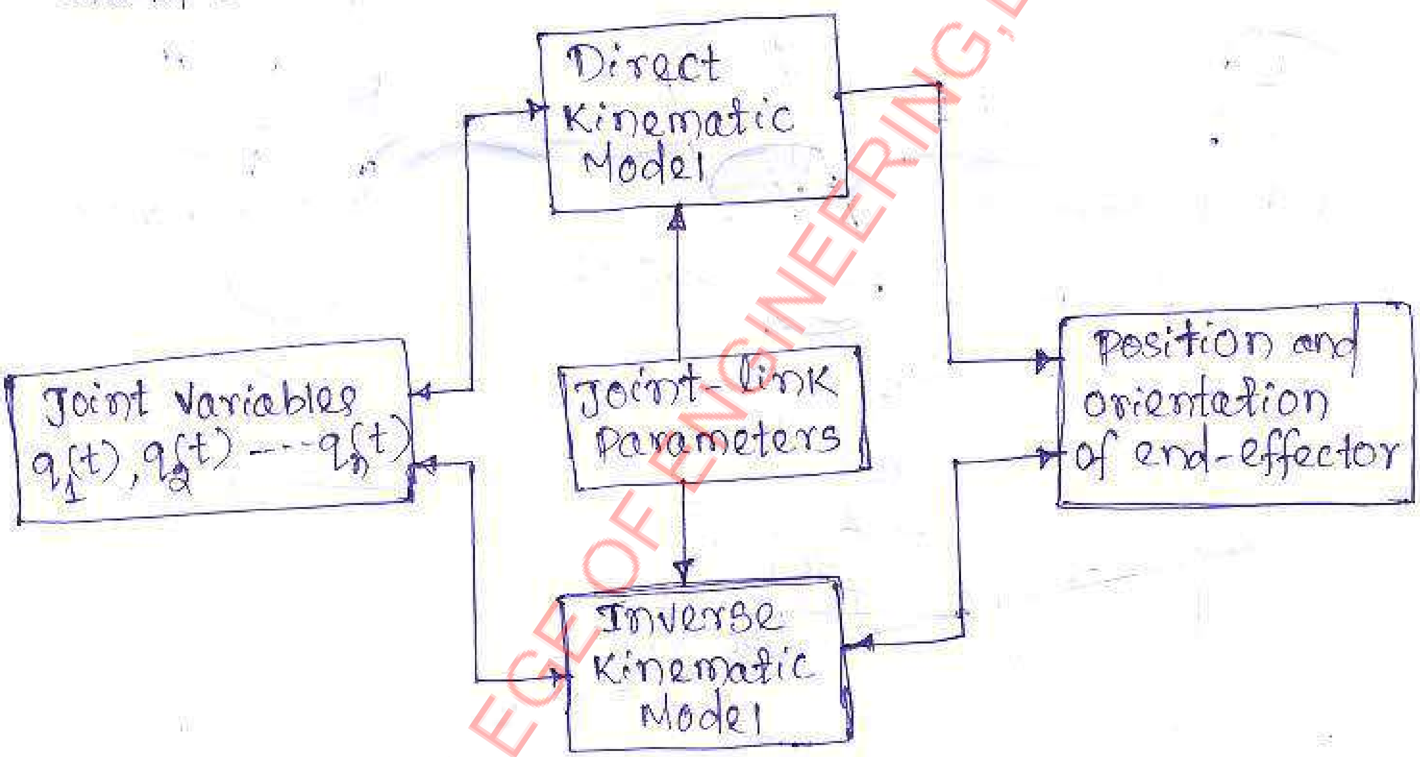
Kinematic Modeling of the manipulator

- With the definition of fixed and variable kinematic parameters for each link, kinematic models can be defined.
- This model is the analytical description of the spatial geometry of motion of the manipulator with respect to a fixed reference frame, as a function of time.
- In particular, the relation betn the joint-variables and the position and orientation of the end-effector is the kinematic model.
- It is required to control position and orientation of the end-ffector, in 3-D space, so that it can follow a defined trajectory or manipulate objects in the workspace. The kinematic modeling problem is divided into two problems as:

① Given the set of joint-link parameters, the problem of finding the position and orientation of the end-effector w.r.to a known reference frame for an n-DOF manipulator is the first problem. This is referred to as direct (forward) kinematic model or direct kinematics. This model gives the position and orientation of the end-effector as a function of the joint variables and other joint-link constant parameters.

(2) For a given position and orientation of the end-effector (of the n-DOF manipulator) w.r.to an immobile reference frame, it is required to find a set of joint variables that would bring the end-effector in the specified position and orientation. This is the second problem and is referred to as the inverse kinematic model or inverse kinematics.

- The problem of manipulator control requires both the direct and inverse kinematic models of the manipulator.

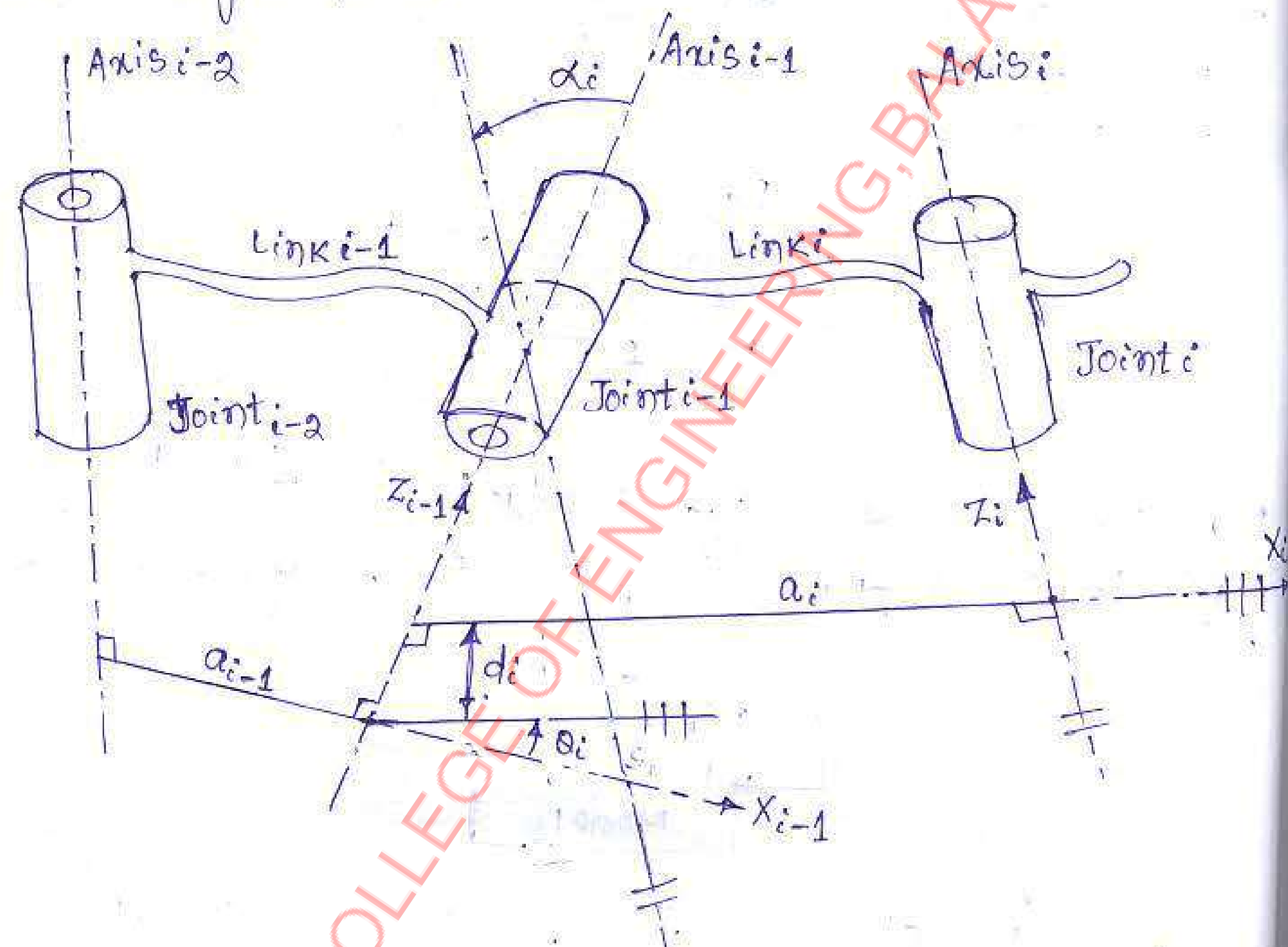


(Direct and Inverse Kinematic Models)

- The block diagram for both the models is as shown in fig., wherein the commonality is the joint-link fixed and variable parameters.
- The task to be performed by a manipulator is stated in terms of the end-effector location in space.
- The values of joint variables required to accomplish the task are computed using the inverse kinematic model.
- To find the location of end-effector in space, at any instant of time, the joint variable values are substituted in the direct kinematic model.

Denavit - Hartenberg Notation (D-H) Convention

The definition of a manipulator with four joint-link parameters for each link and a systematic procedure for assigning right-handed orthonormal coordinate frames, one to each link in an open kinematic chain was proposed by Denavit and Hartenberg (1955) and is known as Denavit-Hartenberg (DH) notation.



① Length of link$_i$ or Link length (a_i) – It is the mutual perpendicular distance betn Axis$_{i-1}$ and Axis$_i$

② Angle of twist of link$_i$ or link twist (α_i) – It is defined as the angle betn Axis$_{i-1}$ and Axis$_i$.

③ offset of link$_i$ or Joint distance (d_i) – It is the distance measured from a point where a_{i-1} intersects the Axis$_{i-1}$ to the point where a_i intersects the Axis$_{i-1}$ measured along the said axis.

④ Joint Angle(θ_i) – It is defined as the angle betn the extension of a_{i-1} and a_i measured about the $Axis_{i-1}$

Rules for Coordinate Assignment

- Z_i is an axis about which the rotation is considered or along which the translation takes place.
- If Z_{i-1} and Z_i axes are parallel to each other, X axis will be directed from Z_{i-1} to Z_i along their common normal.
- If Z_{i-1} and Z_i axes intersect each other, X axis can be selected along either of two remaining directions.
- If Z_{i-1} and Z_i axes act along a straight line, X axis can be selected anywhere in a plane perpendicular to them.
- Y axis is decided as $Y = Z \times X$

We have

$$^{i-1}_{i}T = {}^{i-1}_{A}T\,{}^{A}_{B}T\,{}^{B}_{C}T\,{}^{C}_{i}T$$

$$= \underbrace{Rot(z,\theta_i)\,Trans(z,d_i)}\,\underbrace{Rot(X,\alpha_i)\,Trans(X,a_i)}$$

$$= Screw_Z\ Screw_X$$

$$^{i-1}_{i}T = \begin{bmatrix} C\theta_i & -S\theta_i C\alpha_i & S\theta_i S\alpha_i & a_i C\theta_i \\ S\theta_i & C\theta_i C\alpha_i & -C\theta_i S\alpha_i & a_i S\theta_i \\ 0 & S\alpha_i & C\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

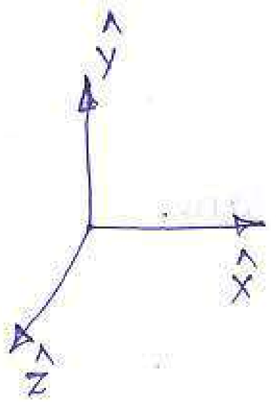
$\boxed{\begin{matrix} C = \cos \\ S = \sin \end{matrix}}$

Now $\,{}^{i}_{i-1}T = \left[{}^{i-1}_{i}T\right]^{-1}$

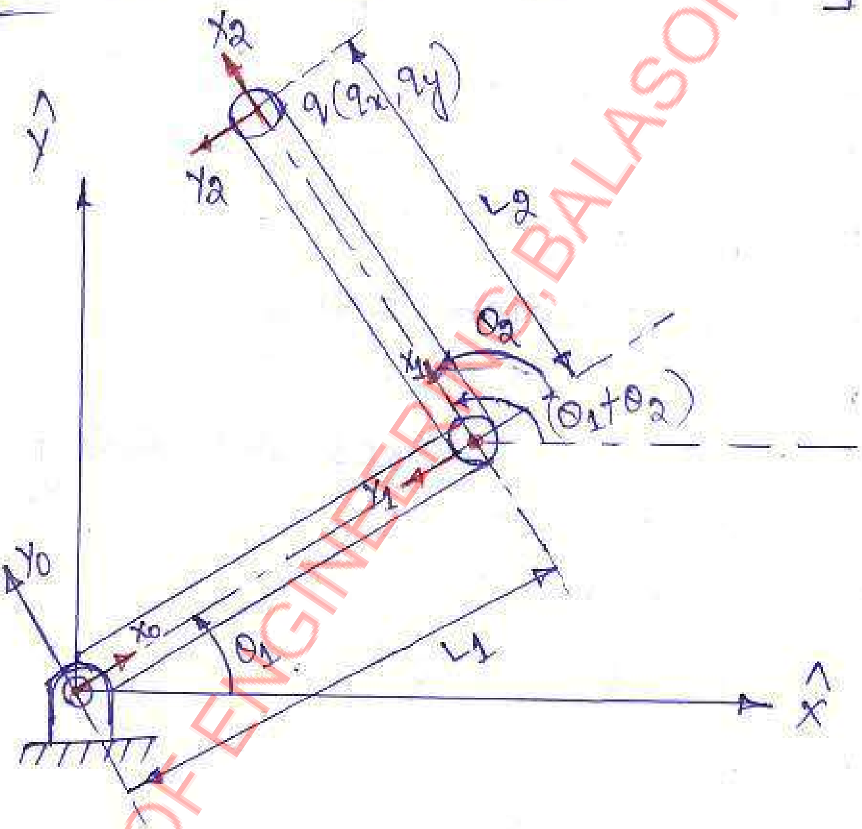
$$= \begin{bmatrix} C\theta_i & S\theta_i & 0 & -a_i \\ -S\theta_i C\alpha_i & C\theta_i C\alpha_i & S\alpha_i & -d_i S\alpha_i \\ S\theta_i S\alpha_i & -C\theta_i S\alpha_i & C\alpha_i & -d_i C\alpha_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Example

2 DOF Serial Manipulator



Reference coordinate system



Frame	θ_i	d_i	α_i	a_i
1	θ_1	0	0	L_1
2	θ_2	0	0	L_2

← D-H Parameter

Forward Kinematics

$$\boxed{{}^{Base}_{2}T = {}^{Base}_{1}T\;{}^{1}_{2}T}$$

$${}^{Base}_{1}T = Rot(\hat{Z}, \theta_1)\,Trans(\hat{X}, L_1)$$

$$= \begin{bmatrix} C_1 & -S_1 & 0 & L_1C_1 \\ S_1 & C_1 & 0 & L_1S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$ {}^{1}_{2}T = Rot(\hat{z}, \theta_2)\, Trans(\hat{x}, L_2) $$

$$ = \begin{bmatrix} C_2 & -S_2 & 0 & L_2 C_2 \\ S_2 & C_2 & 0 & L_2 S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{Base}_{2}T = {}^{Base}_{1}T \; {}^{1}_{2}T $$

$$ = \begin{bmatrix} C_{12} & -S_{12} & 0 & \boxed{L_1 C_1 + L_2 C_{12}} \\ S_{12} & C_{12} & 0 & \boxed{L_1 S_1 + L_2 S_{12}} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{matrix} = q_x \\ = q_y \\ \\ \\ \end{matrix} $$

principle of Trignometry

$$ q_x = L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2) $$

$$ q_y = L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2) $$

<u>Forward Kinematics</u> – $\left.\begin{matrix} L_1, L_2 \\ \theta_1, \theta_2 \end{matrix}\right\}$ <u>known</u>

To determine the position and orientation of the end-effector of the robot provided the length of links and joint angles are known.

COURSE OUTLINES OF MODULE-II

1. **Robot Actuators.**
2. **Pneumatic Actuators.**
3. **Hydraulic Actuators.**
4. **Electrical Actuators.**
5. **Brushless Permanent Magnet DC Motor.**
6. **Stepper Motor.**
7. **Servo-motor.**
8. **Micro-gripper.**
9. **Micro-actuator.**
10. **Application of Robots.**
11. **Trajectory Planning.**
12. **Steps in Trajectory Planning.**
13. **Joint Space and Cartesian Space Techniques.**

References-1. Robotics and Control-R K Mittal & I J Nagrath-TMH Publication.
2. Robotics Technology-S R Deb & S Deb-TMH Publication.
3. Prof. D K Pratihar-IIT Kharagpur.

Robot Actuators

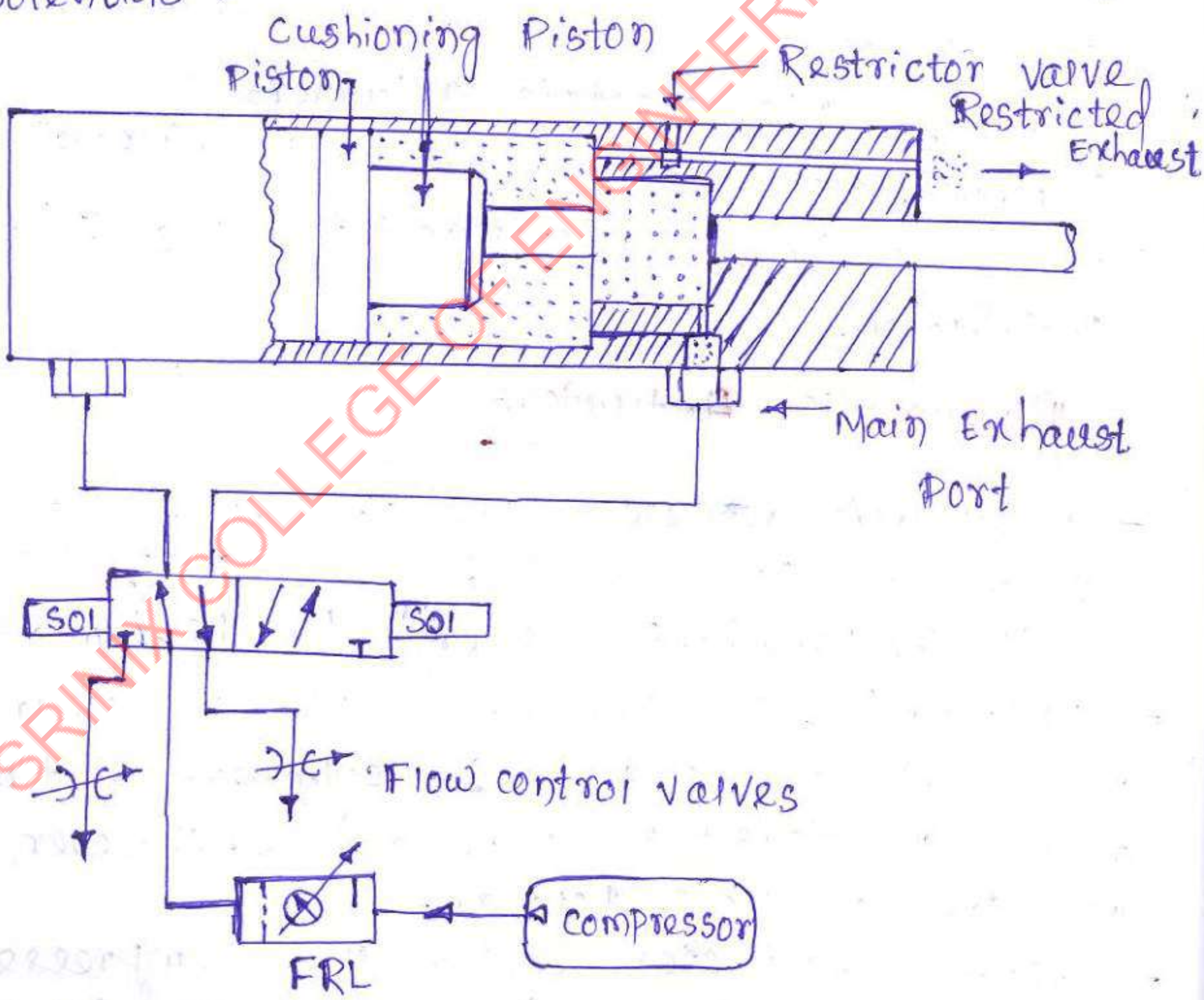
- The robot arm can be put to a desired motion with its payload if actuator modules are fitted in to provide power drives to the system.
- The actuators used in robotic systems to drive the links.
- Actuators are classified into :-

(1). Electromechanical actuators that include
(a) Pneumatic actuators using compressed air
(b) Hydraulic actuators using fluid power
(c) Electric motors with (i) D.C motors (ii) A.C motors
(iii) Stepper motors using electromagnetics
(d) Electrostatic actuators using electrical field that includes piezoelectric actuators
(e) Micro-electro-mechanical systems (MEMS) actuators using combined micromachining and IC fabrication technology.

Pneumatic Actuators

- Pneumatic actuators are the devices used for converting pressure energy of compressed air into the mechanical energy to perform useful work.
- Pneumatic actuators may employ a linear actuator i.e double acting cushioned cylinders or it may employ rotary actuators like vane motors. However, linear actuators are more popular.
- Pneumatic actuators system use compressed air to move the robot arm. Air is compressed by an air compressor and the compressed air is directed through filter, regulator and lubricator (FRL) units to the hose pipes and then to the pneumatic cylinders through the directional control valve.

- For stable supply, an air compressor usually pumps air into a storage tank and from there, it passes through FRL units to the pneumatic cylinder.
- As air enters into the cylinder via the directional control valve, the piston moves on its outward stroke and when air is diverted to enter into the other end of the cylinder, the piston makes the return stroke.
- The return air is exhausted into the atmosphere.
- pneumatic direction control valve can be operated by either levers, rollers or solenoids and this can also be pilot operated.
- Solenoid controlled valves are most common and they can be operated by micro switches with energize the solenoids.



Advantages

(1) Pneumatic actuators generate precise linear motion by providing accuracy.

(2) Pneumatic actuators typical applications involve areas of extreme temperatures.

(3) The cost of pneumatic actuators is low compared to other actuators.

(4) Simple in construction.

Disadvantages

(1) The main disadvantage of a pneumatic system is the mass inertia and delayed response of the robot arm due to the sponginess and reduced repeatability.

(2) Even though the air is easily available, it can be contaminated by oil or lubrication, leading to downtime and maintenance.

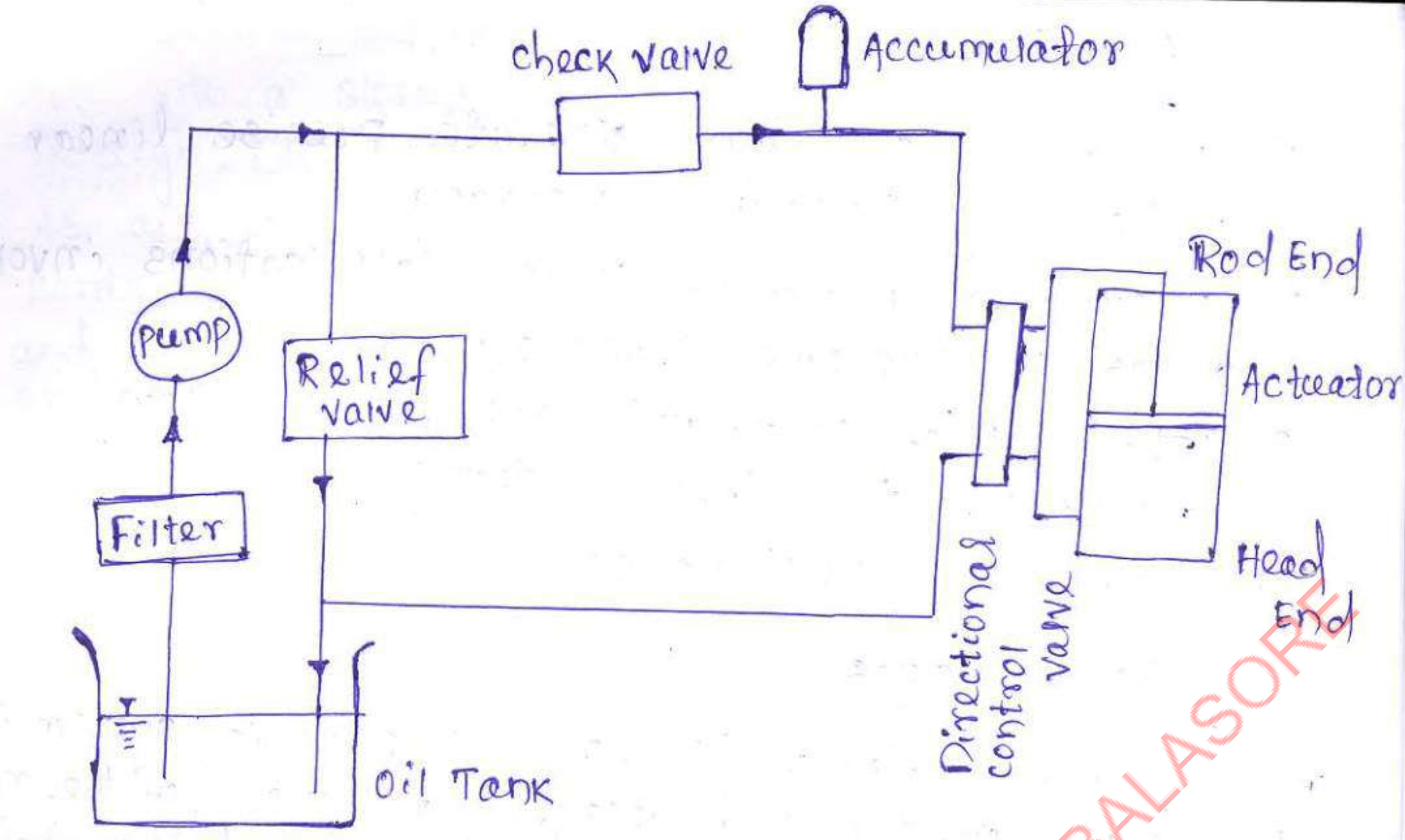
(3) Pressure losses and air's compressibility make pneumatics less efficient than other linear-motion methods.

Hydraulic Actuators

- This actuators can produce large force/torque to drive the manipulator joints without the use of reduction gearing and are easily applied for robotic position control.

- In a hydraulic actuators, both linear and rotational motions are possible.

- Fluid is pumped from the tank and filtered. It then passes through a check valve, accumulator, solenoid controlled - spring centered - direction control valve to the cylinders used for extension of the arm, swing of the shoulder or rotation of the waist.



- The circuit contains a pilot operated relief valve so that the fluid is returned to the tank.
- The filter separates out any foreign particles that may wear off the hydraulic system elements. It also filters the dirt that may be present.
- The accumulator helps the systems to send additional fluid to the cylinder if there is a sudden demand for the fluid and it also acts as a shock absorber.
- The pilot operated relief valve maintains the system pressure constant. It eliminates noise and vibration by streamlining the pulsations of the system pressure and holding the system pressure at the preset value.
- The check valve allows the hydraulic fluid to flow in only one direction and restricts the fluid to flow in the reverse direction. The check valve also helps to maintain system pressure.
- The direction control valve allows the fluid to enter into the valve from the pump and then to either the rod end or head end of the cylinder by moving the spool to the right or to the left.

Advantages

(1) Hydraulic actuators are rugged and suited for high force applications. They can produce forces 25 times greater than pneumatic cylinder of equal size.

(2) A hydraulic actuator can hold force and torque constant without the pump supplying more fluid or pressure due to the incompressibility of fluids.

(3) Hydraulic actuators can have their pumps and motors located a considerable distance away with minimal loss of power.

Disadvantages

(1) Hydraulic will leak fluid and this lead to cleanliness problems.

(2) Due to large number of parts, the linear motions systems that are large and difficult to accommodate.

Electrical Actuators

- The most popular choice for actuators for robotic systems is the electric motor.
- The electric actuators generally require reduction gears of high ratios. The high gear ratio linearizes the system dynamics and reduces the coupling effects.
- Electric actuators are subclassified into four categories (1) AC motor (2) DC motor (3) stepper motor (4) other devices such as solenoid.

Advantages

(1) This actuators offer the highest precision-control positioning.

(2) Because there are no fluids leaks, environmental hazards are eliminated.

(3) In terms of noise, they are quieter than pneumatic and hydraulic actuators.

Disadvantages

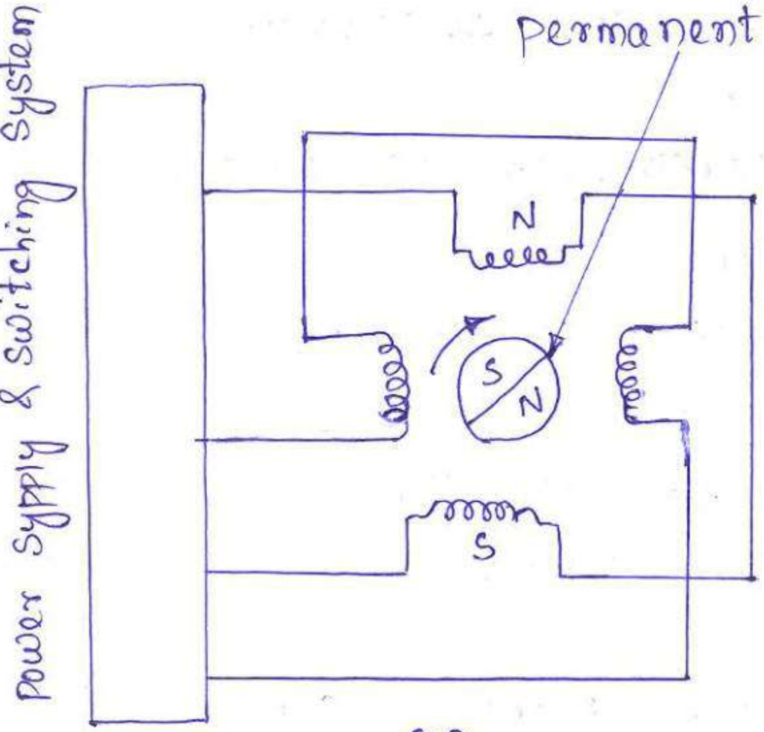
(1) The initial unit cost of an electrical actuator is higher than that of pneumatic & hydraulic actuators.

(2) A continuous running motor will overheat, increasing wear and tear on the reduction gear.

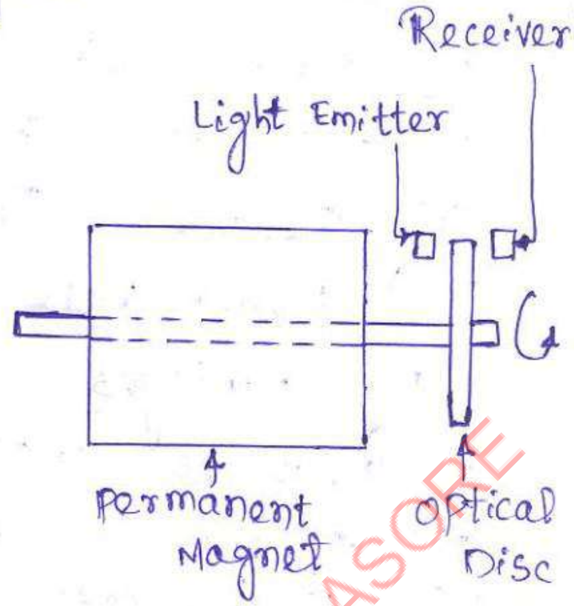
(3) The motor can also be large and create installation problems.

Brushless Permanent Magnet DC Motor

- The above motor also known as electronically commutated motors are synchronous motors that are powered by a DC electric source through an integrated inverter/switching power supply which produces an AC electric signal to drive the motor.
- The DC motors have brushes and a commutator to transmit power to the armature. During the rotation of the armature, the brushes make repeated contacts on the split sectors of the commutator.
- The making and breaking of contacts creates electrical noise besides pitting of the surface due to continuous rubbing and generates problems in the computer-controlled robots.
- Brushless DC motors are therefore developed and the schematic arrangement as shown in fig. A permanent magnet is mounted on the armature shaft instead of on the field and the field is wound.



(a)



(b)

Brushless D.C. motor (a) A schematic diagram of electronic commutation (b) optical disc on an armature.

- The switching of the voltage in the field is reversed by electronic commutation.
- When north pole faces the south pole, rotation stops. When the north pole faces north, rotation takeplace. If the field is reversed at the moment when unlike poles face each other, the armature begins to rotate.
- An optical disc mounted on the armature rotates betn the receiver and the light transmitter.
- When the light path is broken by the disc, the output from the receiver sends a signal to the electronic control to switch on the applied voltage. When the light transmitted reaches the receiver, a signal is also sent to the electronic control that activates the electronic switching to reverse the field. Thus without using the brushes & commutator, it is possible to organize electronic switching and power supply to have continuous rotation of armature.

Advantages

(1) Increased reliability and efficiency
(2) Longer life
(3) Elimination of sparks from commutator
(4) Reduced Friction
(5) Faster rate of voltage & current.

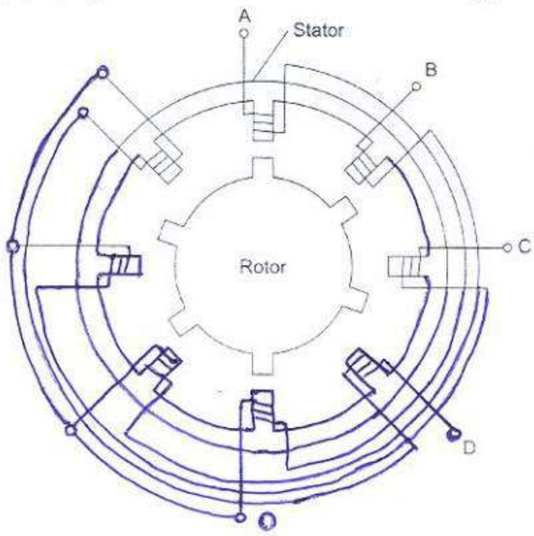
Disadvantages

(1) Requires complex drive circuitry
(2) Requires additional sensors.
(3) Higher cost
(4) Some designs require manual labour.

Stepper Motor

- A stepper motor also known as step motor or stepping motor is a brushless DC electric motor that divides a full rotation into a number of equal steps.
- A stepper motor is an electric motor whose main feature is that its shaft rotates by performing steps, that is by moving a fixed amount of degrees.
- The stepper motor converts d.c. voltage pulse train into a proportional rotation of a shaft.
- There are three different types of stepper motor
  (a) variable reluctance stepper motor
  (b) permanent magnet stepper motor
  (c) Hybrid stepper motor
- The stepper motor is an electromechanical device it converts electrical power into mechanical power.
- The stepper motor uses the theory of operation for magnets to make the motor shaft turn a precise distance when a pulse of electricity is provided.

- The stator has eight poles and the rotor has six poles. The rotor will require 24 pulses of electricity to move the 24 steps to make one complete revolution. Another way to say this is that the rotor will move precisely 15° for each pulse of electricity that the motor receives.



(Variable Reluctance stepper motor)

- If phase 'A' of stator is activated alone, two diametrically opposite rotor teeth align themselves with phase 'A' teeth of stator.
- The next adjacent set of rotor teeth is 15° out of step in the clockwise direction w.r. to stator teeth. Activation of phase 'B' winding would cause the rotor to rotate a further angle of 15° (60° rotor teeth angle - 45° stator teeth angle) in counter-clockwise direction for alignment of the adjacent of diametrically opposite rotor teeth.
- If stator windings are excited in sequence of A, B, C, D, then the rotor will move in consecutive 15° steps in counter-clockwise direction.
- Clockwise rotation of motor will take place if excitation sequences are reversed. When the stator and rotor teeth are aligned, the reluctance is minimized and the rotor is at rest at this position.

Advantages

(1) The rotation angle of the motor is proportional to the input pulse.
(2) Excellent response to starting, stopping and reversing.
(3) The motor has full torque at standstill.
(4) It is possible to achieve very low-speed synchronous rotation with a load that is directly coupled to the shaft.

Disadvantages

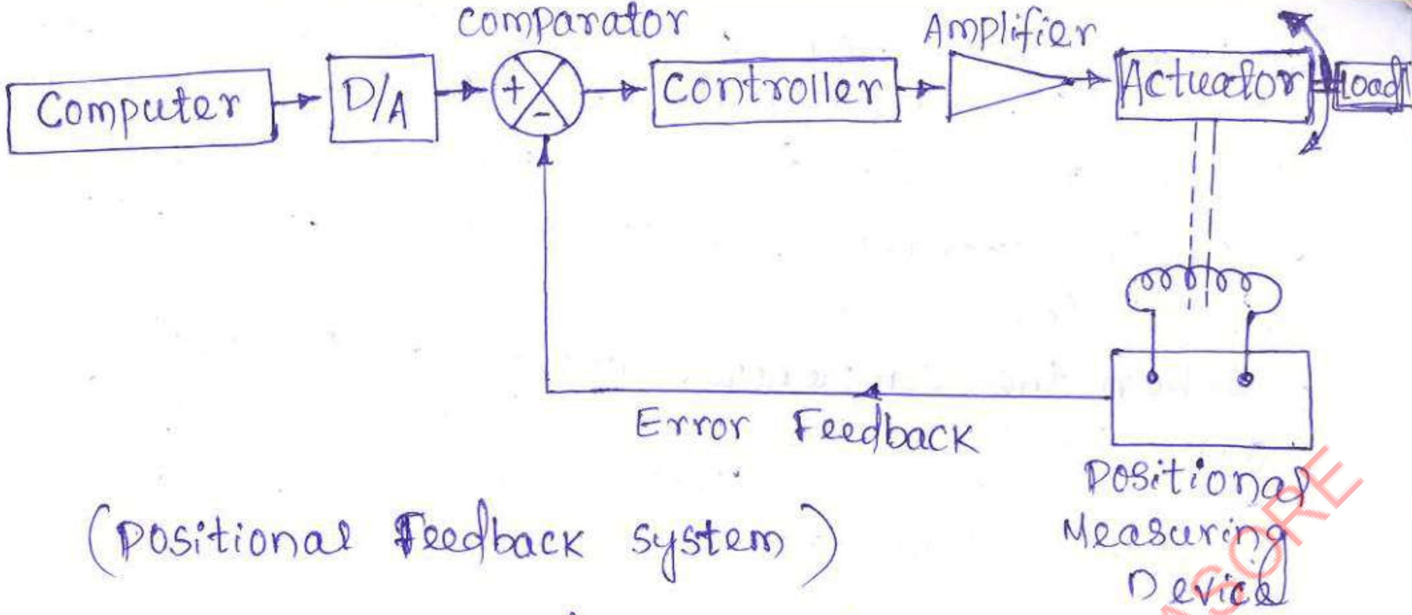
(1) Low efficiency.
(2) Prone to resonances.
(3) Noise and vibration
(4) Progressive loss of torque at high speeds. Hence it is not easy to operate at extremely high speeds.

Servomotor

- A Servomotor is a rotary actuator or linear actuator that allows for precise control of angular or linear position, velocity and acceleration.
- It consists of a suitable motor coupled to a sensor for position feedback. It also requires a relatively sophisticated controller, often a dedicated module designed specifically for use with Servomotors.
- Servomotors are not a specific class of motor, although the term servomotor is often used to refer to a motor suitable for use in a closed-loop control system.

Principles of Servo Control in a Robot

- A servomotor is a closed-loop servomechanism that uses position feedback to control its motion & final position.



(Positional Feedback system)

- Above fig. shows the block diagram of a positional feedback of a robot arm.
- The desired position of the robot arm is given through a computer that sends a digital signal. Finally the robot's arm is shifted to a new position by a d.c servo motor fitted to the arm.
- The digital signal from the computer is converted to an analog signal by a digital to analog (D/A) converter. This analog voltage is fed to the positive input of a comparator (an operational or differential amplifier).
- The output of the comparator is fed to the controller which in turn, sends its output to the actuator (a servo motor) through a variable gain power amplifier.
- A measuring device (a Potentiometer or a shaft encoder or a resolver) is fitted on the output shaft.
- The measuring device produces an electrical signal indicating the current position of the robot arm and the signal of the current positional information is fed back to the negative input of the comparator.

- The comparator compares the desired input signal (setting signal) and the actual output signal obtained through measuring device.
- Their difference (error signal) is amplified and fed to the actuator.
- When the comparator output is zero, the robot arm stops moving as it has reached the desired position. This is the principle of servo control system in a robot.

Advantages

(1) High output power relative to motor size and weight.
(2) Encoder determines accuracy and resolution.
(3) High efficiency. It can approach 90% at light loads.
(4) Servo motor can rapidly accelerate loads.

Disadvantages

(1) Servomotor will become unpredictable when something breaks. So safety circuits are required.
(2) Servo motors can be damaged by sustained overload.
(3) Peak torque is limited to a 1% duty cycle.

Microgripper

- The Microgripper is a Micro-Electro-Mechanical System (MEMS) with the ability to handle and manipulate micron or sub micron objects precisely.
- Grasping and manipulating small or micro-objects is required for a wide range of essential applications such as the assembly of small parts in microsystems or microsurgery nerve repair and selective extraction of cells.

- Microgripper devices are efficient, sense intelligent with precise control and with feedback of the gripping force.
- There are many types of micro grippers based on actuation systems such as thermal, piezoelectric, electrostatic, electromagnetic, vacuum type and mechanical.
- The general requirement of a microgripper is that it should be able to pick up and release a component at a specified position. The positional uncertainty during assembly should be well defined and components should not be damaged during assembly.

Micro Actuator

- A micro actuator is a microscopic servomechanism that supplies and transmits a measured amount of energy for the operation of another mechanism or system.
- Micro actuators are based on three-dimensional mechanical structures with very small dimensions which are produced with the help of lithographic procedures and nonisotropic etching techniques.
- The basic principle can be described as the expression for mechanical work

$$\boxed{W = \vec{F} \cdot \Delta\vec{r}}$$ → work = force × displacement

- The different types of microactuators are electrostatic, Electromagnetic, piezoelectric, fluid and thermal.

Micromotor

- Micromotors in lab automation are used in piezo motors power MRI robot, telemedicine robots, pharmaceutical dispensing, endoscopy surgical precision, automated biopsy device, ultrasound transducer, solution mixers and temp. regulators.
- Micro motors play a significant role in the automobile industry.

Drive Selection

- A robot will require a drive system for moving their arm, wrist and body. A drive system is usually used to determine the capacity of a robot, the speed of the arm movement, the strength of the robot, dynamic performance.
- For actuating the robot joints, there are three different types of drive system available such as electric drive, hydraulic drive and pneumatic drive.

Applications of Robots

Capabilities of Robots

- In order to make the robots useful in manufacturin[g] activities, they should possess the skill of transportation and manipulation.
- one of the important capabilities of the robot is its ability to acquire a part or a tool, transport it through a programmed space and then either release it to the proper location or manipulate to accomplish a certain task.
- Accordingly, there are categories of the robots known as part handling robots, tool handling robots and assembly robots.
- For performing complex operations, either continuous path or point-to-point servo controlled robots with adequate data storage capability are required.

Robot Applications with Examples

	Functions	No-serve robot	Servo-Robot PTP	Servo-Robot CP
Materials Handling	① Part Transfer	*	*	
	② Part Sorting		*	
	③ Heat Treatment	*	*	
	④ Palletizing		*	*
Machine loading and unloading	① Die casting	*	*	
	② Injection Moulding	*	*	
	③ Forming, stamping and Trimming process	*	*	
	④ Metal cutting Machine Tools like Lathe, Machining centre etc		*	
Machining	① Deburring			*
	② Drilling		*	
	③ Grinding		*	*
	④ other Machining		*	*

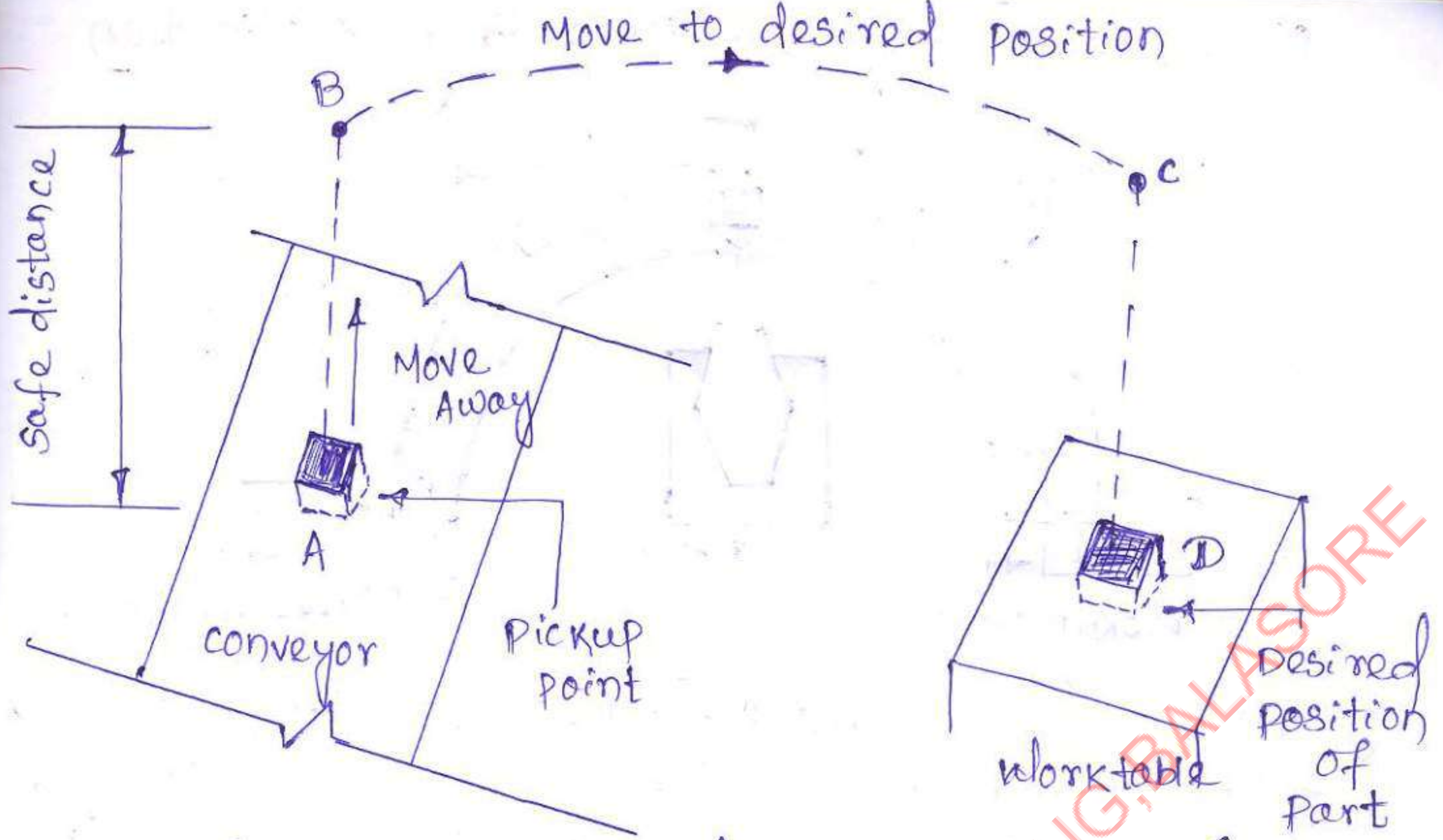
	Functions	No-Serve Robot	Servo-Robot	
			PTP	CP
Maintenance			*	*
Assembly	Mating parts or parts Inserting problems		*	*
Inspection			*	*
Welding	① spot welding ② Arc welding, seam Tracing		*	*
spray Painting/ finishing				*

Material Handling

- The most basic robot application is one in which the robot is required to pick a part or other material from one location and place it at another location. Many tasks performed by a robot require this basic pick-and-place operation. Some examples are
  (1) Material transfer applications.
  (2) Machine loading/unloading applications.
  (3) Assembly operation
  (4) Inspection
  (5) process applications like spot welding.

Material Transfer Applications

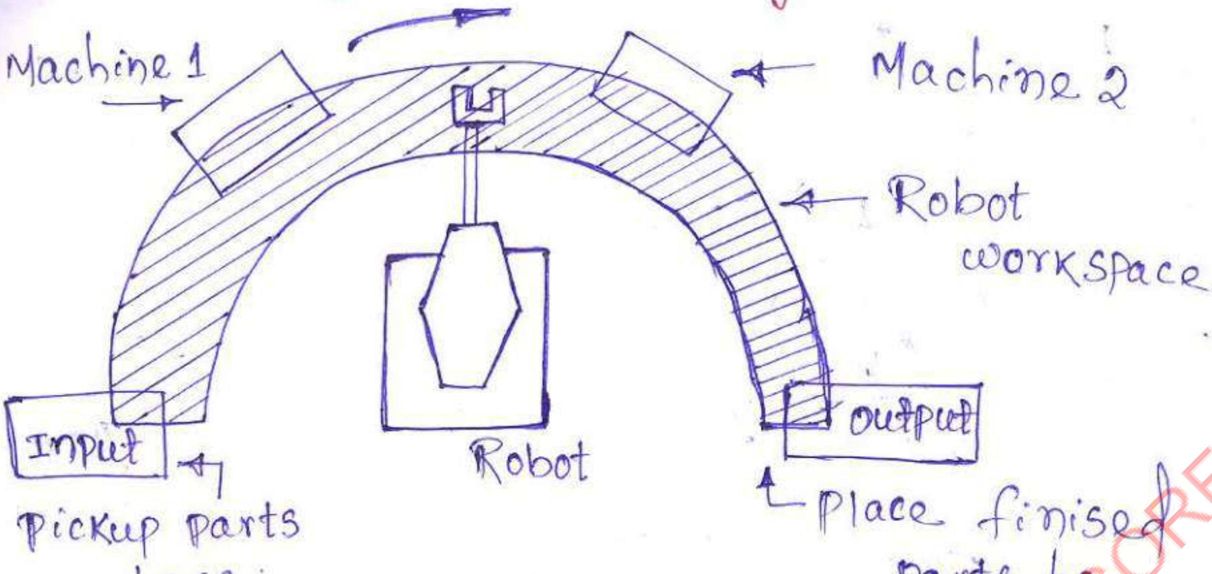
- A material handling operation in which the primary objective is to move a part from one location to another without any complex constraints is the simplest operation for a robot.
- The application usually requires a relatively simple robot with few degrees of freedom and a simple controller.
- These operations are commonly called pick-and-place (pick-n-place) operations.



(A typical Pick-and-Place workcycle)

- The end-effector motion required for the workcycle is only point-to-point motion as the path traversed by end-effector is not important.
- In the simplest operation, the part is made available to the robot at a fixed known stationary location and orientation called "pickup" point.
- The robot end-effector approaches this known location (pickup point, point A), grasps the part in the end-effector (gripper) moves away from this point to safe distance (point B), moves close to the position where the part is to be placed (point C) and places the part at the desired location (delivery point, point D).
- This forms the typical workcycle (A-B-C-D) of the pick-n-place operation as shown in fig.

Machine loading and unloading Application

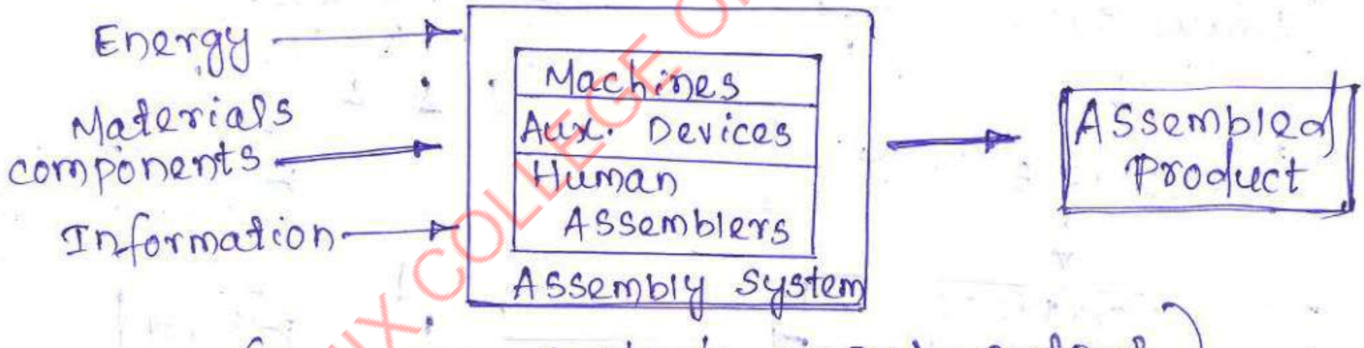


(A robot centered workcell for machine loading/unloading appl.)

- The loading of material or part and unloading it from a machine is the other material handling operation that is well suited for robotic applications.
- The robot's task is to pick the part from a specific location (the pickup point) and place it in desired position and orientation into the work holding device of the machine, which may be a chuck/vice.
- once the part is loaded into the machine, some manufacturing operations are performed on the part by the machine and then the part is unloaded from the machine.
- For unloading, the robot picks the part from the work holding device of the machine and places it at the delivery point or loads it into another machine.
- In the machine loading and unloading operation, the timing of the robot and the machine must be coordinated.
- The robot's cycle time must match the machine's cycle time. For this coordination, the robot controller must establish communication with the machine or monitor the machine operation with the help of suitable sensors and controllers.

Robot Assembly

- The concept of the word assembly differs from firm to firm. It is however, significant as assembly is obviously a major part of the total production process. While designing simple products, the assembly technique can be avoided, however, in the case of complex products one must accept the necessity of assembly operations.
- Components may be composed into a subassembly or into a complete product in the assembly systems.
- The assembly system can be defined as an integrated structure of machines, auxiliary devices and human assemblers, all employed for accomplishing the tasks in a process in which materials, energy and information are fed as input and the assembled product is obtained as the output.
- The is schematically represented in fig. given below



(Assembly system's Input-output)

Inspection

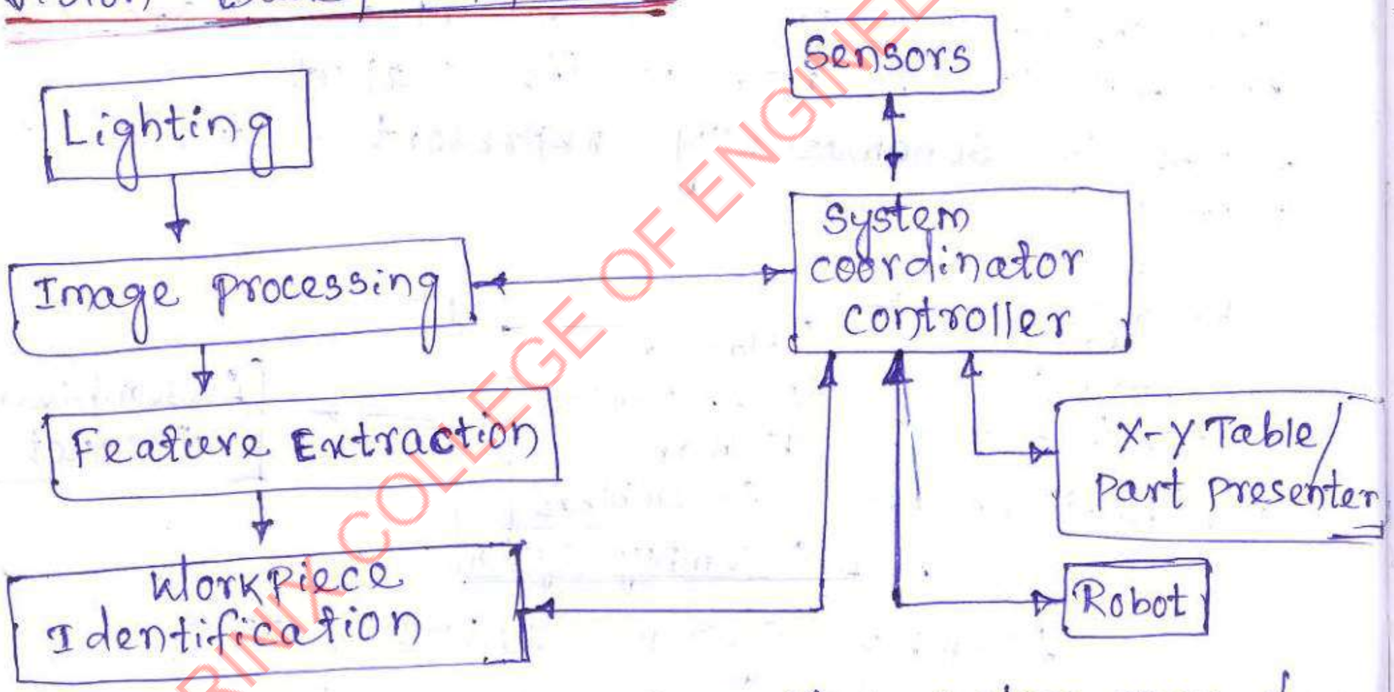
- Inspection function is required in every stage of manufacturing from raw materials to finished products.
- Robots can be used to inspect physical dimensions, surface finish and other characteristics of the raw materials, intermediate stages of parts, finished parts, sub-assemblies or finished products.

- To perform the inspection tasks robot requires various sensors or vision systems.

Sensor Based Inspection

- specific physical dimensions can be determined by the robot with the help of sensors placed on the gripper fingers of a material-handling robot.
- In material handling each part is grasped by the gripper and moved from one place to other.
- The specific physical size information can be obtained by the sensors fitted on the fingers of the gripper and the robot can determine whether the size is within tolerance limits or not.
- If the size is correct, part is placed on the desired place and if the size is incorrect, the part is may be dropped into a waste bin.

Vision Based Inspection



- A typical machine vision inspection system may check workpiece dimensions, transport and position the workpiece.
- The system components viz, sensor or machine vision systems, lighting techniques, vision guided robot manipulator for part handling and robotic X-Y table or part presenter for part presentation may be

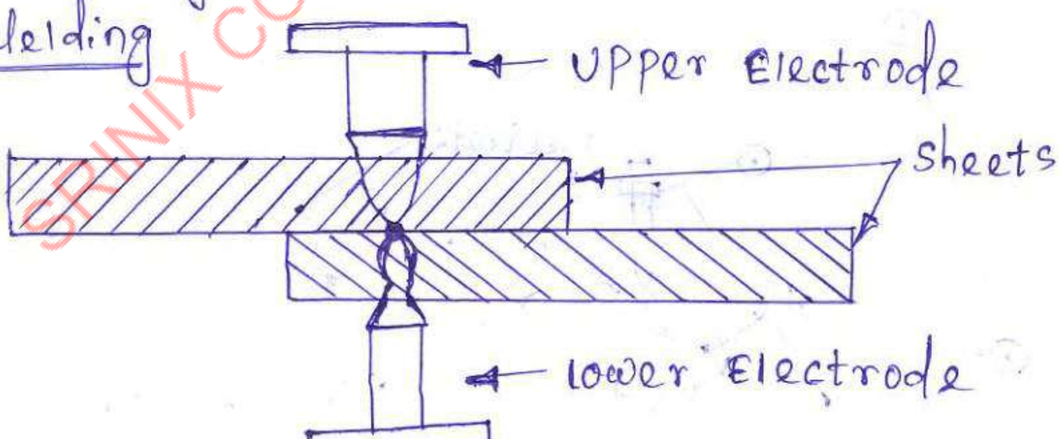
organized to have full automated inspection. fig. shows the block diagram of a vision-based inspection system.

- The part presenter may be loaded with multiple parts. The x-y table brings the parts within the field of view of cameras mounted over the table.
- The vision system identifies the desired part. If the system cannot recognize the part, it sends a signal for rejection and fresh parts are loaded.
- If a part is recognized, the controller directs the part presenter to position and orient the part such that the robot manipulator can pick up the part for further processing or assembly.
- Defects of the parts can be detected by vision-based robot inspection system. It can also check whether a hole is missing or an edge is defective.

Welding

- Robots find wide applications in welding and the robots used for the purpose of welding are tool handling robots.
- Two important classes of welding are performed by the robots. They are (1) spot welding (2) Arc welding.

spot welding



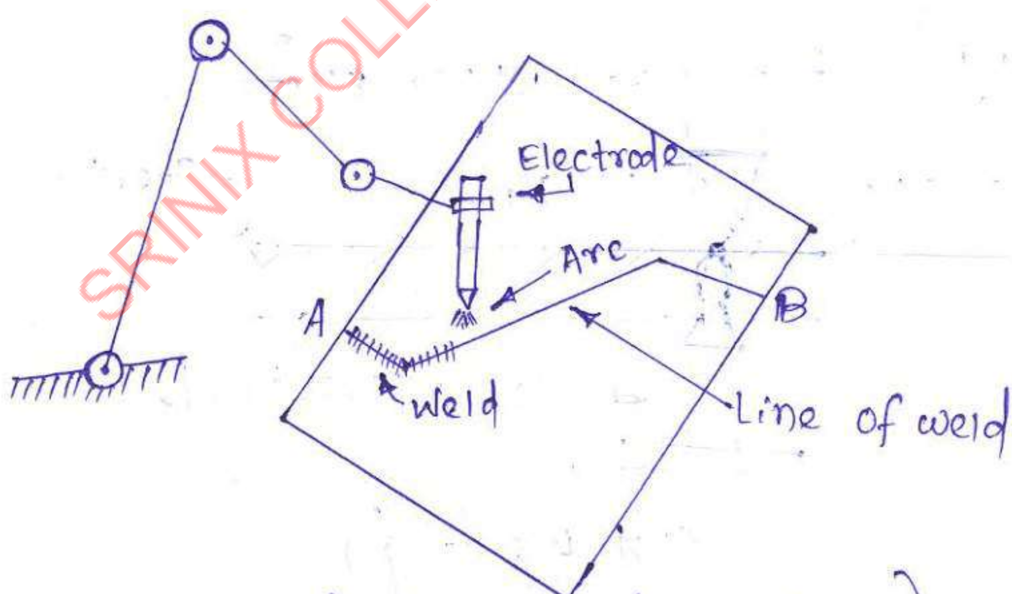
(Spot Welding)

- spot welding is done by fusing two metals at the spots where heat is generated by allowing an electric current to pass through the electrodes for a specific duration of time and pressing the joining surfaces with the electrode

- A. spot welding robot has
  (1) a robotic manipulator with several degrees of freedom.
  (2) a welding gun held on a robot wrist.
  (3) controller and power sources
  (4) I/O interfaces.

The operations involved in spot welding are
(1) squeezing the two metal surfaces betn the electrodes
(2) welding by passing current for specific duration of time depending on the type of the material and its thickness.
(3) releasing the grip.

Arc welding



(A straight line weld in plane)

- Welding application is most common process applications for industrial robots. Arc welding requires continuous long welding to make a welded joint betn two parts.
- A human operator, known as the welder, using the arc welding equipment, generally performs the arc welding.
- The arc welding equipment consists of an electrode holder, an electrode, a low voltage high current electric supply and electric cables.
- The arc is initiated betn the electrode and the metal pieces to be joined and this arc produces temperatures sufficient to melt the parts locally and form a pool of molten metal to fuse the two pieces together.
- If a consumable electrode is used it contributes metal as filler to the molten pool and its size reduces requiring (i) additional movement of electrode towards the parts to maintain the arc (ii) frequent replenishment of electrode.
- If a non-consumable electrode is used, filler metal may be supplied in the form of a separate wire or rod continuously.

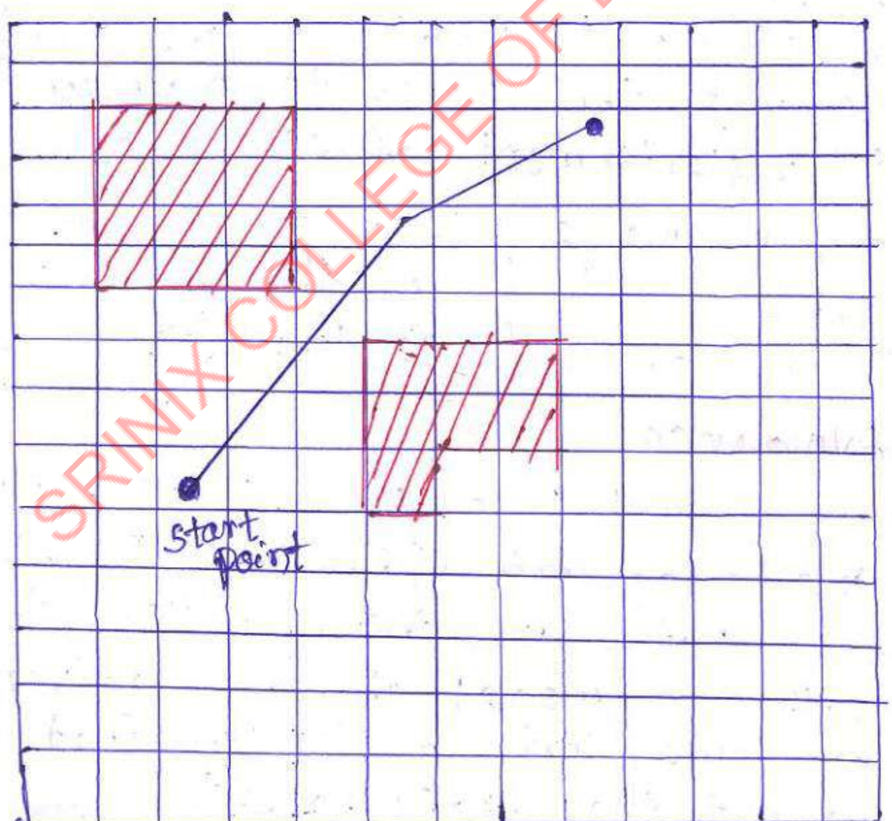
Obstacle Avoidance

- In planning a robot path, it is necessary to deal with obstacles near its operating zone. To find a collision-free path avoiding obstacles, the robot must have either a model of the environment around it or some sort of sensors that give information about the environment.
- To avoid collisions all parts of the robot must be considered, apart from the end-effector.
- When all the necessary information about the environment and the robot geometry is available,

the algorithms to plan for obstacle avoidance can be developed, which may fall in the following three classes as discussed by Lozano-Perez

(1) Hypothesize and test
(2) Penalty Function
(3) Explicit Free space

- In the explicit free space method the available free space is listed, instead of listing obstacles.
- This is done by breaking up the free space into small cubes or rectangular boxes and to store the coordinates of their corners.
- The free space is the space where the robot can go without any collision with the obstacles.
- A path is then searched from start point to the end point which is a sequence of positions of the free space.

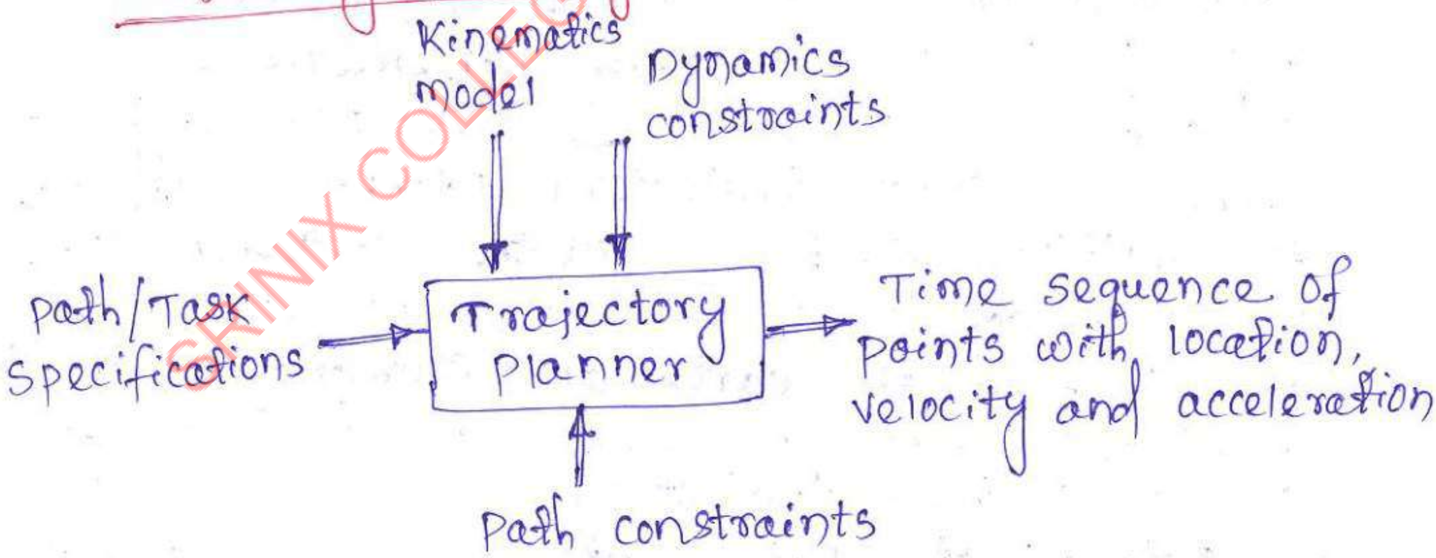


(fig. of collision free path using free space method)

Trajectory Planning

- The Process of computing a sequence of positions, velocities and accelerations.
- A trajectory is a description of the robot motion through space.
- Trajectory planning is the task of associating time with the path.
- The goal of trajectory planning is to describe the requisite motion of the manipulator as a time sequence of joint/link/end-effector locations and derivatives of locations, which are generated by interpolating or approximating the desired path by a polynomial function.
- one of the main objectives of any trajectory-planning algorithm is to achieve a smooth motion of the manipulator. The smooth motion has the important advantage of reducing the vibrations and wear of the mechanical system.

Trajectory Planning Problem



The above block diagram shows the parameters involved in the trajectory-planning problem.

Terminology

(1) Path - A path is the locus of points (either in the joint space or in the cartesian space) to be traversed by the manipulator to execute the specified task.

(2) Trajectory - A trajectory is the time sequence (time history) of position, velocity and acceleration for each joint or end-effector of the manipulator.

(3) Knot points or via points - Knot points or via points or interpolation points are the set of intermediate locations betn the start and goal points on the trajectory through which the manipulator must pass enroute to the destination.

(4) spline - It is the smooth function that passes through the set of via points.

(5) Joint space Trajectory planning - In joint space trajectory planning each path point is specified in terms of a desired position and orientation of the end-effector frame relative to the base frame. Each of these points is converted into a set of desired joint positions by application of inverse kinematics.

(6) Cartesian space Trajectory planning - In cartesian space trajectory planning the path is explicitly specified in the cartesian space. The path constraints (velocity, acceleration etc) are specified in cartesian coordinates and the joint actuators are served in joint coordinates to the specified trajectory.

(7) Path update Rate - The rate at which the trajectory points are computed at run time is called path update rate.

(8) Trajectory Generation - It is the act of computing the trajectory as a time sequence of values in real time using the trajectory planning algorithm based on the spatial and temporal constraints.

Steps in Trajectory Planning

Trajectory planning can be divided into three steps for solving the trajectory planning problem

① Task Description ÷ The first step in the motion-planning problem is to identify the kind of motion required. This specification of the requisite trajectory is the input to the trajectory planning algorithm.

② Selecting and Employing a Trajectory planning Technique ÷ The various trajectory-planning techniques fall into one of the two categories, Joint space techniques or cartesian space techniques. Next step in trajectory planning is to select a particular technique based on the task required.

③ Computing the Trajectory ÷ The final step is to compute the time sequence of values attained by the functions generated from the trajectory planning technique. These values are computed at a particular path update or sampling rate.

Joint space Techniques

- To plan a trajectory, the values of joint variables have to be determined from the end-effector location specified by the user.
- It is useful to recall that joint-space techniques are used for point-to-point motion with or without via points and each path point is specified by the end-effector position and orientation w.r.to the base in cartesian space.

Use of a P-Degree Polynomial as Interpolation Function

- The selection of a single polynomial for the entire joint path depends on the number of constraints imposed and the type of motion desired.
- The minimum number of constraints for a smooth motion betn two points are
  (1) Initial position
  (2) Initial velocity
  (3) Final position
  (4) Final velocity.
- With four constraints, a third-degree polynomial with four coefficients can be used,

$$q(t) = a_0 + a_1(t) + a_2 t^2 + a_3 t^3$$

- If, in addition, the initial and final accelerations are also specified, then one may use a fifth-degree polynomial,

$$q(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5$$

Cubic Polynomial Trajectories

Four constraints as

$$\begin{aligned} q(0) &= q^s & \dot{q}(0) &= 0 \\ q(t_g) &= q^g & \dot{q}(t_g) &= 0 \end{aligned} \quad -(1)$$

q^s = starting value
q^g = goal value

To describe the joint motion, assume that the cubic polynomial is

$$q(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 \quad -(2)$$

which gives a parabolic velocity profile

$$\dot{q}(t) = a_1 + 2a_2 t + 3a_3 t^2 \quad -(3)$$

and a linear acceleration profile

$$\ddot{q}(t) = 2a_2 + 6a_3 t \quad -(4)$$

Applying the constraints of eqn. (1) to eqs. (2) & (3), gives the following set of four equations in four unknowns.

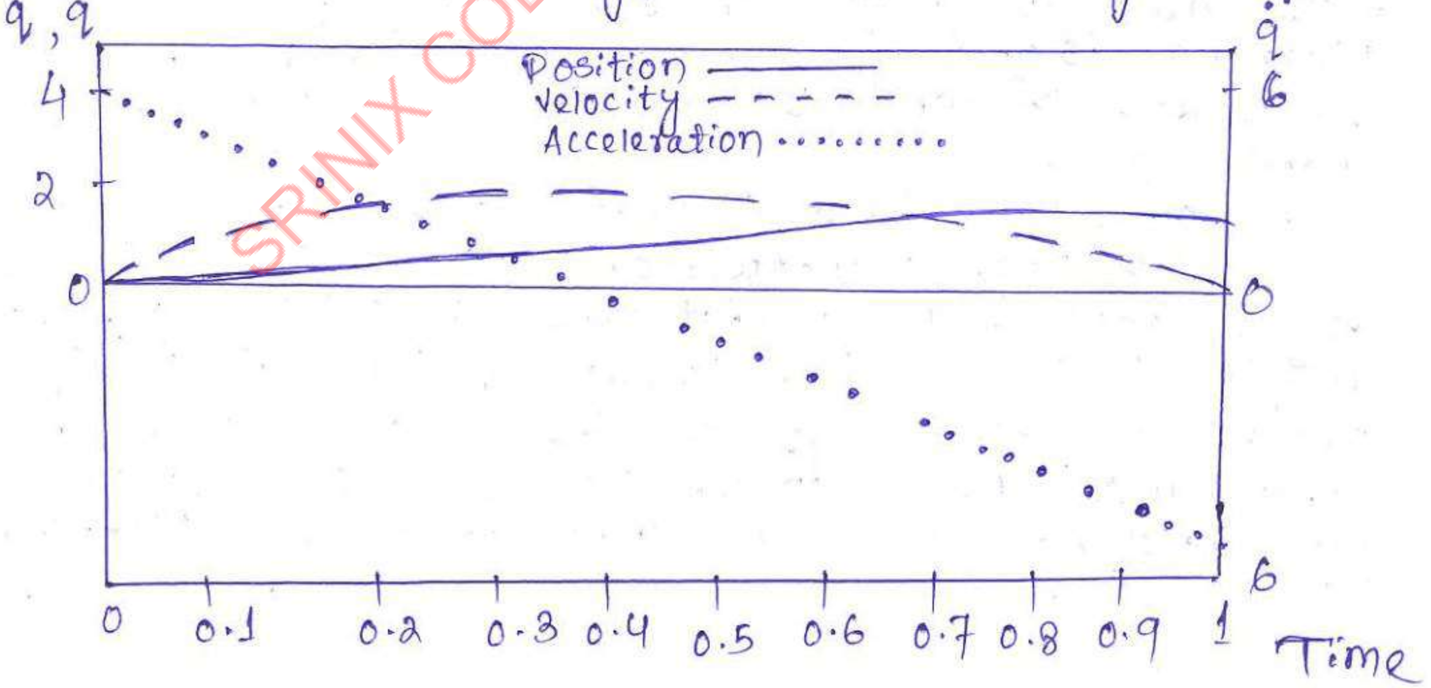
$$a_0 = q^s$$
$$a_0 + a_1 t_g + a_2 t_g^2 + a_3 t_g^3 = q^g \quad - (5)$$
$$a_1 = 0$$
$$a_1 + 2a_2 t_g + 3a_3 t_g^2 = 0$$

The solution of eq. (5) gives the coefficients of cubic polynomial, eqn. (2) as

$$a_0 = q^s$$
$$a_1 = 0$$
$$a_2 = \frac{3}{t_g^2}(q^g - q^s)$$
$$a_3 = -\frac{2}{t_g^3}(q^g - q^s)$$

Thus, the cubic polynomial to interpolate the path connecting the initial joint position to final joint position is

$$q(t) = q^s + \frac{3}{t_g^2}(q^g - q^s)t^2 - \frac{2}{t_g^3}(q^g - q^s)t^3$$



Cartesian Space Techniques

- In cartesian space, the position and orientation of a rigid body can be clearly defined.
- The problem of planning trajectories that enable the manipulator's end-effector to track a given path in cartesian space is investigated in this section.
- The user specifies the desired end-effector path, the travelling time and the tool orientations along the path.

Joint-space versus cartesian space Trajectory planning

- The joint-space trajectory planning is simple to implement and joint coordinates fully specify the position and orientation of end-effector. But when it comes to specifying a task or defining an obstacle in workspace, cartesian coordinates offer a better choice.
- It is easy to specify the position and orientation of a rigid body in space in cartesian coordinates.
- The obstacles and the path followed by the end-effector (tool point) can be expressed in terms of simple transformations and easy to visualize in cartesian space.
- The main drawback with joint-space trajectory planning is that it does not account for the existence of obstacles in the workspace of a manipulator.
- The other drawback is that due to the non linear nature of the manipulator's kinematics model it is difficult to predict the resulting end-effector motion that will be produced by a particular trajectory executed in the joint space. The above mentioned drawbacks could be overcome by employing cartesian space trajectory planning.

- One of the main drawbacks with cartesian space techniques is its computational complexity. Because the manipulator control system controls the joint variables, it is essential to resort to inverse kinematics/dynamics and determine the values of joint variables at every instant of time. This requires much more computations, which reduce the trajectory-sampling rate in real-time operation. As a result the trajectory-tracking accuracy decreases. This problem is not there in joint-space schemes where planning is done directly in joint space.

Example - 1 $\boxed{\text{Cubic spline trajectory}}$

The second joint of a SCARA manipulator is required to move from $\theta_2 = 30°$ to $105°$ in 5 seconds. Find the cubic polynomial to generate the smooth trajectory for the joint. What is the max^m velocity and acceleration for this trajectory?

Ans:- The given parameters of the trajectory are

$\theta^s = 30°$, $\theta^g = 105°$

$v^s = 0$, $v^g = 0$ $t^g = 5$ sec.

The four coefficients of the cubic polynomial are

$a_0 = \theta^s = 30.0$ $\qquad a_2 = \frac{3}{t_g^2}(\theta^g - \theta^s) = 9.0$

$a_1 = 0$ $\qquad a_3 = \frac{-2}{t_g^3}(\theta^g - \theta^s) = -1.2$

Hence the polynomials interpolating the position, velocity and acceleration of the joint are

$$\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3$$

$$= 30 + 9t^2 - 1.2t^3$$

$$\dot{\theta}(t) = 18t - 3.6t^2$$

$$\ddot{\theta}(t) = 18 - 7.2t$$