2 Structure of Robotic System

2.1 ANATOMY OF A ROBOT

The industrial robots resemble the human arm in its physical structure. Like the hand attached to the human body the robot manipulator or robot arm is attached to the base. The chest, the upper arm and fore-arm in the human body compare with the links in the robot manipulators. The wrist, elbow and the shoulder in the human hand are represented by the joints in the robot arm. As the industrial robot arm compares with the human hand, they are also known as "anthropomorphic or articulated robots",

Anatomy		*Representation*
1. Body	⟶	Base
2. Chest	⟶	Link
3. Shoulder	⟶	Joint
4. Upper arm	⟶	Link
5. Elbow	⟶	Joint
6. Fore-arm	⟶	Link
7. Wrist	⟶	Joint

The drives or motion to the links is provided at the joints. The joints motions can be rotational or translatory (sliding). The tool known as end-effector (gripper) is attached to the

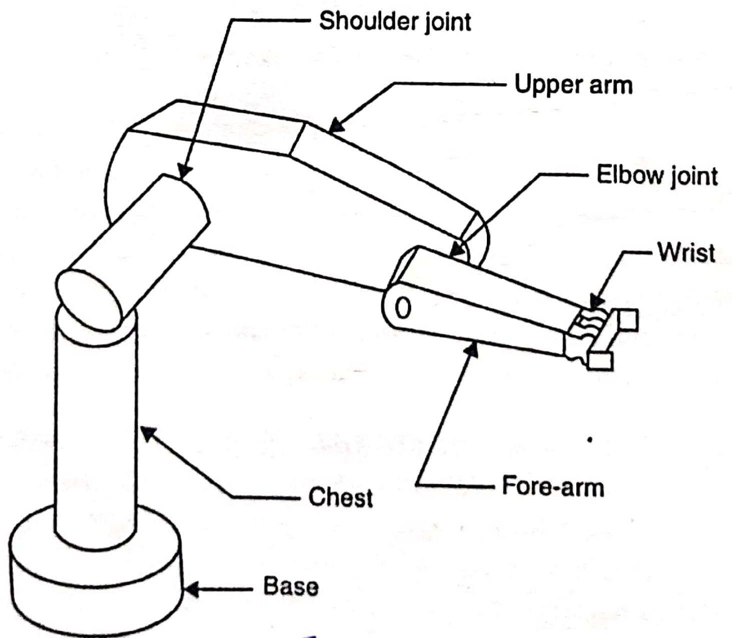


Fig. 2.1. Robot Anatomy.

wrist. The end-effectors are not considered as a part in the robot anatomy. The robot anatomy is shown in Fig. 2.1.

2.2 CLASSIFICATION OF ROBOTS

According to Japanese Industrial Robot Association (JIRA)	*According to Association Francaise de Robotique (AFR)*
1. **Class 1: Material handling device:** A man operated multiple degree of freedom machine used for handling materials.	1. **Type A:** Manual handling devices
2. **Class 2: Fixed Sequence Robot:** Robots performing unchangeable pre-determined stages of work in a sequence (fixed).	2. **Type B:** Automatic handling devices with fixed cycles.
3. **Class 3: Variable Sequence Robots:** Same as the class 2 but the sequences can be easily altered.	3. **Type C:** Programmable with point-to-point or continuous path controlled by servo-motors.
4. **Class 4: Playback Robot:** The motions are taught by the operator which is recorded and then the path is followed by robots.	4. **Type D:** Programmable intelligent robots that can work gathering information from the surrounding.
5. **Class 5: Numerically Controlled Robot:** The operations are programmed by the operator using APT and given to robot.	
6. **Class 6: Intelligent Robots:** These type can understand tasks in a surrounding and act intelligently.	

2.3 ROBOT CONFIGURATIONS

Sl. No.	*Configuration*	*Figure Number*	*Number of Revolute Joints*	*Number of Prismatic Joints*	*Example*	*Type of Work Space*
1.	Cartesian Robot (Gantry Robot) (3 P)	Fig. 2.2. (*a*)	Nil	Three (x, y and z)	IBM's RS–1 robot	Rectangular
2.	Cylindrical Robot (R 2P)	Fig. 2.2 (*b*)	One	Two	GMF's M–14 robot	Cylinder shape
3.	Polar Robot (Spherical Robot) (2 RP)	Fig. 2.2 (*c*)	Two	One	Unimate 2000, Maker–110	Spherical shape
4.	Jointed Arm Robot (Articulated Robot) (3 R)	Fig. 2.2 (*d*)	Three	Nil	Cincinnati Milacron T3	Irregular space

3.	Polar Robot (3R)	• Higher reach from the base • Geometric advantage in specification • Machine loading applications need this type.
4.	Jointed arm or Articulated Robot (2RP)	• Higher reach from the base • Useful in continuous path generation, applied to spray painting and are welding • Reaching the conjested small openings without interference.

2.5 ROBOTIC SYSTEM

The basic functions of an industrial robotic to handle the parts and tools for operations. Robots can be made to think and act on the specific task in a work environment, to provide soft automation to the given job. The tasks are accomplished by a robotic system which is an integration of systems like mechanical system, electrical system, electronic system and computer system.

The various systems that constitute a robotic system can be categorized as follows.

- Manipulator system
- Drive system
- Control system
- End effectors
- Sensors
- Vision system
- Computer software and hardware.

The links and joints, the end-effectors are the mechanical systems, the direct drive systems are generally electric. The control system, sensors and vision system fall under electronic system. The computer system are represented by software programs and computer hardware/ peripherals.

2.6 ROBOT LINKS

The two adjacent joint axes of a robotic manipulator are connected and defined by a rigid body called 'link', which maintains a fixed relationship between the two joint axes through a kinematic function. The relationship is described by two variables—the length of the link, 'a' and the twist of the link, 'α'.

The links are numbered starting from the fixed base of the manipulator, which is called link zero (0). The first moving rigid body is link 1. Between the joint axes i and $(i-1)$ the link is numbered $(i-1)$. A general link is represented in Fig. 2.3.

• Design Considerations of a Link

A robot link is attributed by the following design considerations—

- Strength and stiffness of link.
- The material used for fabrication.

- The weight and inertia.
- The location of the bearings.
- The selection of the type of bearing.
- The fits and tolerances in the joint.
- The external shape and aesthetics.
- The friction and lubrication.

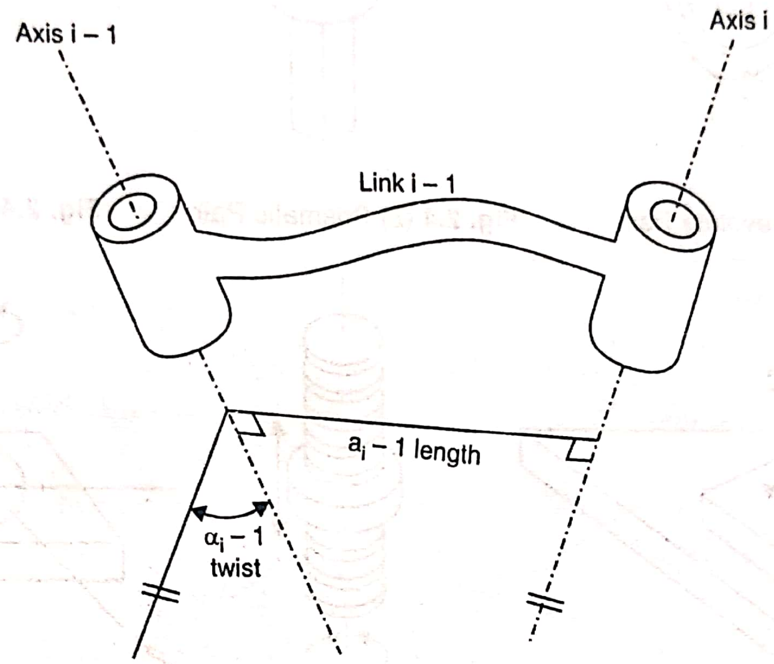


Fig. 2.3. Link Representation.

2.7 JOINTS IN ROBOTS

The relative motion featured by the sliding action between the two surfaces describes the characteristic connection known as the 'lower pair'. The lower pair formed between two links is termed as joint. The motion in the joint can be traslatory (linear/sliding) or rotary/ rotational, about or along the cartesian axes. The joints can exhibit one or more relative motion/s at a time, depending on that they are classified into following categories.

Joints	*Motions*	*Degree of Freedom*	*Figure*
• Revolute Joint	rotary motion	one	Fig. 2.4 (*a*)
• Prismatic Joint	sliding motion	one	Fig. 2.4 (*b*)
• Cylindrical Joint	one sliding and one rotary motions	two	Fig. 2.4 (c)
• Planar Joint	two sliding and one rotary motions	three	Fig. 2.4 (*d*)
• Screw pair	one translatory and one rotary motions	two	Fig. 2.4 (*e*)
• Spherical joint	Three rotary motions	three	Fig. 2.4 (*f*)

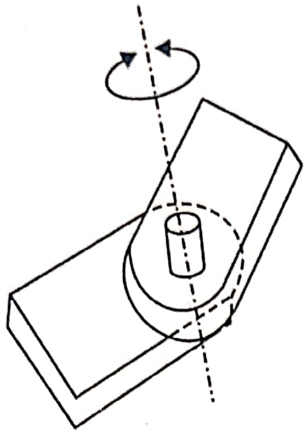


Fig. 2.4 (a) Revolute Pair.

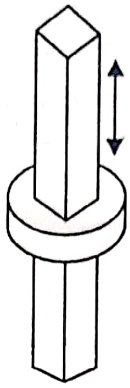


Fig. 2.4 (b) Prismatic Pair.

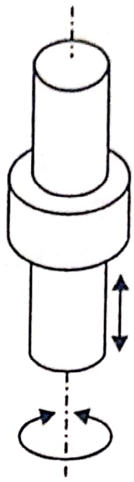


Fig. 2.4 (c) Cylindrical Pair.

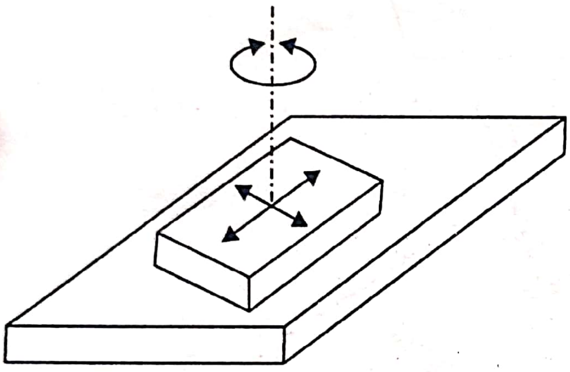


Fig. 2.4 (d) Planar Joint.

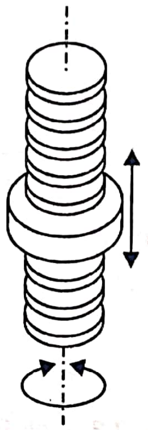


Fig. 2.4 (e) Screw Pair.

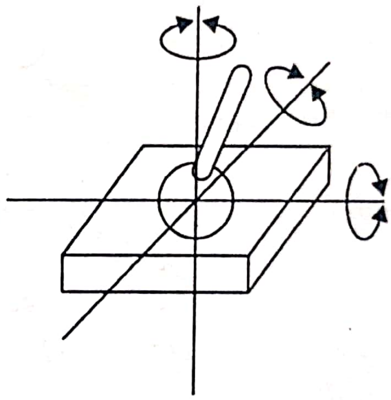
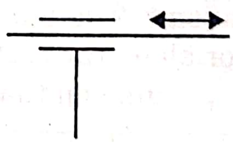
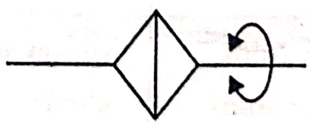
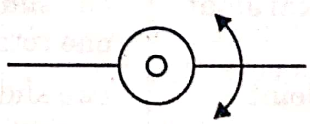
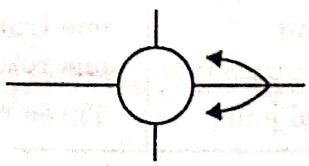


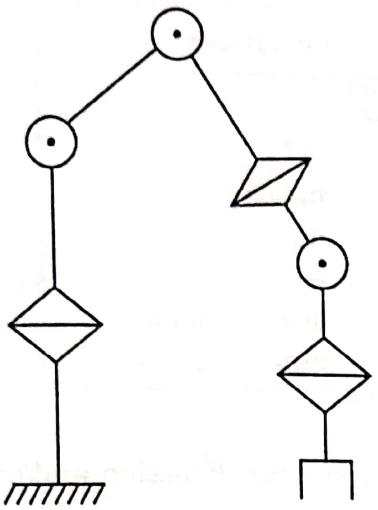
Fig. 2.4 (f) Spherical Joint.

2.7.1 Joint Symbols

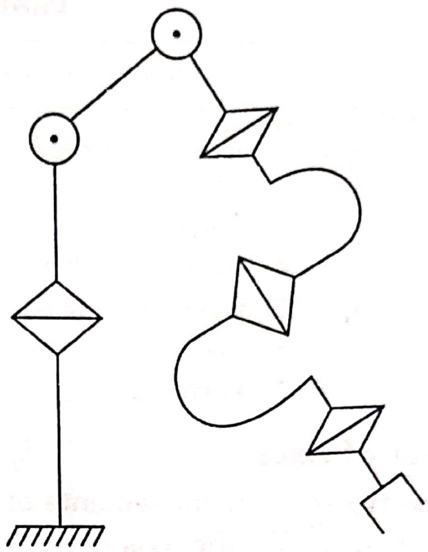
Joint description	*Symbols*
1. Prismatic joint	
2. Axial revolute joint	
3. Normal revolute joint	
4. Back and forth rotation joint	

2.7.2 Functional Diagrams of Robots

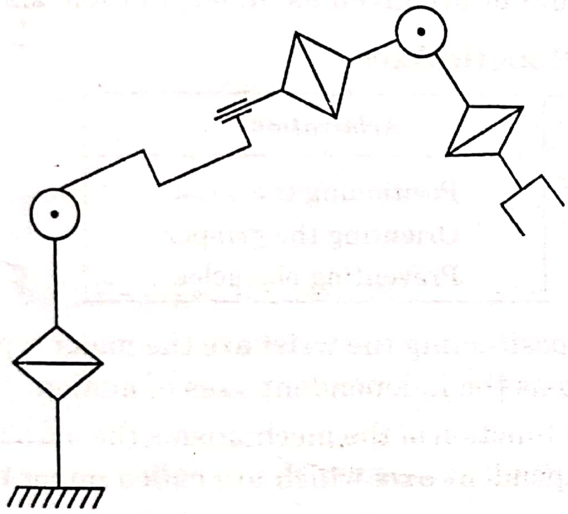
1. PUMA Robot



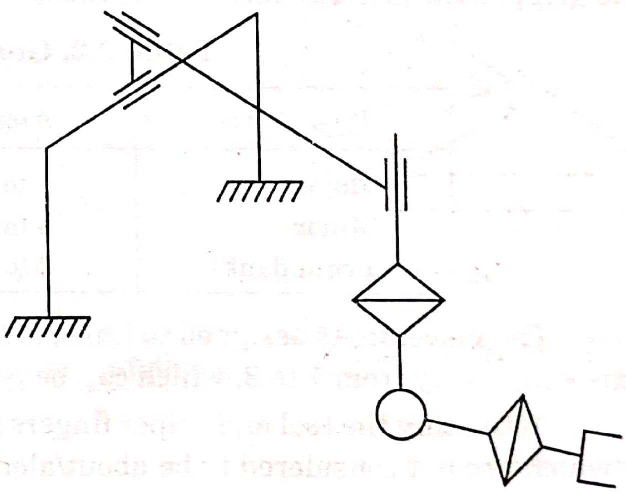
2. TR3-786 Robot



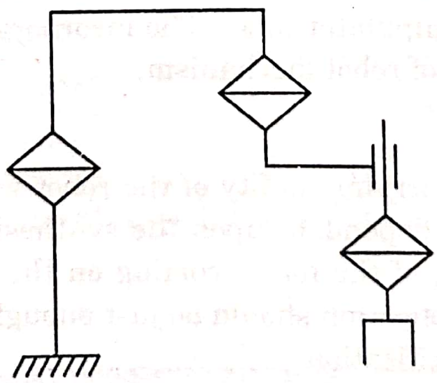
3. Kawasaki Unimate



4. IBM-7565 Robotic System



5. SCARA-Type Robot



2.8 ROBOT SPECIFICATIONS

The broad classification of the robots is conveniently based on drive system types, work space geometries and movement control techniques. Apart from these there are specific characteristics provided to the customer, useful in the selection of the robotic manipulators, precisely to the required application, which are enlisted as below in the table 2.1.

Table 2.1. Robot Features

Specifications	*Dimensions*
1. Number of Axes	—
2. Capacity	kgf
3. Speed	mm/sec
4. Reach and stroke	mm
5. Operating environment	—
6. Tool orientation	deg. or radians
7. Performance parameters	mm.

• Number of Axes

The translatory movements of the links along a particular direction and/or rotational motions about a specific axis decides on the number of axes attached to a given robotic manipulator. To achieve arbitrary position for the wrist and any specific position for the tool or the gripper the general axes for the robotic manipulator are given as under, in table 2.2.

Table 2.2. General Robotic Axes

Type of axis	*Axes*	*Arbitration*
Major	1 to 3	Positioning the wrist
Minor	4 to 6	Orienting the gripper
Redundant	7 to *i*	Preventing obstacles

The movements assigned to links, aiding in positioning the wrist are the major types of axis which vary from 1 to 3, which can be regarded as the independent axes of motion.

Activating the tool and griper fingers are the function of the mechanisms the movement of which are not considered to be about/along independent axis which are called minor types and they vary from 4 to six axes.

The obstacles within the work envelop are to be tackled by one or more redundant axes assigned to the redundant manipulator links. The incorporation of the redundant axes adds extra complexity to the design of robot mechanism.

• Capacity

"It is nothing but load carrying ability of the robot with the allowed deflection of the manipulator end". Capacity is dependent upon the synthesis of the manipulator dimension based on statics and dynamics of the forces coming on the manipulator. The selection of a particular robot for a given application should be just enough to the required capacity rather than to go in for additional specification.

• Speed

"It is the distance moved by the tool tip in unit time". The time required to execute periodic motion while performing work, can be one of the meaningful measure of speed. Some time the accuracy with which a task is to be performed may over ride the speed. The higher speed may be a requisite in high volume production. Higher speeds put a limit on the capacity of the robot.

• Reach and Stroke

The reach and the stroke are the measures of the dimensions of the work volume. They can be horizontal and vertical in the sense of movements. The respective reach and stroke are given in the Fig. 2.5 for a cartesian robot which has a cubical or parallelopiped work volume. A general relation between stroke and the reach is given by

$$\text{Reach} \geq \text{Stroke}$$

The equality of reach with stroke is a remote possibility in practicle situations.

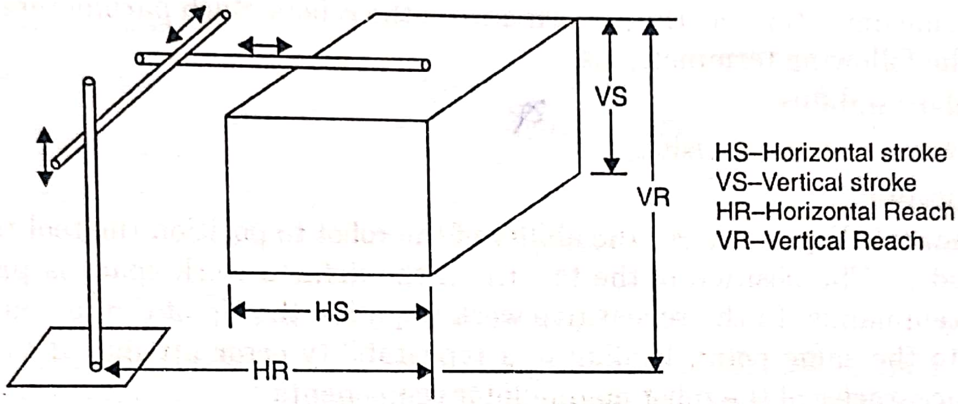


Fig. 2.5. Stroke and Reach.

• Operating Environment

The nature of the work performing surrounding of a particular robot is specific to an application. The application of robot to a job can have following types of operating environments

+ Dangerous to human beings.
+ Unhealthy in nature.
+ Harsh and difficult to access.
+ Complex and contaminated.
+ Extremely clean and dustless.
+ Ordinary and workable.

The examples of applications are movement of nuclear materials, spray coating or painting, welding (spot/continuous), loading and unloading, handling the electronic components and assembly of parts.

• Tool Orientation

The minor axes of movements determine the assumed orientation of the tool or gripper within the work envelope described by the major axes of motion. One of the tool orientation conventions is to specify the yaw-pitch-roll (YPR) of the end-effector or tool as is attributed to the aircraft movements.

For a partial rotation of angle ϕ degree

$$A_c = \frac{\phi}{2^k} \text{ degrees} \quad ...(2.5)$$

The spatial resolution represented with the mechanical components due to inaccuracies is illustrated by a statistical distribution is shown in Fig. 2.8.

If σ is the standard deviation about the mean point of the programmed position of tool tip, the spatial resolution takes the form

$$R_s = R_t + 6\sigma \quad ...(2.6)$$

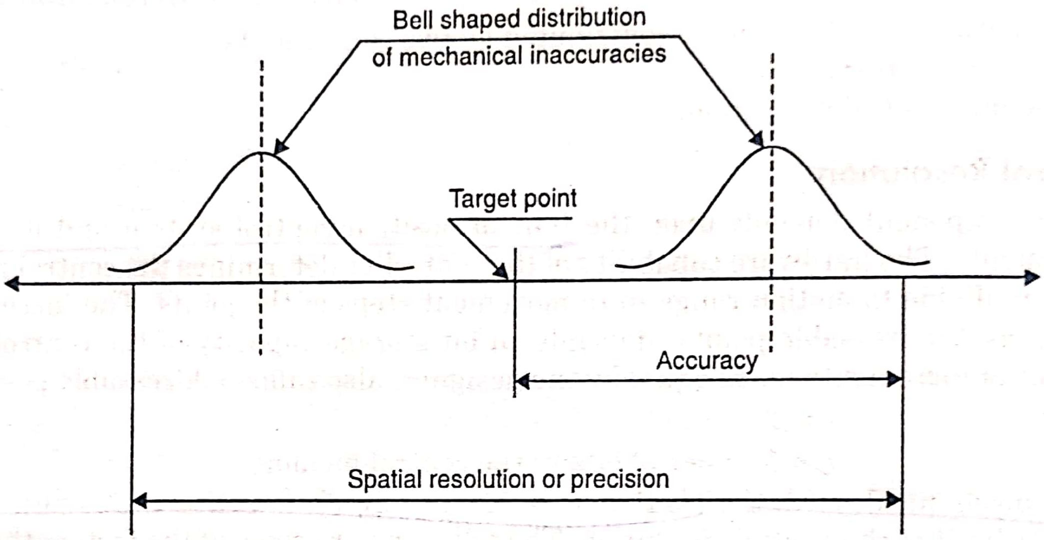


Fig. 2.8. Representation of Spatial Resolution and the Accuracy.

The spatial resolution of a particular joint in a robot arm is due to the specifications of the drive system position sensors and power transmission mechanism like gears, sprockets, chains, belts and cables. The programmed reference signal of the controlling computer generated inside is sent to the external analog feedback position control system through an 'k' bit digital to analog converter which decides the spatial resolution of the joint in focus.

Resolution for a Cylindrical Co-ordinated Robot

The work envelope of the cylindrical robot and the elemental sweep is as shown in the Fig. 2.9 (*a*). The horizontal precision is lowest at the outer most radius or reach and highest at the inner most reach.

The grid element shown in Fig. 2.9 (*b*) is not a square but a sector. But for a very small division it almost looks like a square.

Hence,

The radial precision (resolution) = dr

Minimum angular resolution = $rd\phi$

Worst angular resolution = $Rd\phi$.

Assuming grid element to be a square,

the horizontal resolution $= dh = \sqrt{(dr)^2 + (Rd\phi)^2}$ ...(2.7)

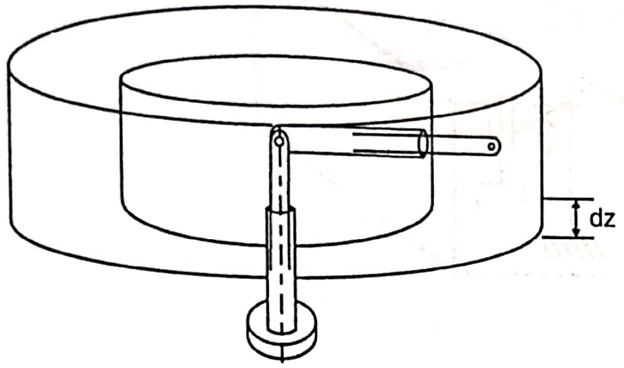
the vertical resolution $= dz$

Now,

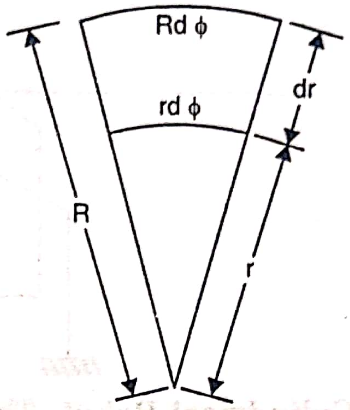
the total control resolution is given by

$$dT = [(dr)^2 + (Rd\phi)^2 + (dz)^2]^{1/2} \quad ...(2.8)$$

If a spherical robot is considered both the vertical and the horizontal precision are highest along the inside surface and decreases as the arm extends outward, and minimum at the outer most surface. If the robot with articulated joints is considered both the resolutions vary over the work space.



(a)



(b) Total Resolution.

Fig. 2.9

Accuracy

"Accuracy is the measure of the robot's ability to orient and locate the tool tip at a desired target location in the prescribed work volume or envelop".

Accuracy is related to resolution because as the resolution value is less, the accuracy is more. So higher resolution gives better accuracy, the ability to achieve the prescribed target location. In a worst case the desired point may lie in between the two target points. The error in positioning is the other name to the inaccuracy given by the term,

$$\frac{\text{Control resolution}}{2} \leq \text{error}, \qquad \ldots(2.9)$$

where the mechanical components of inaccuracies are neglected as they are more complicated to define and quantify. Hence the precision related to the accuracy gives a picture of discrete grid nodes that can be visited by the wrist end or the tool tip within the work space. Hence, the best accuracy is half of the grid size as shown in the Fig. 2.10.

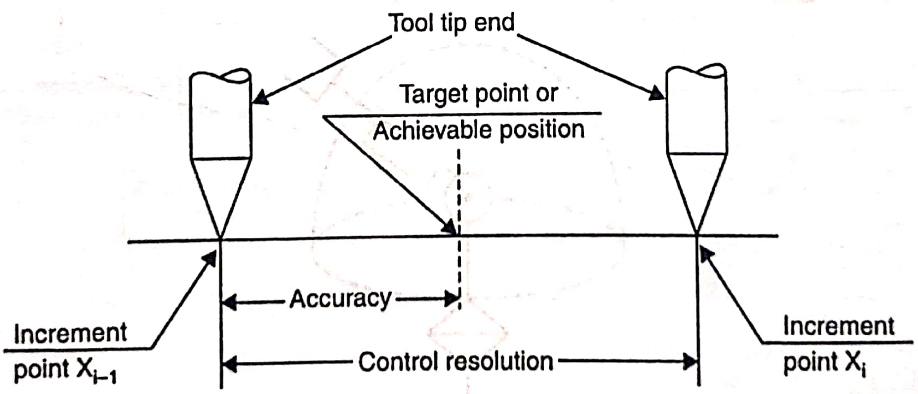
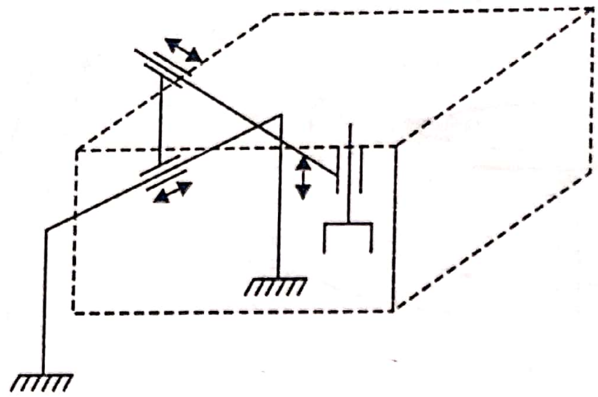


Fig. 2.10. Representation of Control Resolution and Accuracy.

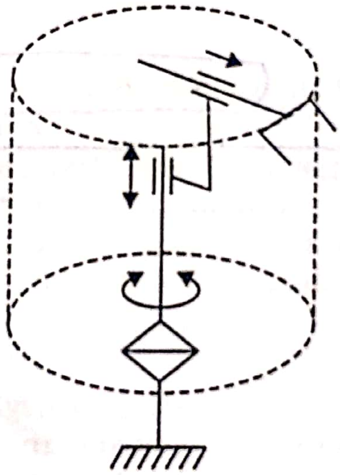
After a periodic operation set the robot may have to be calibrated to maintain the reasonable accuracy. The limit switch sensors of the robots are reset or zeroed during the periodic maintenance schedule. Further intelligent algorithms with real time solutions are needed to define and re-define the control strategies to compensate for the uncertainity in environment and position.

2.9.1 Types of Work Spaces

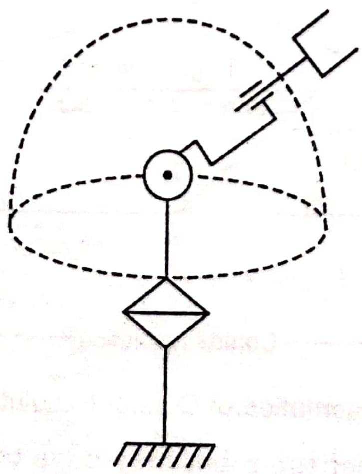
1. Cartisian Robot. This has three linear motions in x, y, and z direction. The work space covered is cuboidal type.



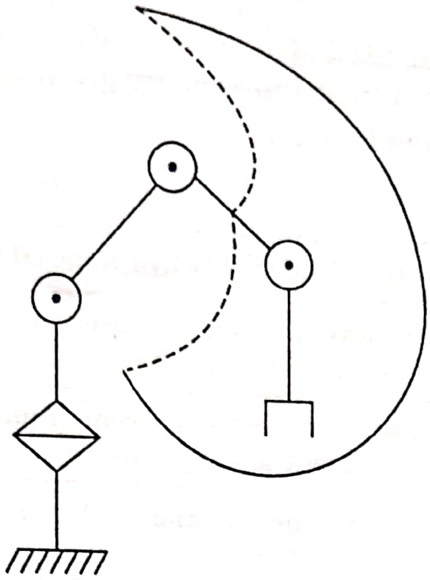
2. Cylindrical Robot. This has two linear motions in z and radial direction and a rotary motion about z-axis forming a cylindrical work envelope.



3. Polar Robot. This has one linear motion and two rotary joints moving about z and y axis. The work space generated is spherical in shape.

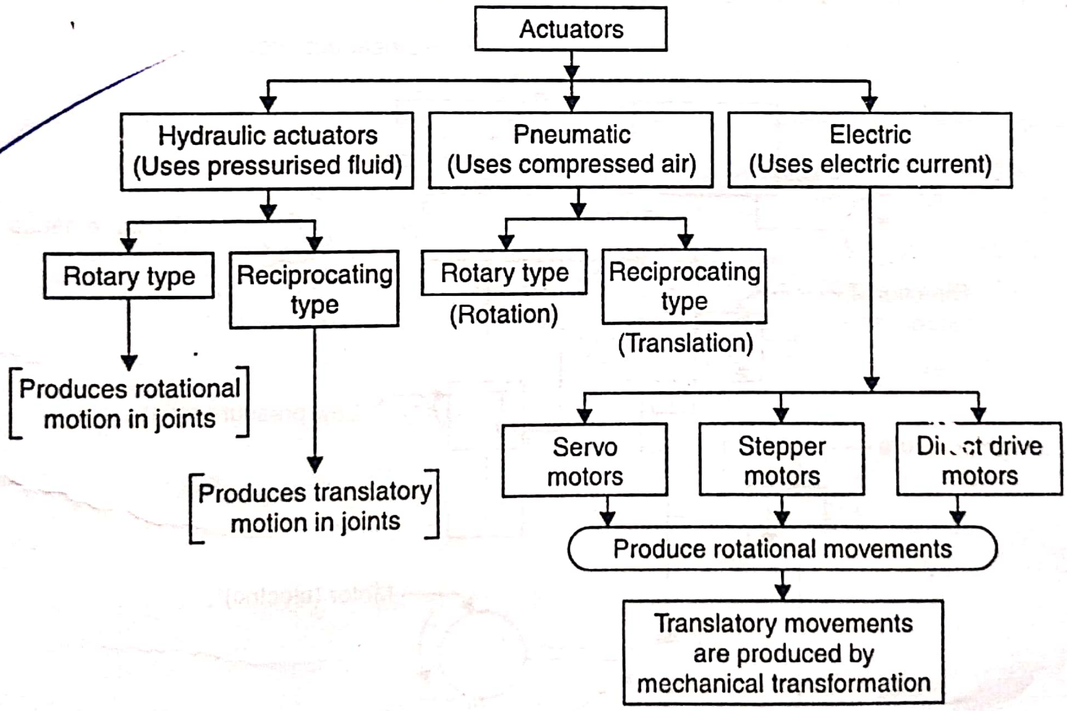


4. Combined Type (Revolute Robot). This has all the three joints revolute which produce rotary movements in x, y and z direction giving a irregular shaped work envelope.



2.10 ROBOT DRIVE SYSTEMS

The links of the robots move about the prescribed axis by receiving the power through, what are called the drive systems, also known as actuators. The movements produced may be translatory in nature or rotary about a joint. At the joints the actuators provide required force or torque for the movement of the links. The movements of all the links, combined together form the arm end or wrist motion. The source of power for the actuators can be through the compressed air, pressurised fluid or the electricity, based on which they are classified as follows.



2.11 HYDRAULIC ACTUATORS

The hydraulic actuators receive pressurised hydraulic oil with controlled direction and pressure through a system known as 'power packs'. The speed and volume flow rates are also controlled by the elements of the power pack. To produce linear motion the hydraulic cylinders

linear

are used and hydraulic motors are used to produce rotational movements. A list of elements of a hydraulic power pack along with their function are given here.

Elements of Power pack and functions

	Elements	*Functions*
1.	Reservoir or tank	Stores and supply hydraulic oil to the system, in a closed circuit.
2.	Hydraulic pump	Receives oil from the reservoir and pressurises the oil in accordance with its capacity.
3.	Electric motor	Receives electric current from mains and provides rotational movement to the pump.
4.	Valves	Control the direction of flow, regulate the pressure and provide safety to the system.
5.	Hoses and pipes	Provide connection between the various elements transporting the high pressure oil.

- **Hydraulic System**

The hydraulic circuit shown in Fig. 2.11 (*a*) shows symbolically the hydraulic system of linear actuator in a simplest arrangement. On the forward stroke of the piston of the cylinder the high pressure relief valve is effective and in the return stroke the low pressure relief valve acts to regulate the system pressure. The load handling capacity is determined by the system pressure in the forward stroke. The directional control valve controls the direction of motion of the piston in case of the linear actuators.

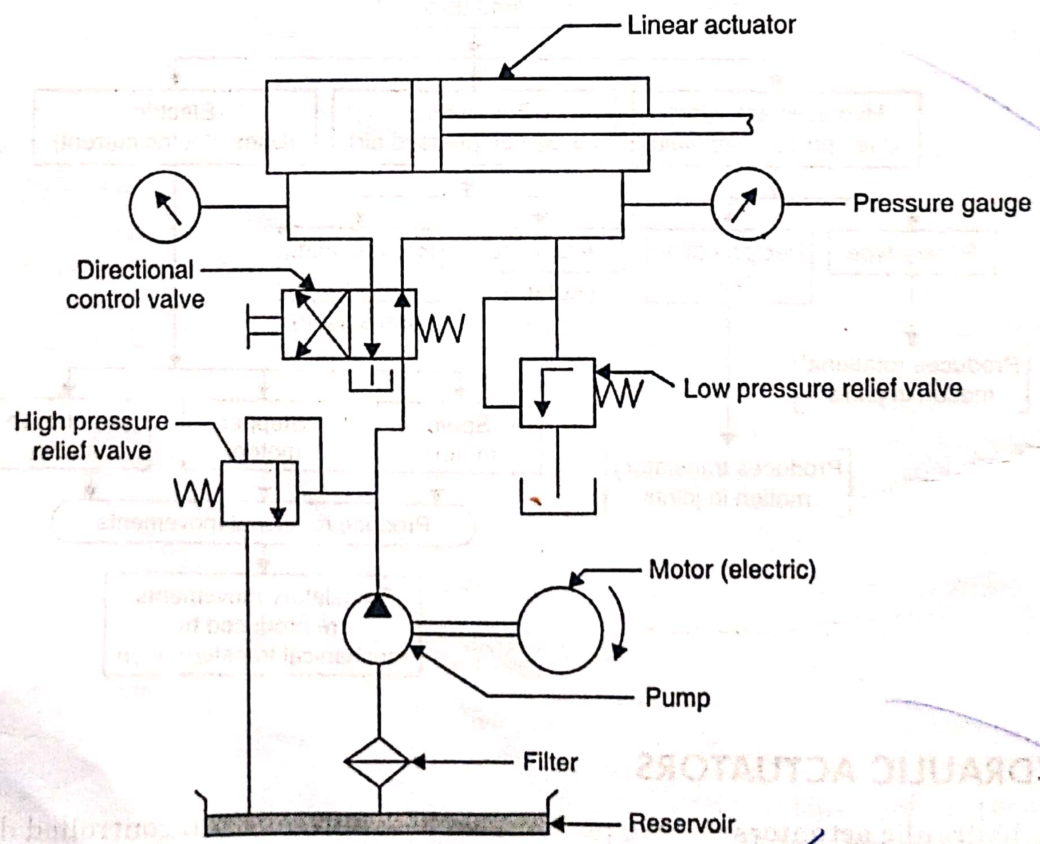


Fig. 2.11. (*a*) Typical Hydraulic Circuit.

Wreck

hydraulic motors → rotational movement
hydraulic cylinder → linear movement

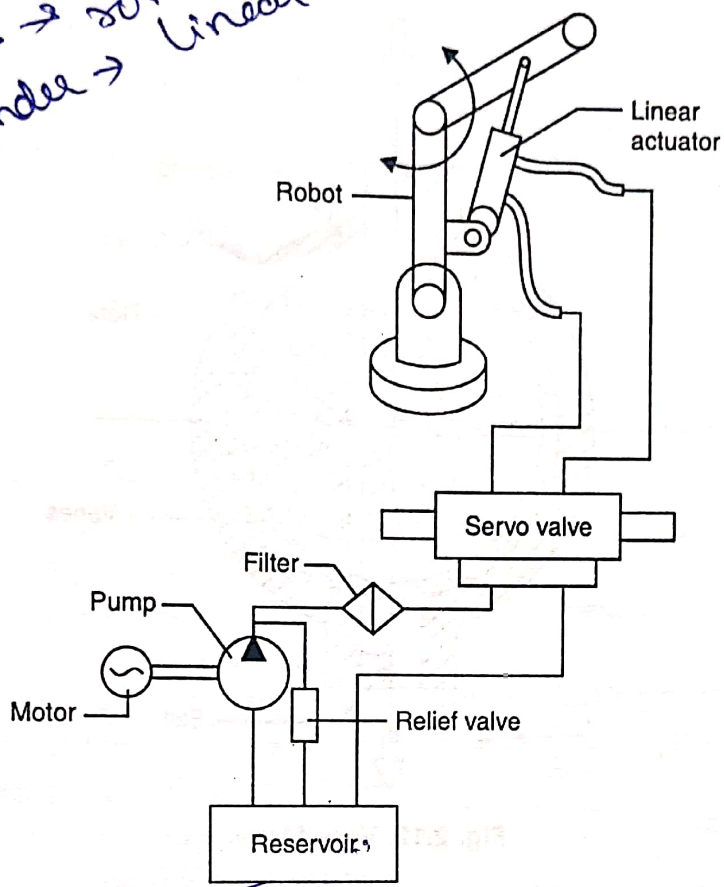


Fig. 2.11. (*b*) Hydraulic system for Robot.

• **Hydraulic Motors**

These are a type of power utilizing elements which convert hydraulic energy into mechanical rotational work useful in driving the links with revolute joints, in this context. One of the types of hydraulic motors, the vane motor is shown in Fig. 2.12, which is most commonly used type.

The motor consists of a circular rotor mounted ecentrically inside a circular stator ring. The rotor has got suitable slots for accommodating radially moving vanes. The rotational output of the motor depends on the eccentricity '*e*' of the rotor with respect to the stator.

The power output, $$P = \frac{D_r . e . V_r . p}{1000} \text{ kW} \quad ...(2.10)$$

where D_r = outermost diameter of the vane, *m*

e = ecentricity, *m*

V_r = linear speed of rotation = $\frac{2\pi NR}{60}$ m/sec

N = revolution per minute

$R = D_r/2$

p = pressure of the oil supplied to the motor.

And the torque developed, $$T = \frac{60,000 \text{ P}}{2\pi \text{ N}} \text{ kN-m} \quad ...(2.11)$$

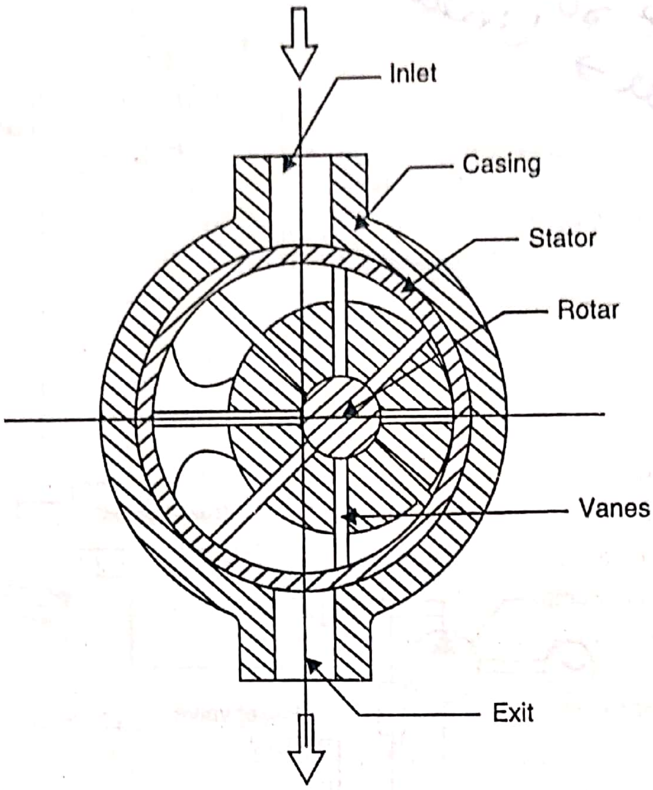


Fig. 2.12. Vane Motor.

• **Linear Actuators**

The actuators that provide linear reciprocating motion to the prismatic joints, by utilizing hydraulic power are known as linear actuators or cylinders, the constructional details are as shown in Fig. 2.13.

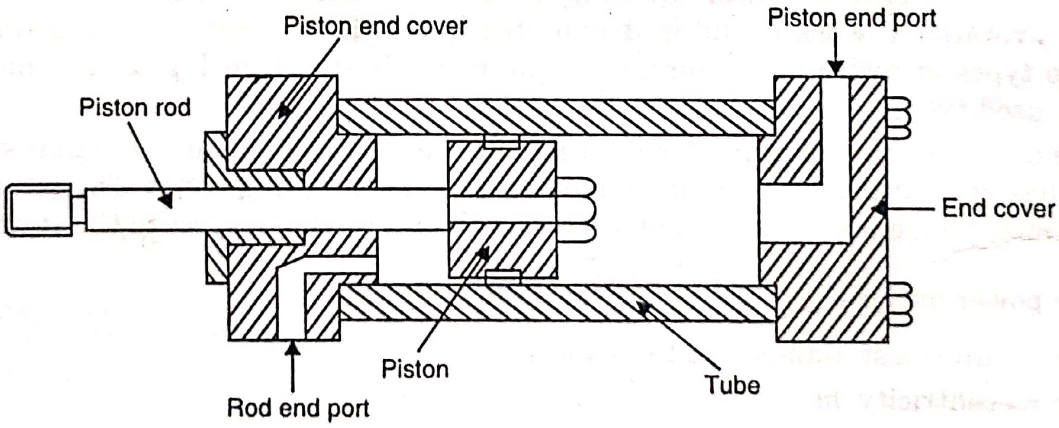


Fig. 2.13. Construction of Cylinder.

A cylinder essentially consists of a piston located in the tubular housing and a piston rod passing through one of the end covers. The ports provided in the end covers permit entry and return of the hydraulic oil.

If the hydraulic oil is supplied to the cylinder is at a pressure pN/m^2 with a volume flow rate of Q m^3/sec, the power delivered is given by

$$P = \frac{p \cdot Q}{1000} \text{ kW.} \qquad \text{...(2.12)}$$

The force developed in the rod is given by

$$F = p \cdot \frac{\pi}{4} \cdot D_p^2 \quad ...(2.13)$$

where D_p = diameter of the piston in meter.

The speed of motion, $$V_e = \frac{Q}{4} = \frac{4Q}{\pi D_p^2} \quad ...(2.14)$$

This is the speed in extension of the rod.

The speed of retraction, $$V_r = \frac{4Q}{\pi(D_p^2 - D_r^2)} \quad ...(2.15)$$

• Features of Hydraulic Actuators

- provide high power in small light components
- have flat load-speed or torque speed characteristics
- can operate safely and continuously under stall conditions
- provide stepless variation in speed
- have longer life and reliability due to the lubricating properties of the oil.
- can be easily built using readily available standard elements.
- have contaminant sensitive elements.
- the operation is noisy.
- higher inertia on the robot joints.
- power loss and unclean work area due to possibility of leak.
- less deflection due to low compliance of the elements.

• Applications of Hydraulic Actuators

1. Used to drive the spray coating robots.
2. Used in heavy part loading robots.
3. Useful in material handling robot system.
4. Used to drive the joints of assembly (heavy) robots.
5. Useful in producing translatory motion in cartesian robot.
6. Useful in robots operating in hazardous, sparking environments.
7. Useful in gripper mechanisms.

2.12 PNEUMATIC ACTUATORS

The principles of pneumatic actuators match with that of hydraulic actuator. The working fluid in case of this is the compressed air. The pressure of air used in this varies from 6–10 MPa. Because of low air pressure the components are light and the force/torque transmitted is also less, Pneumatic cylinders are used to actuate the linear joints and pneumatic motors are used to drive the revolute joints. The main problem with the pneumatic devices is that the working fluid (air) is compressible, hence the actuator drifts under loads.

The pneumatic actuators are characterised by the following features:

- Lowest power to weight ratio.
- Highly compliant system.
- Drift under load constantly.
- Low, inaccurate response due to low stiffness.
- Less leakage of air and not susceptible to sparks.
- Uses low pressure compressed air, hence less actuation force or torque.
- Useful in on-off applications like pick and place robots.
- Simple and low cost components.
- Reliable and easily available components.
- The exact positions of the actuators can be controlled by servocontrol valves by differential movements.

2.13 ELECTRIC DRIVES

• Principle

A rotational movement is produced in a rotor when an electric current flows through the windings of the armature setting up a magnetic field opposing the field set up by the magnets.

• The Main Components

Rotor, stator, brush and commutator assembly. The rotor has got windings of armature and the stator has got the magnet. The brush and the commutator assemblies switch the current to the armature maintaining an opposed field in the magnets.

• Performance

The torque on the rotor of the electric motor is given as

$$T_m = K_m \cdot I_a, \qquad \text{...(2.16)}$$

where K_m = motor torque constant

I_a = armature current.

$$= \frac{V_{in} - e_b}{R_a}, \qquad \text{...(2.17)}$$

where V_{in} = input voltage to the motor

e_b = back e.m.f.

R_a = armature resistance,

But e_b is the back e.m.f., the opposing voltage produced in the winding due to the rotation of the rotor. e_b is given as

$$e_b = K_b \cdot \omega \qquad \text{...(2.18)}$$

where K_b = voltage constant, ω is the angular velocity.

• Selection

The selection of the electric drive is based on the torque rating and the current rating of the motor. The torque rating of a electric motor is derived from the power rating of the motor. If P_m is the power rating the torque rating

$$T_r = \frac{60\, P_m}{2\pi\, N_m}, \quad \text{where, } N_m = \text{speed specification of the motor.}$$

- **Types**

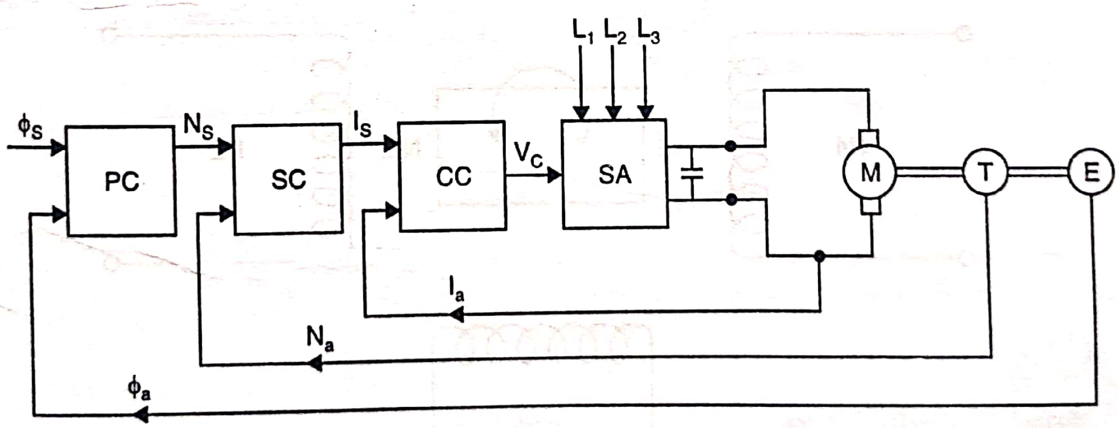
The most commonly used electric drives in robotics are

1. DC Servo motor
2. AC Servo motor
3. Stepper motor.

- **Features**

DC Servo Motors	*AC Servo Motors*	*Stepper Motors*
• Higher power to weight ratio.	• Rotor is a permanent magnet and stator is housing the winding.	• Moves in known angle of rotation.
• High acceleration.	• No commutators and brushes.	• Position feed back is not necessary.
• Uniform torque.	• Switch is due to AC but not by commutation.	• Rotation of the shaft by rotation of the magnetic field.
• Good response for better control.	• Fixed nominal speed.	• Needs microprocessor circuit to start.
• Reliable, sturdy and powerful.	• Favourable heat dissipation	• Used in table top robots.
• Produces sparks in operation, not suitable for certain environments.	• More powerful.	• Finds less use in industrial robots.
	• Reversibility of rotation possible.	• Extensive use is robotic devices.

- **Servo Motors**



PC = Position controller
SC = Speed controller
CC = Current controller
SA = Servo amplifier
M = DC/AC motor
T = Tacho-generator
E = Encoder.

N_a = actual speed
ϕ_a = actual position
I_a = actual current
L_1, L_2, L_3 = 3-phase supply.
ϕ_s, N_s, I_s, = desired position, speed and current
V_c = control voltage.

Fig. 2.14 (*a*)

The desired position (ϕ_s) is compared with the actual position (ϕ_a) feedback from the encoder (E). This gives the desired speed (N_s), which is compared with the actual speed (N_a) obtained as feedback from the tacho-generator (T). This gives the desired current (I_s) which is adjusted by the inner loop giving a feedback of actual current (I_a). A control signal (V_c) is generated which alongwith supply voltage V_d from a 3-phase system is given to the motor as input. In a servo-motor the position and speed of motor is controlled by the feedback control. The block diagram of servo motor is shown in Fig. 2.14(*a*).

2.14 STEPPER MOTORS

The stepper motors are unique type of motors that produce rotational movement in the form of finite angular steps. The intermittent electrical pulses make the stepper motor shaft to rotate in steps.

The Fig. 2.14 (*b*) shows the schematic arrangement of the stepper motor principle. The stator in this case is made up of four-electromagnetic poles. The rotor is a permanent magnet with two poles N and S. When the excitation of pole 2 (P2) is changed to P3 pole the magnetic north of the rotates by 90° clockwise. By continuous change in excitation in the order P2-P3-P4-P1-P2 the clockwise rotation is produced in the shaft of the rotor, which results in continuous movement.

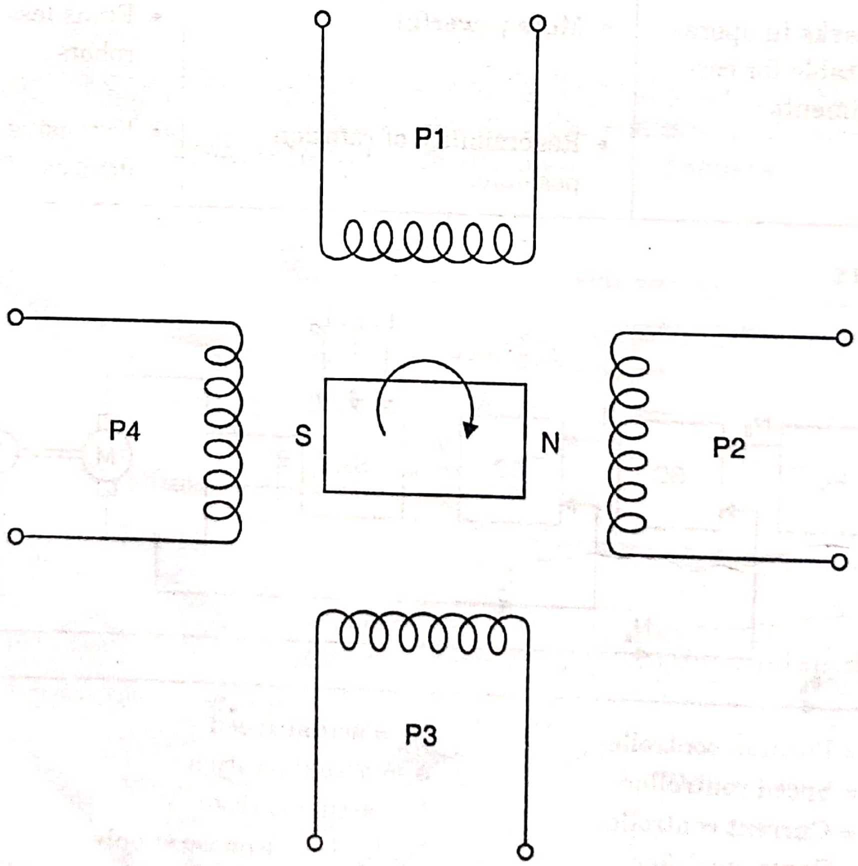


Fig. 2.14. (*b*) Schematic of Stepper Motor.

- **Construction of Stepper Motor**

Multiple pole stepper Motor :

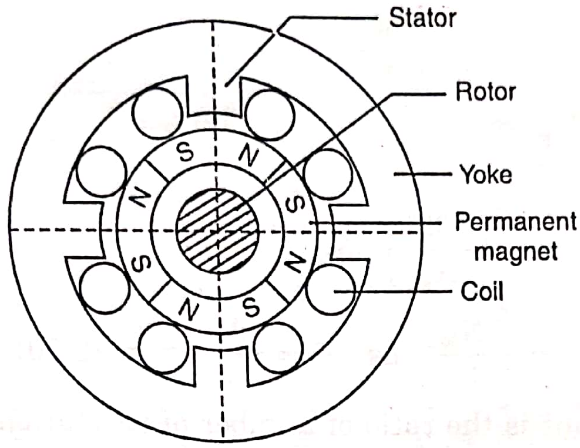


Fig. 2.14. (*c*) Permanent magnet stepper motor.

The stator has a winding made of concentrated coils on distinct poles. The rotor is permanent magnet cylinder.

Single-phase stepper motor:

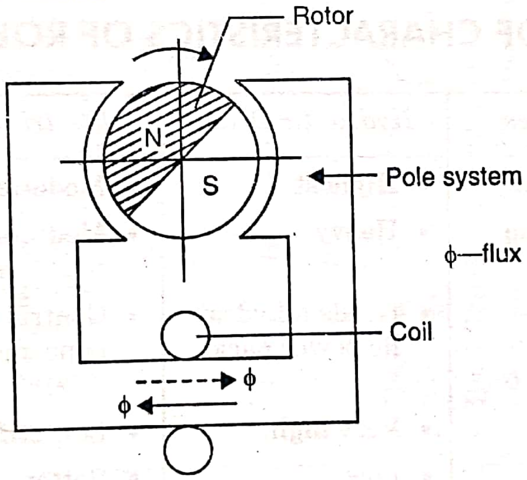


Fig. 2.14. (*d*) Single phase stepper motor.

Single phase stepper motor with two poles is shown in Fig. 2.14(*d*). By reversal of the current in the coil the polarity changes continuously by change in flow of flux in the poles. The rotor which is the permanent magnet makes rotation.

Resolution of Stepper Motor

Resolution is determined by the number of stator poles in the stepper motor.

Step angle, $$A_s = \frac{360°}{n_s}, \quad \text{...(2.19)}$$

where n_s is number of poles

or $$n_s = \frac{360°}{A_s}$$

The resolution is given by the inverse of the number of steps or the poles,

$$\boxed{R_s = \frac{A_s}{360°}} \quad \text{...(2.20)}$$

Pulse:

Single pulse of electrical signal is necessary for the rotor to rotate by one step. For one rotation number of pulse,

$$n_p = n_s = \frac{360°}{A_s} \quad \text{...(2.21)}$$

The pulse count for N_R revolutions of the rotor

$$n = N_R \cdot n_p$$

From (2.21),

$$n = \left(\frac{360°}{A_s}\right) \cdot N_R$$

or

$$n = \frac{N_R}{R_s} \quad \text{as} \quad R_s = \frac{A_s}{360°} \text{ from (2.20)}$$

Hence the pulse count is the ratio of number of revolutions and the resolution of the stepper motor.

If the rotor is rotating with a speed of N_m revolutions per minute,

The pulse rate,

$$n_r = \frac{N_m}{R_s} = \frac{\text{number of revolution / min}}{\text{Resolution}}$$

2.15 COMPARISION OF CHARACTERISTICS OF ROBOT DRIVE SYSTEMS

Sl. No.	*Comparing Features*	*Hydraulic Drive*	*Electric Drive*	*Pneumatic Drive*
1.	Power to weight-ratio—	• Highest	• Moderate	• Lowest
2.	Payload carried by the robot—	• Heavy	• Medium	• Low
3.	Controlling devices—	• Needs a hydraulic power pack	• Control system is needed	• Pneumatic power control devices needed
4.	Size and stiffness—	• Very high.	• Low stiffness	• Very low
5.	Compliance of the system—	• Low	• Better	• Good
6.	Leakage and cleanliness—	• Worst	• Nil	• Better
7.	Reliability of the components—	• Low	• High	• Higher
8.	Accuracy and response—	• Good	• Higher	• Bad
9.	Need for maintainance—	• Needed more	• Low	• Less
10.	Pressure, Torque and inertia on the actuator—	• High	• Medium to high	• Low to medium
11.	Range of operational speeds—	• Wide	• Comparatively less	• Very little
12.	Striking or generation of spark—	• Not there	• Possible	• No sparks
13.	Path generation application—	• Continuous path	• Both continuous pick and place	• Only in pick and place types

2.16 WRISTS AND MOTIONS

Orthogonal Axis Wrists

Pitch-Roll Wrist

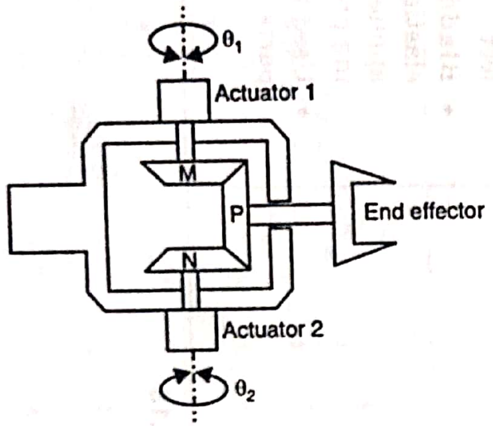


Fig. 2.15. Pitch-Roll Gripper Wrist.

Features and Applications

- Uses set of three (M, N, P) bevel gears
- Configuration resembles a "universal joint"
- The shafts of M and N are driven beg two separate stepper motors
- Pure "roll motion" is produced by when M and N are driven in opposite direction with same speed.
- Pure "pitch motion" is exhibited by the motion of M and N in the same direction with same speed.
- Applied to hold the tool (electrode) in a welding robot.

Pitch-Roll-Yaw type Wrist

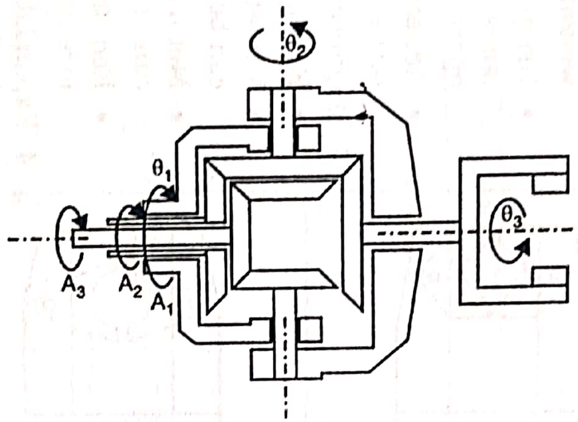


Fig. 2.16. Non-orthogonal Wrist.

Features and Applications

- Uses set of five bevel gears
- Actuators are remotely located.
- By different combinations of rotation and speed of the actuators the wrist attains pitch-roll-yaw motions.
- It has got three consecutive intersecting axes, which are orthogonal.
- Applied to hold the gripper in assembly and handling operations.
- This has three intersecting but non-orthogonal axes.

Non-Orthogonal Axis Wrists

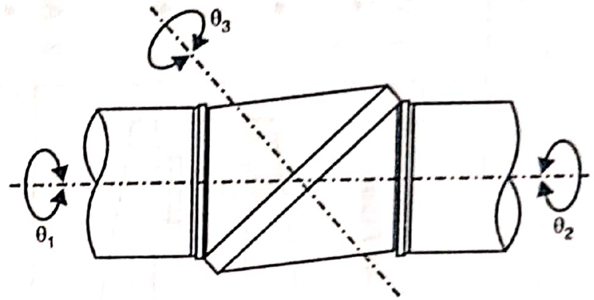


Fig. 2.17. Pitch-Roll-yaw Wrist.

Features and Applications

- This is also called "Three Roll Wrist".
- All three joints of the wrist rotate continuously driven by actuators.
- This has got some unattainable orientations.
- Design of such wrist is complicated.
- Driven by two actuators, to produce three rolls of movements.
- Used in pick and place, assembly robot. ex. Cincinatti Milacron.

2.18a PNEUMATIC GRIPPERS

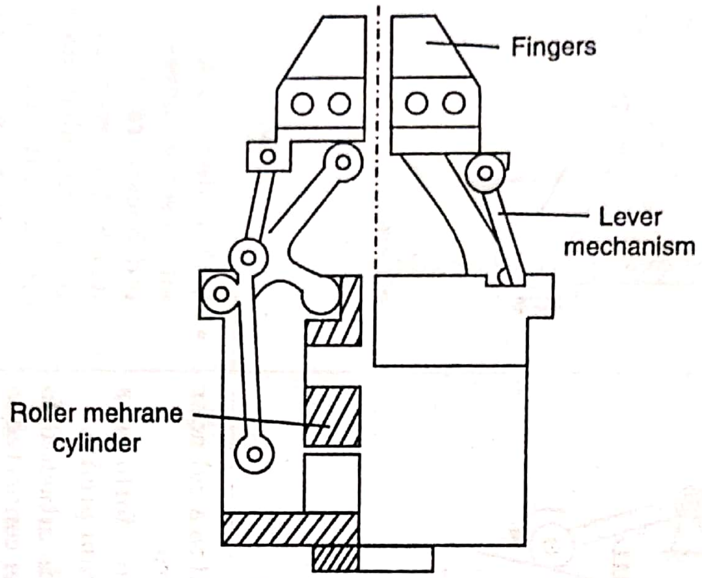


Fig. 2.19. (*b*) Pneumatic Gripper.

This pneumatic gripper is equipped with ~~roller membrane cylinder with~~ a rolling motion replacing conventional piston cylinder. The motion is transmitted to gripper fingers by means of lever mechanism. The grippers are actuated by switching valves in the circuit. The finger stroke is limited by end stops or the workpiece to be gripped. The gripping force is determined by the pressure of air applied and the leverage.

2.19 FORCE ANALYSIS OF GRIPPER MECHANISM

A gripper mechanism consisting of fingers, linkages frame and a pneumatic cylinder is shown in Fig. 2.20. Air pressure supplied to the cylinder aids in actuating the fingers to grab an object with a gripper force P_g.

If the mass of the object is '*m*' and '*g*' is gravity acceleration.

The force due to mass $= m.g. = W$, newtons. ...(2.22)

The friction between the finger pads is responsible for the gripper to hold the object exerting the force W.

The friction force is given by,

$$f = \mu \, NP_g, \qquad \text{...(2.23 a)}$$

where μ = coefficient of friction,

N = the number of fingers.

Due to the uncertaining of circumstances the capacity of the fingers had to be increased due to incorporate a safety by a factor of safety, *n*.

i.e., $$F_d = \text{design force} = n.W \qquad \text{...(2.23 b)}$$

Equating equations (2.23 *a*) and (2.23 *b*)

$$n.\mathrm{W} = \mu\, \mathrm{NP}_g$$

and
$$\mathrm{P}_g = \frac{n.\mathrm{W}}{\mu\, \mathrm{N}} = \frac{n.m.g}{\mu\, \mathrm{N}} \quad ...(2.24)$$

If the gripper is accelerating or decelerating by '*a*'

$$\mathrm{P}_g = \frac{n.m}{\mu\, \mathrm{N}}(g \pm a) \quad ...(2.25)$$

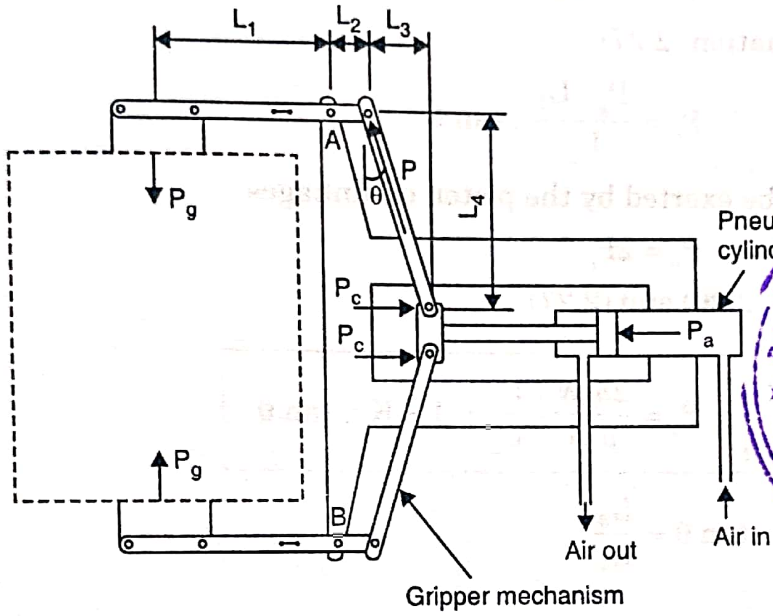


Fig. 2.20. Force Analysis of Gripper Mechanism.

'*a*' takes the positive sign when accelerating down and takes negative sign when accelerating up.

The expression (2.25) can also be written as

$$\boxed{\mathrm{P}_g = \frac{n.(mg)}{\mu\, \mathrm{N}}(1 \pm \mathrm{K}_f)} \quad ...(2.26)$$

The factor $\mathrm{K}_f = \dfrac{a}{g}$ and weight of the object, W = (*mg*)

Table 2.3

Accelerating motion	*Factor* $(1 \pm \mathrm{K}_f)$
• Accelerating down	3
• Accelerating up	1
• Accelerating in horizontal direction	2

- **Linkage Analysis**

Referring to the Fig. 2.20 and taking moment about the point A,

$$P_g \cdot L_1 - (P \cos\theta) \cdot L_2 = 0$$

$$P = \frac{P_g \cdot L_1}{(L_2 \cdot \cos\theta)} \qquad \text{...(2.27)}$$

where $\theta = \tan^{-1}\left(\frac{L_3}{L_4}\right)$ and P = linkage force in Newton Resolving the force, P

$$P_c = P \cdot \sin\theta$$

Substituting equation (2.27)

$$P_c = \frac{P_g \cdot L_1}{L_2} \cdot \tan\theta.$$

But the force to be exerted by the piston on linkages

$$P_a = 2P_c$$

Using equations (2.26) and (2.27)

$$\boxed{P_a = \frac{2n\,W}{\mu\,N}\left(\frac{L_1}{L_2}\right)(1 \pm K_f).\ \tan\theta} \qquad \text{...(2.28)}$$

Substituting $\tan\theta = \frac{L_3}{L_4}$

$$P_a = \frac{2nW}{\mu\,N}\left(\frac{L_1 \cdot L_3}{L_2\,L_4}\right)(1 \pm K_f) \qquad \text{...(2.29)}$$

Power requirements:

If the diameter of the piston of the actuator is d_p

Area of the piston, $A_p = \frac{\pi}{4} \cdot d_p^{\,2}$ in m^2

The pressure of air needed $= \frac{P_a}{A_p} = p$

$$p = \frac{4}{\pi} \cdot \frac{P_a}{d_p^{\,2}}$$

The power required to produce this pressure, $p(N/m^2)$

$$P_R = \frac{p \cdot Q}{1000}\ \text{kW} \qquad \text{...(2.30)}$$

where Q is the discharge (volume flow rate) of air in m^3/sec.

-7. Bno

2.20 GRIPPER DESIGN CONSIDERATION

Part Specification	*Performance Specification*	*Source Specification*	*Position Specification*	*Environmental Specification*	*Material Specification*
• Weight of the part • Size and shape of the component • Tolerance on the part size. • Change of shape and size during processing. • Surface finish of the part. • Care for delicacy of the part to be handled.	• Co-efficient of friction between part and object. • Speed and acceleration during motion. • Accuracy and repeatability of the robot. • Interchangeability of fingers. • Memory capacity of the controller. • Control resolution of the robot. • Lead time and cycle time.	• Pneumatic: air pressure and discharge, and cylinder size. • Electrical: The power rating and specification of actuator. • Hydraulic: The oil pressure, volume flow rate and the power pack specification. • Mechanical: Linkage design and transmission design specification.	• Holding methods. • Physical difficulty • Length of fingers • The object and tool orientation. • Product design changes. • Spare parts specifications.	• Heat and temperature of object and atmosphere. • Humidity and moisture. • Dirty and safety. • Hazardness of chemicals used.	• Strength and rigidity. • Durability and fatigue factors. • Friction properties. • Factor of safety. • Design standards. • Compatibility with the environment.

2.21 SELECTION CONSIDERATION OF GRIPPER (END-EFFECTOR)

Actuation Selection	*Drive Selection*	*Protection Selection*	*Process Selection*
• Mechanical or friction gripping methods. • Pad shape selection. • Vacuum actuation • Magnetic grasping. • Adhesive gripping. • Expandable bladder type actuation.	• Pneumatic drive systems. • Hydraulic drive System for heavy duty operation. • Electrical drive for light duty application. • Speed reduction of the mechanical transmission.	• Heat shield for sensors and actuators. • Forced cooling by air or water cooling to take away the heat. • Selection of heat resistance materials for fingers and components of gripper. • Shield from hazardous chemicals.	• Accurate processing methods for fingers. • Leak prevention for pneumatic/hydraulic actuators. • Interchangeability standards for the fingers. • Shape compatible processing methods for fingers. • Ease of assembly of fingers and linkages.

PROBLEMS

Example 2.1. *A cylindrical co-ordinated robot has a vertical reach of 500 mm and a stroke of 320 mm. What is the minimum height of the work table to be to able the robot to reach the object kept on the table?*

Sol. Data:

V = maximum vertical reach = 500 mm.

L = length of the stroke = 320 mm.

H = minimum height of the table = ?

$$H = (V - L) = (500 - 320) = 180 \text{ mm.}$$

Ans. Minimum height of the table = 180 mm.

Example 2.2. *A cartesian robot has a horizontal reach of 450 mm and a horizontal stroke of 250 mm. What is the maximum limit within which the object placed is not reachable?*

Sol. Data:

H = maximum horizontal reach = 450 mm.

S = stroke length = 250 mm.

L = non-reachable maximum limit = ?

$$L = (H - S) = (450 - 250) = 200.$$

Ans. Non-reachable maximum limit = 200 mm.

Example 2.3. *One of the links of a robot has a telescoping arm with a stroke of 512 mm. The control memory of the robot has 8-bit storage capacity for this axis. Determine the control resolution for the same.*

Sol. Data:

S = stroke length = 512 mm.

K = storage capacity = 8 bit memory.

From the equation (2.2),

Total control resolution,

$$R_t = \frac{S}{(2)^k} = \frac{512}{(2)^8} = 2 \text{ mm.}$$

Ans. Total control resolution = 2 mm.

Example 2.4. *A cartesian robot has a slide with a total range of 1.2 m and it is desired that it will have a control resolution of 0.46 cm on this axis. Determine the bit storage capacity which the control memory must possess to accomodate this level of precision.*

(VTU, Jan./Feb. 2003)

Sol. Data:

Total range of linear movement, = S = 1.2 m (1200 mm)

Control resolution, R_t = 0.46 cm (4.6 mm)

From the equation (2.2).

$$R_t = \frac{S}{2^k}$$

$$2^k = \frac{S}{R_t}$$

$$k(\log_e 2) = \log_e \left(\frac{S}{R_t}\right)$$

$$k = \log_e \left(\frac{S}{R_t}\right) \Big/ \log_e (2) \quad \text{...}(i)$$

$$= \frac{\log_e \left(\dfrac{1200}{4.6}\right)}{\log_e (2)} = 8.027.$$

Ans. The number of bits of storage capacity = 8.

Example 2.5. *A large cartesian co-ordinate robot has one orthogonal slide with a total stroke of 1024 mm. This axis has the maximum control resolution of 0.25 mm. Determine the number of bit storage capacity which the robot control memory must possess to provide this level of precision.*

Sol. Data:

Total stroke, S = 1024 mm

Control resolution, R_t = 0.25 mm

The number of bits of storage capacity, from relation (*a*) of example 2.4.

$$k = \frac{\log_e [S/R_t]}{\log_e [2]}$$

$$= \frac{\log_e [1024 / 0.25]}{\log_e (2)} = 12.$$

Ans. The number of bit storage capacity = 12.

Example 2.6. *The telescopic arm of an industrial robot obtains total range of rotation of 120°. The robot has a 12 bit storage capacity for the axis. The arm fully extends to 1500 mm and fully retracts to 750 mm from the pivot point. Determine the robots control resolution (i) for the axis in degrees of rotation and (ii) on linear scale in fully extended and retracted position.*

(VTU, May/June 2004)

Sol. Data:

Range of rotation, $\phi = 120°$

Number of bit storage capacity, $k = 12$

Maximum reach of extension, $H_{max} = 1500$ mm

Minimum reach of retraction, $H_{min} = 750$ mm.

Control resolution of rotation, $A_c = ?$

Control resolution of linear scale, $R_t = ?$

(*i*) Using the equation (2.5),

The control resolution of rotation,

$$A_c = \frac{\phi}{2^k} = \frac{120}{(2)^{12}} = 0.0293°$$

(*ii*) Stroke

$$S = (H_{max} - H_{min})$$
$$= (1500 - 750) = 750 \text{ mm.}$$

From equation (2.2),

$$R_t = \frac{S}{2^k} = \frac{750}{(2)^{12}} = 0.183 \text{ mm.}$$

Ans. (*i*) Control resolution for rotation = 0.0293°

(*ii*) Control resolution for translation = 0.183 mm.

Example 2.7. *The mechanism connecting the wrist assembly is a twisting joint which can be rotated through 8 full revolutions from the start to end position. It is desired to have control resolution of rotation of ± 0.35° at the least. What is number of bit storage capacity to achieve this resolution?*

Sol. Data:

The degrees of rotation = 360° × no. of revolution

i.e., $\phi = 8 \times 360° = 2880°$

Total resolution $= \pm 0.35°$

So, control resolution $= A_c = 0.70°$

Using the equation (2.5),

$$A_c = \frac{\phi}{2^k} \quad \text{or} \quad 2^k = \frac{\phi}{A_c}$$

$$k \cdot \log_e (2) = \log_e [\phi/A_c]$$

$$k = \frac{\log_e [\phi/A_c]}{\log_e (2)} = \frac{\log_e (2880 / 0.7)}{\log_e (2)} = 12.006.$$

Ans. The number of bit storage capacity = 12.

Example 2.8. *An incremental shaft encoder with 2 emitter detector pairs and 12 slots around the circumference is used to monitor the angular position of a high speed motor shaft. The precision of the load shaft is measured and found to be 0.05 degree per count. What is the gear ratio between high speed shaft and the load shaft?*

Sol. Using the equation (2.4),

$$A_c = \frac{2\pi}{nZ \cdot 2^k} = \frac{360}{nZ \cdot 2^k},$$

where n = number of slots = 12,

k = number of emitter detector pairs, = 2,

Z = speed reduction ratio = ?,

A_c = The angular control resolution, = 0.05° (precision).

Hence
$$Z = \frac{360}{n \cdot A_c \cdot 2^k}$$
$$= \frac{360}{(12)(0.05) \cdot (2)^2} = 150.$$

Ans. The gear reduction ratio between high speed shaft and the load shaft = 150 : 1.

Example 2.9. *A cylindrical robot has a prismatic joint with a range of travel of 800 mm. The control memory for this joint has 10 bit capacity. It has been recorded that the associated mechanical inaccuracies with the said arm show a random distribution of random variable of the robot position about the mean position of the taught point gives a standard deviation of 0.1 mm. The standard deviation is equal in all direction. Determine the following:*

(*a*) *The control resolution for the axis.*

(*b*) *The spatial resolution for the prismatic joint.*

(*c*) *The accuracy defined.*

(*d*) *The repeatability of the robot link.*

Sol. Data:

The stroke, S = 800 mm

The bit storage capacity, k = 10

The standard deviation of the mechanical inaccuracies,

$$\sigma = 0.1 \text{ mm}.$$

(*a*) Control resolution,

Using the equation (2.2),

$$R_t = \frac{S}{2^k} = \frac{800}{(2)^{10}} = 0.78125 \text{ mm}.$$

(*b*) The spatial resolution,

From the equation (2.6),

$$R_s = R_t + 6\sigma$$
$$= 0.78125 + 6(0.1) = 1.38125 \text{ mm}.$$

(*c*) The accuracy

Using the relation (2.9),

$$\text{error (accuracy)} \geq \frac{R_t}{2}$$

$$\text{accuracy} \geq \frac{0.78125}{2} = 0.3906 \text{ mm}.$$

(*d*) The repeatability $R_p = \pm 3\sigma$

$$= \pm 3(0.1) = \pm 0.3 \text{ mm.}$$

Ans. (*a*) Control resolution = 0.78125 mm,

(*b*) Spatial resolution = 1.38125 mm,

(*c*) The accuracy ≥ 0.3906 mm,

(*d*) The repeatability = ± 0.3 mm.

Example 2.10. *The base joint of the cylindrical robot is driven by a 12-bit memory converter and has a swing range of 360°. The radial axis is driven by an 8-bit memory converter, and has a horizontal reach of 300 mm and a stroke of 200 mm. The vertical motion has a drive of 10 bit memory converter with a vertical reach of 480 mm and a stroke of 360 mm. Compute the following.*

(*a*) *Volume of the work envelope.* (*b*) *Radial resolution.*

(*c*) *Vertical resolution.* (*d*) *Angular resolution.*

(*e*) *Horizontal resolution.* (*f*) *The total resolution.*

Sol. (*a*) Volume of the work envelope,

$$V = \pi(r_1^2 - r_2^2)\, h$$

where $r_1 = 300$ mm, $r_2 = (r_1 - s) = (300 - 200) = 100$ mm.

$$h = (480 - 360) = 120 \text{ mm.}$$

Hence, $V = \pi(300^2 - 100^2)(120) = 30.16 \times 10^6 \text{ mm}^3$.

(*b*) Radial resolution,

$$dr = \frac{(r_1 - r_2)}{2^{k_r}}, \quad \text{where} \quad k_r = 8$$

$$= \frac{(300 - 100)}{2^8} = 0.78125 \text{ mm.}$$

(*c*) Vertical resolution,

$$dz = \frac{(Z_1 - Z_2)}{2^{k_z}}$$

where $k_z = 10$, $Z_1 = 480$ mm., $Z_2 = (480 - 360) = 120$ mm.

$$= \frac{(480 - 120)}{2^{10}} = 0.3516 \text{ mm.}$$

(*d*) Angular resolution

$$d\phi = \frac{\phi}{2^{k_\phi}} \quad \text{where} \quad K_\phi = 12, \quad \phi = 360°$$

$$= \frac{360}{2^{12}} = 0.088 \text{ deg } (1.534 \times 10^{-3} \text{ radian})$$

Minimum angular resolution $= r_2\, d\phi = 100 \times 1.534 \times 10^{-3}$

$= 0.1534$ mm.

Maximum angular resolution, $= r_1\, d\phi = 300 \times 1.534 \times 10^{-3}$

$= 0.46$ mm.

(*e*) Horizontal resolution,

$$dh = [(dr)^2 + (Rd\phi)^2]^{1/2}$$

$$= [(0.78125)^2 + (0.46)^2]^{1/2} = 0.907 \text{ mm.}$$

(*f*) Total resolution,

Using relation (2.8), $$dT = \sqrt{(dr)^2 + (Rd\phi)^2 + (dz)^2}$$

$$= \sqrt{(0.78125)^2 + (0.46)^2 + (0.3516)^2} = 0.973 \text{ mm.}$$

Ans. (*a*) Work volume = 30.16×10^6 mm³

(*b*) Radial resolution = 0.78125 mm

(*c*) Vertical resolution = 0.3516 mm.

(*d*) Angular resolution, minimum = 0.1534 mm

maximum = 0.46 mm.

(*e*) Horizontal resolution = 0.907 mm

(*f*) Total resolution = 0.973 mm.

Example 2.11. *A double acting, single-ended piston hydraulic cylinder is used to actuate one of the linear arm joints of a cartesian robot. The diameter of the piston is 10 cm and the diameter of the rod is 5 cm. A pump supplies hydraulic oil at a rate of 36 cm³/sec with a pressure of 40 N/cm². Determine :*

(*a*) *The force that can be applied by the piston in the forward and the reverse strokes.*

(*b*) *The maximum velocity with which rod can operate in forward and reverse directions.*

Sol. Data:

The diameter of the piston $= D_p = 10$ cm (0.1 m)

The diameter of the rod, $D_r = 5$ cm (0.05 m)

Discharge rate to the cylinder, $Q = 36$ cm³/sec (3.6×10^{-5} m³/s)

The supply pressure of oil, $p = 40$ N/cm² = (4×10^5 N/m²)

(*a*) The force exerted on the piston

* in the forward stroke $= p \,.\, A_p$

$$= \frac{\pi D_p^2 \,.\, p}{4} = \frac{\pi (0.1)^2 \times 4 \times 10^5}{4}$$

$F_f = 3142$ N.

* in the reverse stroke, $F_r = p \,.\, (A_p - A_r)$

$$= p \,.\, \frac{\pi}{4} (D_p^2 - D_r^2)$$

$$F_r = (4 \times 10^5) \frac{\pi}{4} (0.1^2 - 0.05^2) = 2356.2 \text{ N.}$$

(*b*) The maximum velocity of the rod

* In the forward stroke,

$$(V_{max})_f = \frac{Q}{A_p} = \frac{4Q}{\pi D_p^2} = \frac{4 \times 3.6 \times 10^{-5}}{\pi (0.1)^2}$$

$= 4.58 \times 10^{-3}$ m/sec (4.58 mm/sec)

*In the reverse stroke,

$$(V_{max})_r = \frac{Q}{(A_p - A_r)} = \frac{4Q}{\pi (D_p^2 - D_r^2)}$$

$$= \frac{4 \times 3.6 \times 10^{-5}}{\pi(0.1^2 - 0.05^2)}$$

$= 6.11 \times 10^{-3}$ m/sec (6.11 mm/sec).

Ans. (*a*) Force exerted

in the forward stroke = 3142 N.

in the reverse stroke = 2356.2 N.

(*b*) Velocity of rod

in the forward stroke = 4.58 mm/sec

in the reverse stroke = 6.11 mm/sec.

Example 2.12. *A hydraulic rotary van actuator is used to drive the revolute joint of a cylindrical robot with the power source delivering 27 cm³ / sec of oil at a pressure of 705 N / cm². The outer and the inner vane radius are 10 cm and 5 cm respectively. The thickness of the vane is 1 cm. Determine :*

(*a*) *The angular velocity of the motor.*

(*b*) *The torque developed in the motor shaft.*

Sol. Data :

Outer radius of vane, $R = 10$ cm

Inner radius of vane, $r = 5$ cm

Discharge rate, $Q = 27$ cm³/sec.

Supply pressure, $p = 705$ N/cm²

Thickness of the vane, $t = 1$ cm

(*a*) Angular velocity,

$$\omega = \frac{2\theta}{(R^2 - r^2).t} = \frac{2 \times 27}{(10^2 - 5^2) \times 1.0} = 0.72 \text{ rad/sec.}$$

(*b*) The torque developed,

$$T = \frac{1}{2} \cdot \frac{p.t(R^2 - r^2)}{100}$$

$$= \frac{1}{2} . (705) \times 1.0 \times (10^2 - 5^2) = 264.4 \text{ N.m.}$$

Ans. (*a*) The angular velocity, $\omega = 0.72$

(*b*) The torque developed, T = 264.4 N.m.

Example 2.13. *A DC servomotor used to drive a robot joint has a torque constant, 1.25 N-m / A and a voltage constant of 12 × 10⁻³ V / rpm. The armature resistance of 2.5 ohms. A voltage of 25 V is applied at a point of time of robot cycle when the joint is stationary.*

Determine,

(*a*) *the torque of the motor immediately after the voltage is applied.*

(*b*) *the back e.m.f. and the respective torque corresponding to rotational speeds of 250 rmp. and 500 rpm.*

Sol. Data :

Torque constant, $K_m = 1.25$ N-m/A.

Voltage constant, $K_b = 12 \times 10^{-3}$ V/rpm.

Armature resistance, $R_a = 2.5$ ohm.
Starting voltage applied, $V_{in} = 25$ V.

(*a*) Torque at the start of rotation

Using the equations (2.16), (2.17) and (2.18)

$$T_m = K_m I_a$$

$$= \frac{K_m(V_{in} - e_b)}{R_a} = \frac{K_m(V_{in} - K_b \cdot \omega)}{R_a}$$

at the start $\omega = 0$

So $$T_m = \frac{K_m V_{in}}{R_a} = \frac{1.25(25)}{2.5} = 12.5 \text{ N.m.}$$

(*b*) When the speed of rotation, $\omega = 250$ rpm.

$$e_b = K_b \cdot \omega = 12 \times 10^{-3} \times 250 = 3\text{V}$$

and $$T_m = \frac{K_m(V_{in} - e_b)}{R_a} = \frac{1.25\,(25-3)}{2.5} = 11 \text{ N.m.}$$

When the speed of rotation is, $\omega = 500$ rpm

$$e_b = K_b \cdot \omega = 12 \times 10^{-3} \times 500 = 6\text{V}$$

and $$T_m = \frac{K_m(V_{in} - e_b)}{R_a} = \frac{1.25(25-6)}{2.5} = 9.5 \text{ N.m.}$$

Ans. (*a*) Torque at the start = 12.5 N.m.
(*b*) Torque at 250 rpm. = 11 N.m.
500 r.p.m. = 9.5 N.m.

Example 2.14. *A stepper motor actuates a arm of a pick and place robot. The step angle of the motor is 10°. For each pulse received from the pulse train source, the motor rotates through a distance of one step angle.*

(*a*) *What is the resolution of stepper motor?*

(*b*) *What is the control resolution and accuracy of rotation?*

(*c*) *How many pulses are required to rotate the motor through four complete revolutions?*

(*d*) *If it is desired to rotate the motor at a speed of 20 rpm what must be the pulse rate generated by the controller?*

Sol. Data:

The step angle, $A_s = 10°$

(*a*) Resolution of the stepper motor

$$R_s = \frac{A_s}{360°} = \frac{10°}{360°} = 0.027°$$

(*b*) Control resolution $= R_s = 0.027°$

$$\text{Accuracy} \geq \frac{0.027}{2} = 0.0135°$$

(*c*) Pulse counts

$$n = \frac{(N_R)360°}{A_s} = \frac{N_R}{R_s}$$

where N_R = number of revolutions = 4

$$\therefore \qquad n = \frac{4}{(1/36)} = 144 \text{ pulses.}$$

(*d*) Pulse rate, $$n_r = \frac{N_m}{A_s R_s}$$

where N_m = number of revolutions per minute = 20 rpm

So, $$n_r = \frac{20}{(1/36)} = 720 \text{ pulses/min.}$$

Ans. (*a*) Resolution of stepper motor $= \frac{1}{36} = 0.027°$.

(*b*) Control resolution = 0.027°, Accuracy = 0.0135°.

(*c*) Number of pulses for 4 rotations = 144 pulses.

(*d*) Pulse rate for 20 rpm = 720 pulses/min.

Example 2.15. *A stepper motor is used to drive a prismatic joint of a cartesian robot. The motor shaft is connected to a screw shaft with a pitch of 3 mm. The control resolution of 0.6 mm is desired from the controller. Determine*

(*a*) *The number of step angles on the motor to achieve this control resolution.*

(*b*) *The pulse rate required to drive the joint with a linear speed of 75 mm/sec.*

Sol. Data :

The screw pitch, $p_s = 3$ mm

Control resolution, $R_c = 0.6$ mm

(*a*) The number of step angles,

The number of step angle of stepper motor,

$$A_s = \frac{360°.R_c}{p_s}$$

$$= \frac{360° \times 0.6}{3} = 72°$$

The number of step angles $= \frac{360}{A_s} = \frac{360}{72} = 5$ steps.

Resolution of motor $= R_s = \frac{A_s}{360} = \frac{72°}{360} = 0.2°$

(*b*) The pulse rate, Velocity = 75 mm/sec.

3 mm of screw movement corresponds to 1 rotation of the shaft. Hence for 75 mm movement

$$N_m = \frac{75}{3} = 25 \text{ rps.}$$

But the pulse rate,

$$n_r = \frac{N_m}{R_s} = \frac{25}{0.2} = 125 \text{ pulse/sec.}$$

Ans. (*a*) Resolution of motor = 0.2°

The number of step angles = 5

(*b*) The pulse rate = 125 pulses/sec.

Example 2.16. *The mechanical gripper uses friction to grasp a part weighing 25 N. The co-efficient of friction between the part and the gripper pad shown in Fig. 2.20 is 0.3. The gripper is accelerating down with a acceleration = 9.81 m/s². The diameter of the piston of pneumatic cylinder is 65 mm. Assume a factor of safety = 1.5 and assume the lengths L_1 = 60 mm, L_2 = 40 mm, L_3 = 15 mm, L_4 = 45 mm.*

Calculating the following :

(a) The gripping force to retain the part.

(b) Actuation force required to achieve this gripping force.

(c) The pressure of air needed to operate the piston.

(d) The power required if the discharge is 0.015 m³/sec.

Sol.

(*a*) The gripping force to retain the part

Using the expression (2.26)

$$P_g = \frac{n \cdot W}{\mu \cdot N}(1 + k_f)$$

where $n = 1.5$, $W = 25$ N

$\mu = 0.3$, $N = 2$

$$k_f = \frac{a}{g} = \frac{9.81}{9.81} = 1.$$

Hence $$P_g = \frac{1.5(25)}{0.3(2)}(1 + 1) = 125 \text{ N.}$$

(*b*) Actuation force needed with the use of equation (2.29)

$$P_a = \frac{2nW}{\mu N}\left(\frac{L_1 \cdot L_3}{L_2 \cdot L_4}\right)(1 + k_f)$$

$$= \frac{2(1.5)(25)}{0.3(2)}\left(\frac{60 \times 15}{40 \times 45}\right)(1 + 1) = 125 \text{ N}$$

(c) The pressure of the air needed to operate piston using the expression (2.13)

$$p = \frac{4}{\pi}\frac{p}{d_p^2}$$

where d_p = 65 mm (0.065 m)

$$p = \frac{4}{\pi} \cdot \frac{125}{(65)^2} = 0.0376 \text{ N/mm}^2 \ (3.76 \times 10^5 \text{ N/m}^2)$$

(*d*) The power required

$$P_R = \frac{p \cdot Q}{1000}$$

where volume flow rate, Q = 0.015 m³/sec

$$P_R = \frac{3.76 \times 10^6 \times 0.015}{1000} = 5.65 \text{ kW.}$$

Ans. (*a*) Gripping force = 125 N

(*b*) Actuation force = 125 N

(*c*) Pressure of air = 3.76×10^5 N/m²

(*d*) Power required = 5.65 kW.

EXERCISE

2.1. Enumerate the complete Robot classification. *(VTU–Jan./Feb. 2003)*

2.2. Describe the complete classification of Robotic systems. *(VTU–Jan./Feb. 2004)*

2.3. Define a robot and with a diagram explain the anatomy of a robot. *(VTU–Jan./Feb. 2004)*

2.4. With neat sketches differentiate and highlight the four common types of robot configurations. *(VTU–Jan./Feb. 2003)*

2.5. Explain how the performance of robotic system is studied? *(VTU–Jan./Feb. 2003)*

2.6. Compare three basic types of drives enlisting their merits and demerits. *(VTU–Jan./Feb. 2004)*

2.7. What are the merits and demerits of electric drive system, of a robot. *(VTU–May/June 2004)*

2.8. Discuss the criteria of selection of drive systems for the robots, highlighting the merits and demerits of the system. *(VTU–Jan./Feb. 2003)*

2.9. Discuss briefly about the grippers and give its classification. *(VTU–May/June 2004)*

2.10. Describe with a neat sketch degrees of freedom associated with a robot wrist. *(VTU– May/June 2004)*

2.11. Give a general representation of the robot link, discussing its design considerations.

2.12. With neat sketches, explain different configurations of robot joints.

2.13. Enlist the robot specifications and explain each of them briefly.

2.14. Define repeatability, resolution and accuracy.

2.15. Enumerate the factors that contribute to the limitation of the spatial resolution.

2.16. Derive and explain the total resolution with reference to a cylindrical co-ordinate robot.

2.17. Give a brief classification of actuators used in robots.

2.18. Enlist the main elements of a hydraulic system used in robot and explain their functions briefly.

2.19. With a neat sketch explain the following hydraulic actuator.

(*i*) Rotary actuator. (*ii*) Linear actuator.

2.20. Explain the features and applications of hydraulic actuators in robotics.

2.21. Compare the features of most commonly used electric actuators in robotics.

2.22. Explain the performance and selection criteria of electric motors in robotics.

2.23. Explain with a schematic diagram explain the operating principle of a stepper motor used in robotics.

2.24. With neat sketches, give the classification of the wrist based on the type of motions.

2.25. Explain the features and applications of any two types of wrist.

2.26. Give a brief classification of gripper finger types.

2.27. With neat sketches explain any two types of gripper mechanisms.

2.28. Derive with usual notations the expression for force exerted by the mechanical grippers in robotics.

2.29. Discuss the gripper design considerations in robotics.

2.30. Explain the selection criteria of end-effectors in robotics.

2.31. An industrial Robot with a prismatic joint has a telescoping range of 0.6 m. The robots control memory has the following bit storage capacity.

(*a*) 10 bit storage capacity. (*b*) 12 bit storage capacity.

Determine the control resolution for the two cases separately.

2.32. A cartesian robot with three linear motions has the traversing range of 50 cm, 70 cm and 90 cm with a control memory of 8 bit, 10 bit and 12 bit storage capacity respectively. Determine the total control resolution of the robots work volume.

2.33. A servomotor used to actuate one of the joints of the cylindrical robot has a torque constant of 30 N-m/A and a voltage constant of 15×10^{-3} V/rpm. The armature resistance is 30 Ω. When the joint is stationary the voltage applied is 60 V. Determine

(*a*) The torque exerted by the motor on the joint when the robot is stationary.

(*b*) Determine the back e.m.f. and the torque when the motor is running at 500 rpm and 1000 rpm.

2.34. Explain the construction and working of a pneumatic gripper.

2.35. Explain the construction and working of a multipole stepper motor.

2.36. Sketch and explain single phase stepper motor.

2.37. With a block diagram explain the functioning of a servo-motor.

2.38. What is workspace ? Give the functional diagram with the workspace for the following robots

(*a*) 3R-robot (*b*) 2RP robot

(*c*) R2P robot (*d*) 3P-robot

2.39. Give the functional diagrams for the following robots

(*a*) POMA robot (*b*) Kawasaki Unimate robot

(*c*) I3 robot (*d*) IBM robot

(*e*) SCARA robot.

2.40. Explain the application of Hydraulic system to a robot actuation.