NEHRU COLLEGE OF ENGINEERING AND RESEARCH CENTRE
(NAAC Accredited)
(Approved by AICTE, Affiliated to APJ Abdul Kalam Technological University, Kerala)

DEPARTMENT OF MECHATRONICS ENGINEERING

COURSE MATERIALS

MR 302 ROBOTICS ENGINEERING

VISION OF THE INSTITUTION
To mould true citizens who are millennium leaders and catalysts of change through excellence in education.
MISSION OF THE INSTITUTION
NCERC is committed to transform itself into a center of excellence in Learning and Research in Engineering and Frontier Technology and to impart quality education to mould technically competent citizens with moral integrity, social commitment and ethical values. We intend to facilitate our students to assimilate the latest technological know-how and to imbibe discipline, culture and spiritually, and to mould them in to technological giants, dedicated research scientists and intellectual leaders of the country who can spread the beams of light and happiness among the poor and the underprivileged.

ABOUT DEPARTMENT

- Established in: 2013
- Course offered: B.Tech Mechatronics Engineering
- Approved by AICTE New Delhi and Accredited by NAAC
- Affiliated to the University of Dr. A P J Abdul Kalam Technological University.

DEPARTMENT VISION

To develop professionally ethical and socially responsible Mechatronics engineers to serve the humanity through quality professional education.

DEPARTMENT MISSION

1) The department is committed to impart the right blend of knowledge and quality education to create professionally ethical and socially responsible graduates.

2) The department is committed to impart the awareness to meet the current challenges in technology.

3) Establish state-of-the-art laboratories to promote practical knowledge of mechatronics to meet the needs of the society

PROGRAMME EDUCATIONAL OBJECTIVES

I. Graduates shall have the ability to work in multidisciplinary environment with good professional and commitment.

II. Graduates shall have the ability to solve the complex engineering problems by applying electrical, mechanical, electronics and computer knowledge and engage in lifelong learning in their profession.

III. Graduates shall have the ability to lead and contribute in a team with entrepreneur skills, professional, social and ethical responsibilities.

IV. Graduates shall have ability to acquire scientific and engineering fundamentals necessary for higher studies and research.

PROGRAM OUTCOME (PO'S)

Engineering Graduates will be able to:

PO 1. Engineering knowledge: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.

PO 2. Problem analysis: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.

PO 3. Design/development of solutions: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

PO 4. Conduct investigations of complex problems: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.

PO 5. Modern tool usage: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.

PO 6. The engineer and society: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.

PO 7. Environment and sustainability: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.

PO 8. Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

PO 9. Individual and team work: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.

PO 10. Communication: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.

PO 11. Project management and finance: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.

PO 12. Life-long learning: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

PROGRAM SPECIFIC OUTCOME(PSO'S)

PSO 1: Design and develop Mechatronics systems to solve the complex engineering problem by integrating electronics, mechanical and control systems.

PSO 2: Apply the engineering knowledge to conduct investigations of complex engineering problem related to instrumentation, control, automation, robotics and provide solutions.

COURSE OUTCOME

After the completion of the course the student will be able to

SUBJECT CODE: C311	
COURSE OUTCOMES	
CO 1	Acquire the basic knowledge in fundamentals of Robots and its anatomy.
CO 2	Understand the various drive mechanisms in robotics applications.
CO 3	Acquire knowledge about the various robot end effectors and grippers.
CO 4	Understand the various sensors used in robotics applications.
CO 5	Identify various kinematics and transformations in robotics interpolation.
CO 6	Interpret about various programming methods and real-time applications of robots.

CO VS PO'S AND PSO'S MAPPING

CO Vs PO														
SUBJECT														
COURSE COUTCOME	PO 1	PO 2	PO 3	PO 4	PO 5	PO 6	PO 7	PO 8	PO 9	PO 10	PO 11	PO 12	PS O1	PS O2
CO 1	3	-	2	-	-	-	-	-	-	-	-	3	3	3
CO 2	3	-	2	-	-	-	-	-	-	-	-	3	3	3
CO 3	3	-	2	-	-	-	-	-	-	-	-	3	3	3
CO 4	3	-	2	-	-	-	-	-	-	-	-	3	3	3
CO 5	3	-	2	-	-	-	-	-	-	-	-	3	3	3
CO 6	3	3	3	3	-	-	-	-	-	-	-	3	3	3

Note: H-Highly correlated=3, M-Medium correlated=2, L-Less correlated=1

SYLLABUS

Module 1

Robotics – Introduction–Basic Structure– Classification of robot and Robotic systems –laws of robotics – robot motions – work Volume- Spatial resolution – Accuracy and Repeatability of Robots- wrist configurations- motion – roll – Pitch – Yaw

Module 2

Drives – Hydraulic motor – DC servo motors – stepper motors – operation. Mechanical Components of Robots- Power transmission systems- Gear transmission. Belt drives- cables Roller Chains- Link – Road Systems- Rotary to linear motion conversion- Rack and pinion drives- ball bearing screws speed reducers- Harmonic drives.

Module 3

Robot End Effectors: Types of end effectors – Mechanical grippers – Types of Gripper mechanisms – Grippers force analysis – Other types of Grippers – Vacuum cups – Magnetic Grippers – Adhesive Grippers – Robot end effector interface.

Module 4

Sensors in Robotics: Position sensors – Potentiometers-encoders – LVDT- Velocity sensors-Acceleration Sensors Force- Pressure and Torque sensors- Touch and Tactile sensors Proximity-Range and sniff sensors- RCC- VOICE recognition and synthesizers- contact and non-contact sensors.

Module 5

Descriptions – Positions – Orientations- frames- Mappings – Changing descriptions from frame to frame. Transformation arithmetic – translations – rotations – transformations – transform equations – transformation of free vectors. Introduction to manipulations – Forward Kinematics and inverse Kinematics.

Module 6

Methods of Robot Programming (Quantitative treatment only) – on-line/off-line – Show and Teach – Teach Pendant – Lead and Teach.. Lead Teach method – robot program as a path in space – motion interpolation – WAIT – SIGNAL – DELAY Commands Application – Machining – Welding – Assembly – Material Handling – Loading and Unloading in hostile and remote environment.

QUESTION BANK

Q:NO	QUESTIONS	CO	KL	PAGE NO:
MODULE I				
1	How you represent a robot configuration by joints? Support your answer with one example. [Hint: Joint notation]	CO1	K2	15
2	What is degree of freedom?	CO1	K3	9
3	Illustrate the basic structure of an Industrial manipulator?	CO1	K2	45
4	With neat sketch, explain the Classification of Industrial manipulator Based on Physical Configuration?	CO1	K3	46
5	Write a short note about the classification of industrial robots based on Control Systems?	CO1	K2	15
6	Describe about the factors that affect the accuracy of an industrial robot?	CO1	K2	18
7	Write a short note about the significance of spatial resolution in robotic system?	CO1	K5	43
8	With a neat sketch explain the wrist configuration of an arm robot?	CO1	K2	18
MODULE II				
1	Illustrate the working principal of a rack and pinion setup?	CO2	K2	45
2	Write a short note about Ball Bearing Screws?	CO2	K2	46
3	What is a harmonic drive? What are the advantages of using it?	CO2	K2	47

4	What are the different types of actuators used in a robot?	CO2	K1	48
5	Differentiate between pneumatic systems and hydraulic systems?	CO2	K1	49
6	Write a short note about stepper motor?	CO2	K3	57
7	What are the applications of lead screw?	CO2	K2	47
8	Write a short note about links in power transmission?	CO2	K2	56
9	Differentiate between AC servo motor and DC servo motor?	CO2	K2	54
	MODULE III			
1	Illustrate the working of a gripper?	CO3	K3	58
2	What is the difference between a gripper and a tool? Explain with neat sketch?	CO3	K3	59
3	What are the different ways used by a gripper to hold an object? Explain with proper sketch?	CO3	K2	60
4	Explain about linkage based actuation mechanism in a gripper?	CO3	K3	62
5	How can we actuate a gripper using rack and pinion setup?	CO3	K5	64
6	Write a short note about Cam actuation in a gripper?	CO3	K3	65
7	Write a short note about Screw actuation in a gripper?	CO3	K2	66
8	Write a short note about linkage actuation in Mechanical Gripper?	CO3	K1	67
9	Short note about vacuum gripper?	CO3	K1	68
10	Write a short note about magnetic gripper?	CO3	K2	69

11	What are the specific applications of Adhesive grippers?	CO3	K1	70
12	How hooks are used in gripping mechanisms?	CO3	K2	70
13	How physical support of end effector is maintained?	CO3	K1	71
MODULE IV				
1	Differentiate between transducer and sensor?	CO4	K2	71
2	Write a short note about touch Sensor?	CO4	K1	72
3	Write a short note about force Sensor?	CO4	K2	73
4	What are the methods used to find the offset force of a wrist?	CO4	K3	75
5	Define the steps used to calculate joint force?	CO4	K1	77
6	Short note about Tactile array sensor?	CO4	K2	80
7	Illustrate the working of Proximity and Range Sensor?	CO4	K2	80
8	What are the applications of sensors in robotics?	CO4	K2	82
9	Illustrate the camera system used in a robotic system?	CO4	K2	84
10	What are the steps involved in the vision sensing of a robot?	CO4	K2	85
MODULE V				
1	Illustrate Revolute joint?	CO5	K2	86
2	Illustrate Prismatic joint?	CO5	K2	87
3	Illustrate Helical joint?	CO5	K3	88
4	Differentiate between spherical and cylindrical jont?	CO5	K2	88

5	What is kinematic chain?	CO5	K3	89
6	Illustrate Degree of freedom?	CO5	K2	90
7	Transformation matrix used for linear transformation?	CO5	K2	90
8	Transformation matrix used for rotary transformation?	CO5	K3	91
9	Write a short note about forward kinematics?	CO5	K3	92
10	Write short note about inverse Kinematics?	CO5	K2	93
MODULE VI				
1	What are the methods used in robotic programming?	CO6	K1	95
2	Explain about lead through programming method?	CO6	K2	96
3	Define paths in robotics?	CO6	K2	97
4	What are the methods used to define position in space?	CO6	K3	98
5	Explain x-y-z motion method?	CO6	K2	99
6	Explain joint movement method?	CO6	K2	100
7	Explain tool coordination motion?	CO6	K2	101
8	What are the reasons to define a point?	CO6	K2	100
9	How speed is controlled in each and every motion of a robot?	CO6	K2	102
10	Explain WAIT signal in robot programming?	CO6	K2	103
11	Explain DELAY signal in robot programming	CO6	K2	106
12	Write a program and explain the basic structure?	CO6	K2	106

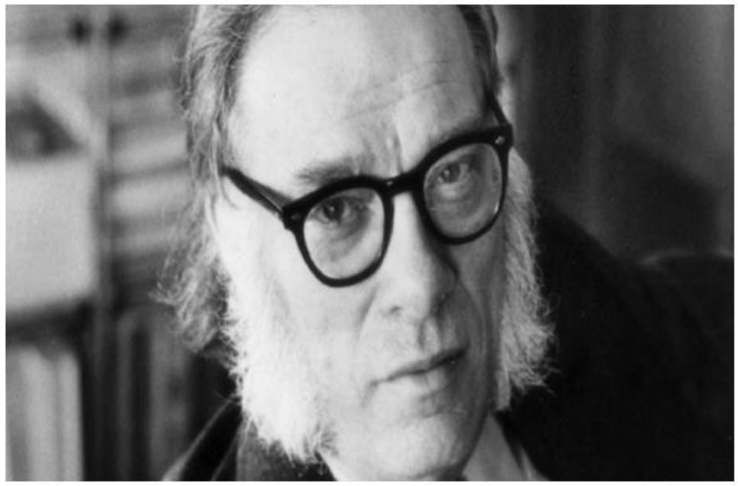
APPENDIX 1

CONTENT BEYOND THE SYLLABUS

MODULE 1

INTRODUCTION

Identify this person



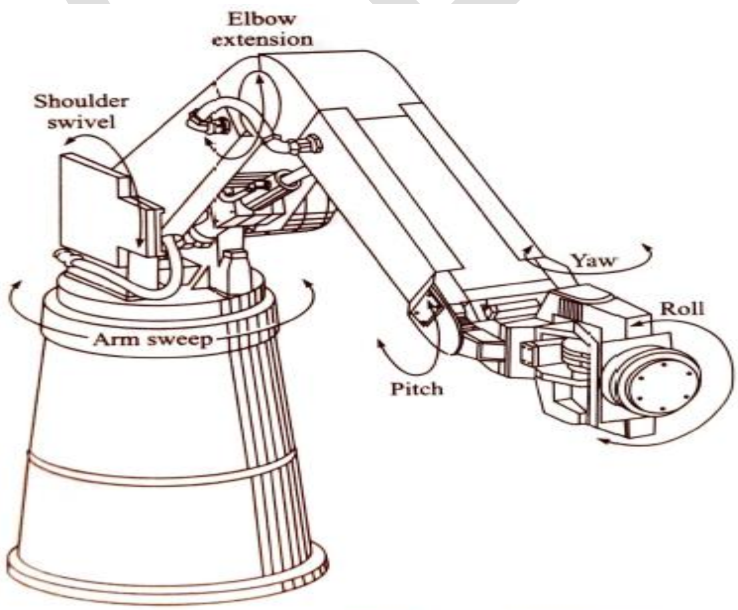
Issac Asimov
Writer, Professor of Bio chemistry
Lived from 1920 - 1992
Best Known for Science fictions

Some of them..

ROBOT

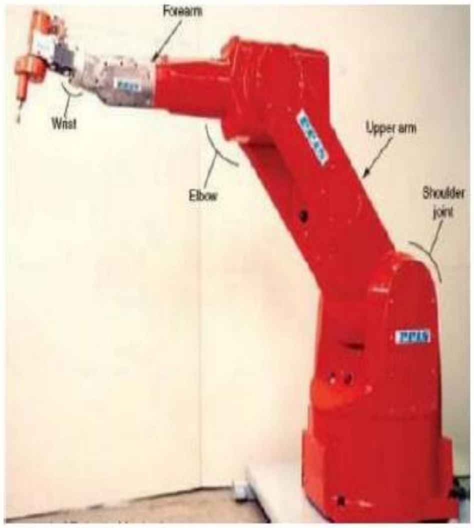
- A robot is formally defined in the International Standard of Organization (ISO) as are programmable, multifunctional manipulator designed to move material, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks.
- Robots are broadly classified as industrial and non-industrial or special-purpose.
- Strictly speaking, a manipulator which when controlled by a computer, is called a robot.
- Industrial robots are intended to serve as general purpose, unskilled or semi-skilled labor, e.g. for welding. Painting, machining, etc.
- Alternatively, a special-purpose robot is the one that is used in other than a typical factory environment

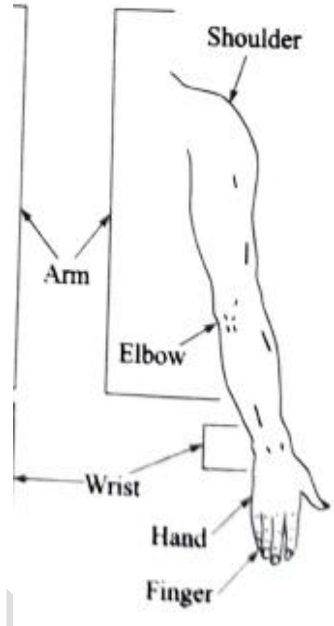
BASIC STRUCTURE



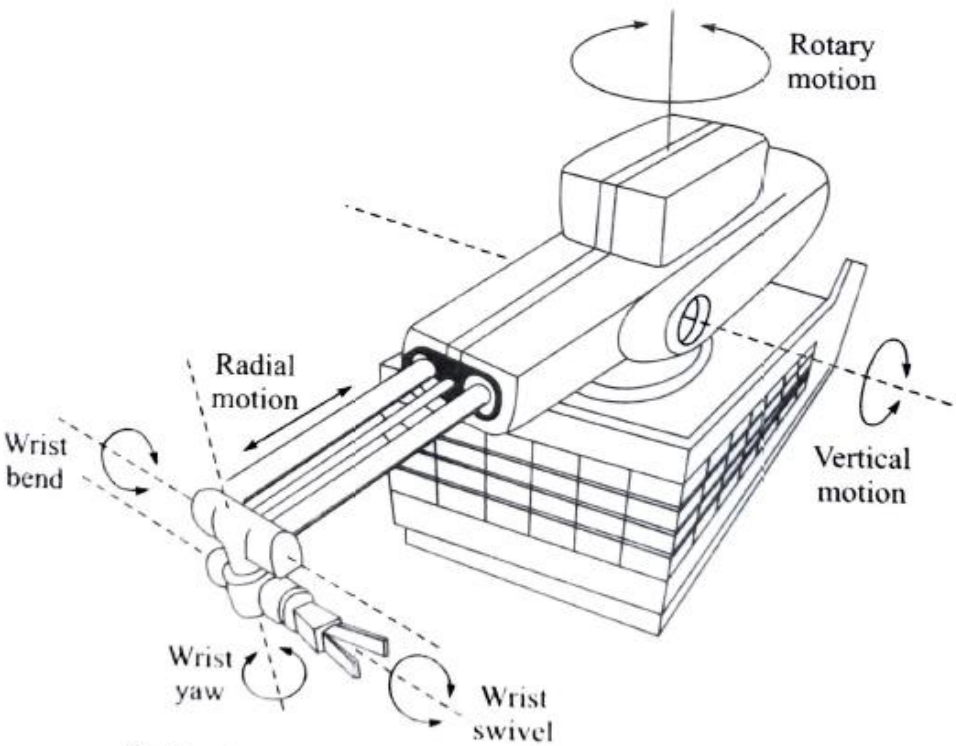
(a) Cincinnati Milacron (T3) [Courtesy: Koivo (1989)]

Manipulator Vs Human Arm





(b) Equivalent human parts



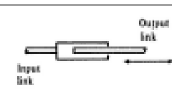
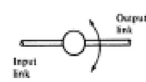
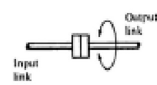
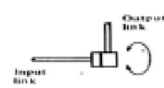
(b) Sketch of Unimate robot [Courtesy:Critchlow (1985)]

Fig. 1.1 Unimate robot

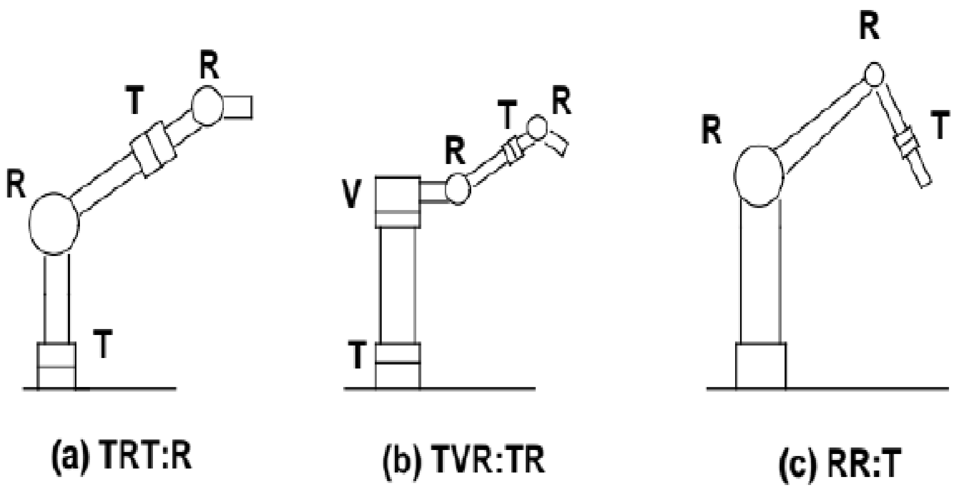
Typical Industrial Manipulator

- Base
- Links forming the rigid structure / rigid structure between the joints
- Links connected by different types joints
- A wrist
- End effector connected to the wrist

Joint notations

Notation	Type	Illustration
L	Linear	
R	Rotational	
T	Twisting	
V	Revolving	

Joint representation



LAWS OF ROBOTICS

"The three laws"

- Law 1 : A robot may not injure humanity or through inaction, allow humanity to come to harm
- Law 2: A robot must obey orders given to it by human beings, except where such orders would conflict with a higher order law
- Law 3: A robot must protect its own existence as long as such protection does not conflict with a higher order law

CLASSIFICATION OF ROBOT AND ROBOT SYSTEM

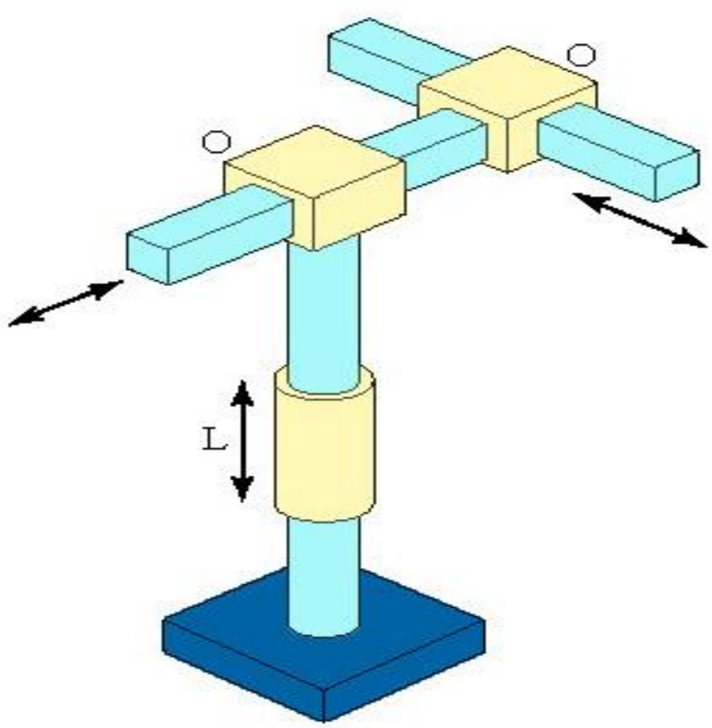
Robots may be classified, based on:

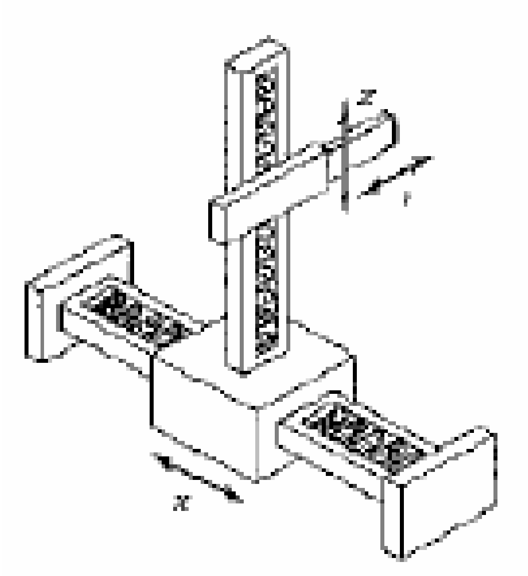
1. **Physical Configuration Or Co-Ordinate Systems**
2. **Control Systems**

CLASSIFICATION BASED ON PHYSICAL CONFIGURATION (OR) CO-ORDINATE SYSTEMS:

1. **Cartesian configuration**
2. **Cylindrical configuration**
3. **Polar configuration**
4. **Joint-arm configuration**
5. **SCARA robot**

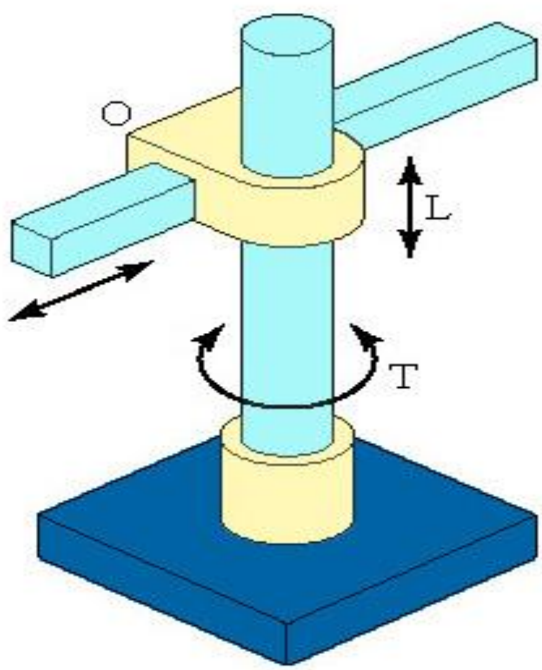
CARTESIAN CONFIGURATION

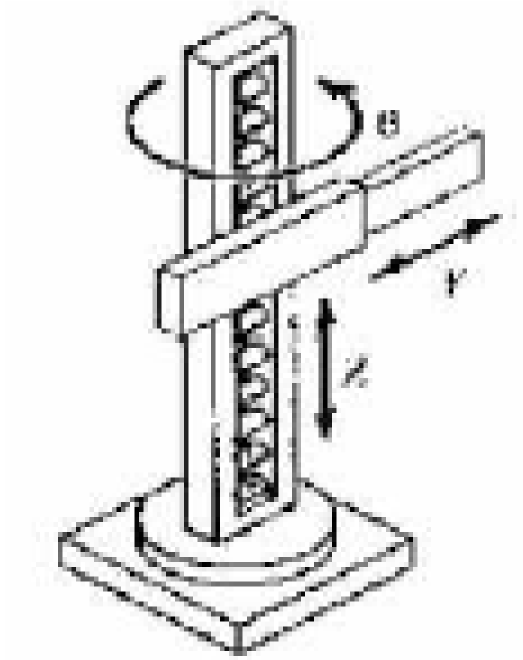




- Consists of three sliding joints, two of which are orthogonal
- Other names include rectilinear robot and x-y-z robot
- Robots with Cartesian configurations may also consist of links connected by linear joints (L). EXAMBLE: Gantry robots

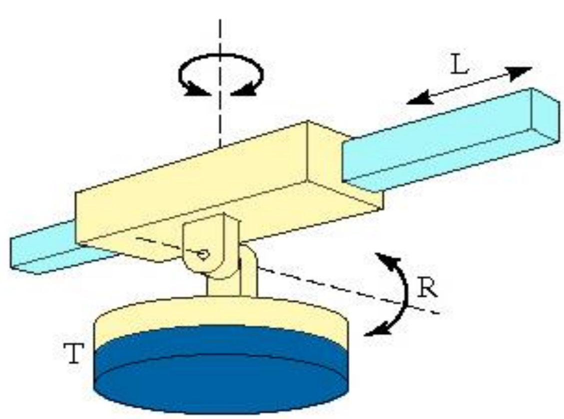
CYLINDRICAL CONFIGURATION





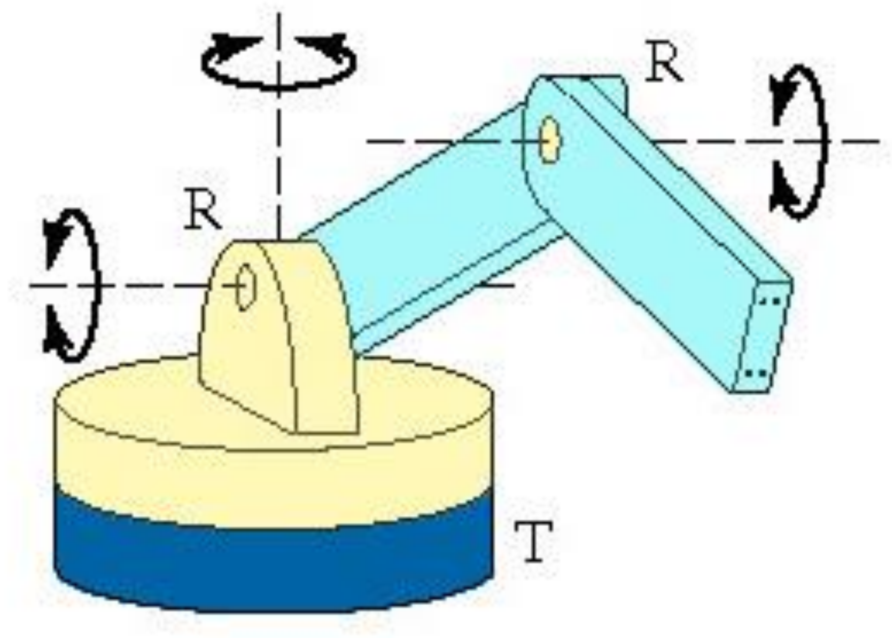
- Notation TLO:
- Consists of a vertical column, relative to which an arm assembly is moved up or down
- The arm can be moved in or out relative to the column
- Robots with cylindrical configuration have one rotary (R) joint at the base and linear (L)
- joints succeeded to connect the links.
- The designation of the arm for this configuration can be TRL or TRR.
- Robots with the designation TRL are also called spherical robots.
- Those with the designation TRR are also called articulated robots.
- An articulated robot more closely resembles the human arm.

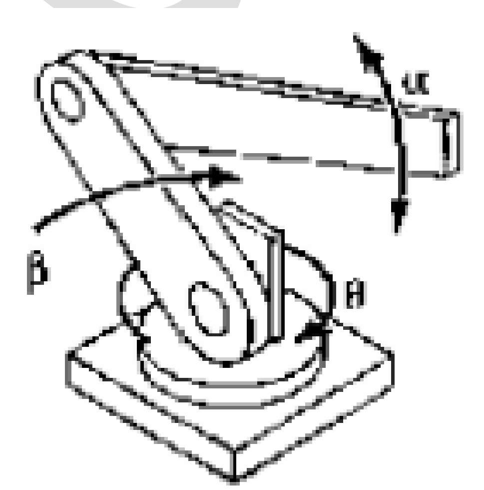
POLAR CONFIGURATION



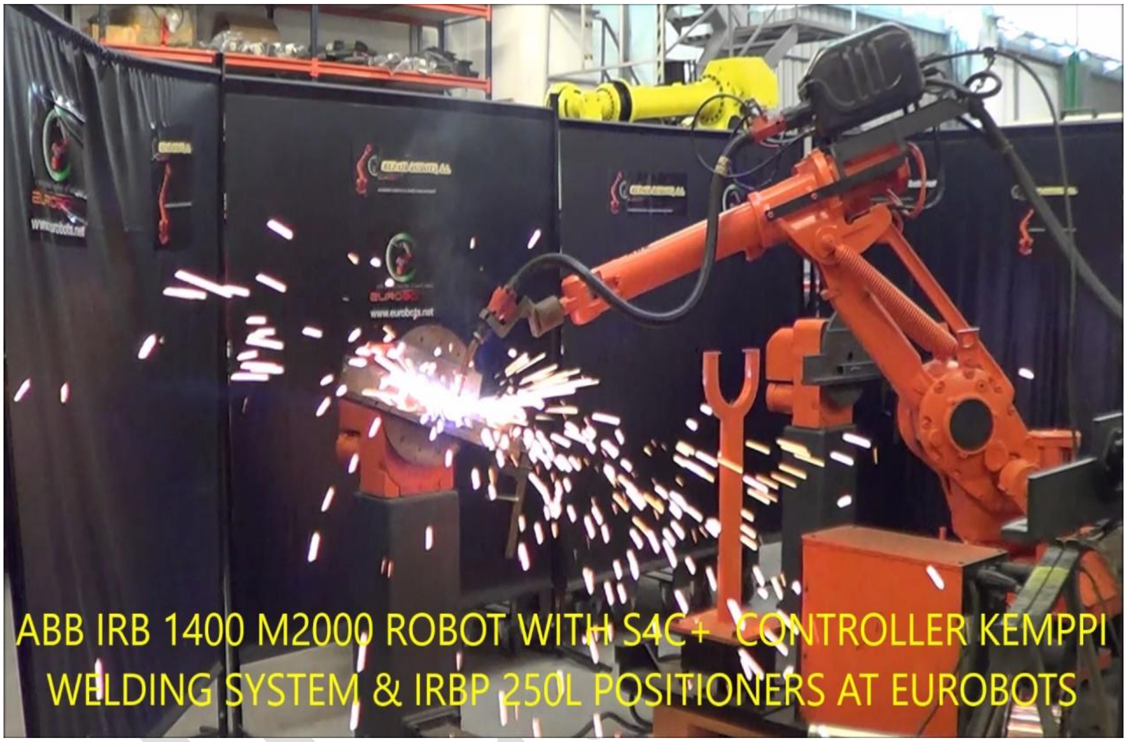
- Notation TRL:
- Consists of a sliding arm (L joint) actuated relative to the body, which can rotate about both a vertical axis (T joint) and horizontal axis (R joint)

JOINT-ARM CONFIGURATION





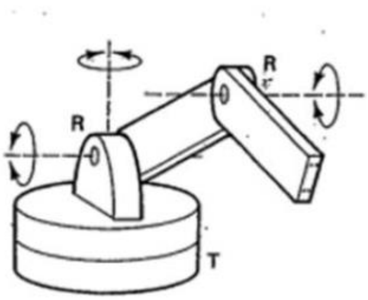
- Notation TRR
- General configuration of a human arm
- The jointed-arm is a combination of cylindrical and articulated configurations.
- The arm of the robot is connected to the base with a twisting joint. The links in the arm are connected by rotary joints.
- Many commercially available robots have this configuration.

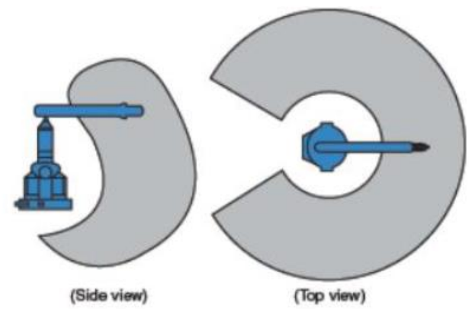


BASED ON JOINTED ARM CONFIGURATION

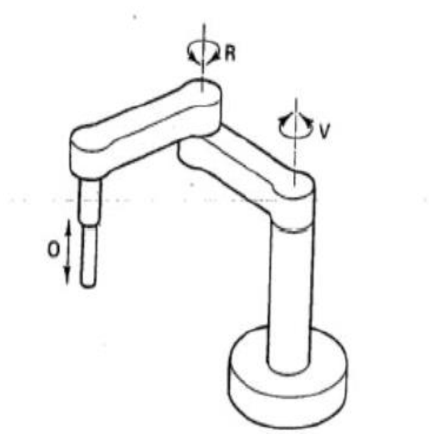
1. **Vertically articulated**
2. **Horizontally articulated**

Vertically articulated



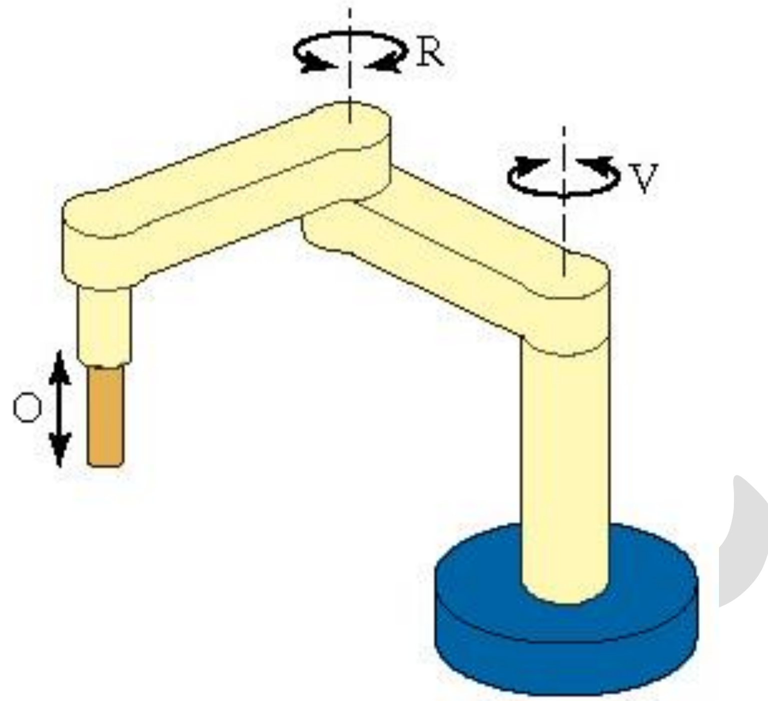


Horizontally Articulated



SCARA- Selective Compliance Assembly robot arm

SCARA ROBOT



- Notation VRO
- SCARA stands for Selectively Compliant Assembly Robot Arm
- Similar to jointed-arm robot except that vertical axes are used for shoulder and elbow joints to be compliant in horizontal direction for vertical insertion tasks

CLASSIFICATION BASED ON CONTROL SYSTEMS

1. **Point-to-point (PTP) control robot**
2. **Continuous-path (CP) control robot**
3. **Controlled-path robot**

POINT TO POINT CONTROL ROBOT (PTP)

- The PTP robot is capable of moving from one point to another point. The locations are recorded in the control memory. PTP robots do not control the path to get from one point to the next point. Common applications include:
- Component insertion
- Spot welding
- hole drilling
- Machine loading and unloading
- Assembly operations

CONTINUOUS-PATH CONTROL ROBOT (CP)

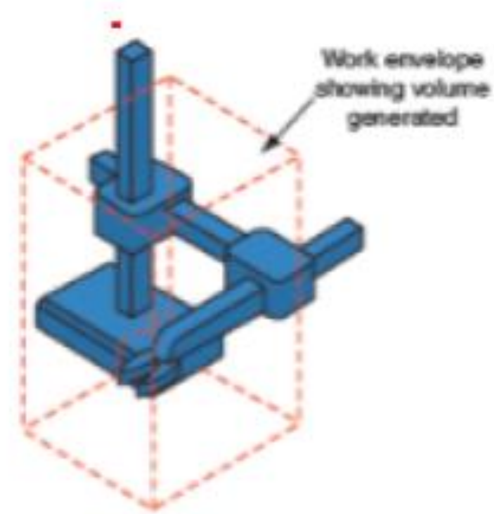
- The CP robot is capable of performing movements along the controlled path.
- With CP from one control, the robot can stop at any specified point along the controlled path.
- All the points along the path must be stored explicitly in the robot's control memory.
- Applications Straight-line motion is the simplest example for this type of robot.
- Some continuous-path controlled robots also have the capability to follow a smooth curve path that has been defined by the programmer**.**

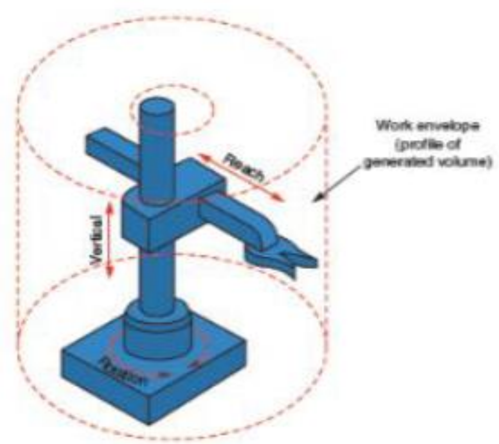
CONTROLLED-PATH ROBOT

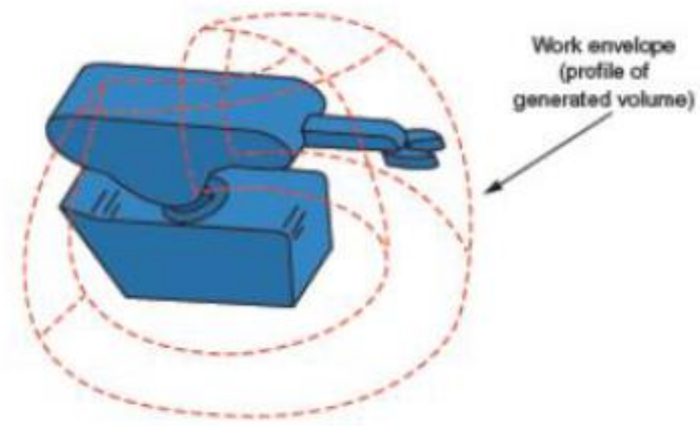
- In controlled-path robots, the control equipment can generate paths of different geometry such as straight lines, circles, and interpolated curves with a high degree of accuracy.
- Good accuracy can be obtained at any point along the specified path.
- Only the start and finish points and the path definition function must be stored in the robot's control memory.
- It is important to mention that all controlled-path robots have a servo capability to correct their path.

WORK VOLUME

- Robot reach, also known as the work envelope or work volume, is the space of all points in the surrounding space that can be reached by the robot arm.
- Reach is one of the most important characteristics to be considered in selecting a suitable robot because the application space should not fall out of the selected robot's reach.
- For a Cartesian configuration the reach is a rectangular-type space.
- For a cylindrical configuration the reach is a hollow cylindrical space.
- For a polar configuration the reach is part of a hollow spherical shape.
- Robot reach for a jointed-arm configuration does not have a specific shape.







ROBOT MOTIONS

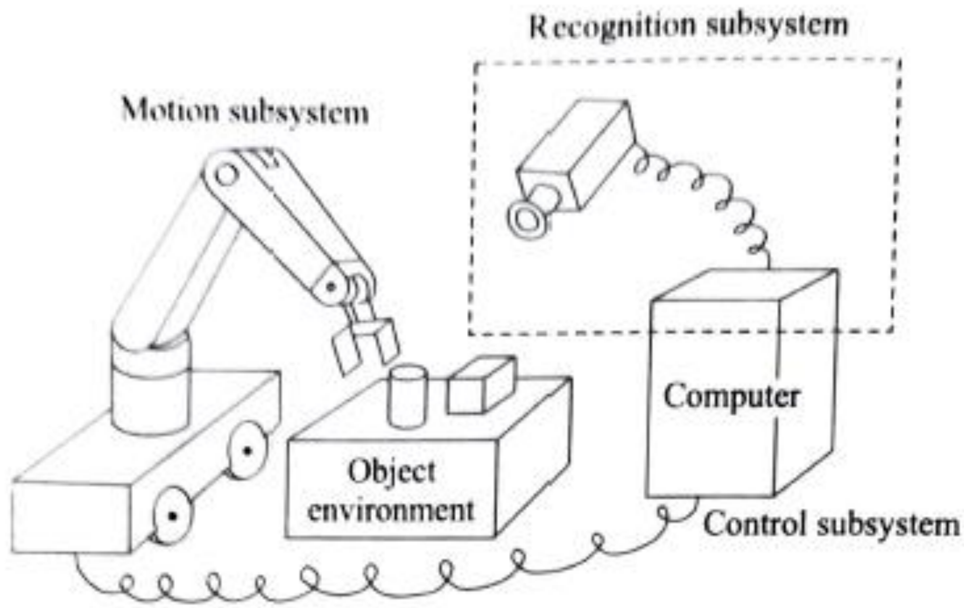


Fig. 2.1 Robot subsystems and their interactions
[Courtesy: Yoshikawa (1990)]

(i) A Motion Subsystem The motion subsystem is the physical structure of the robot that carries out a desired motion similar to human arms, as illustrated in Fig. 2.2.

(ii) A Recognition Subsystem The recognition subsystem uses various sensors to gather information about the robot itself and any objects being acted upon, and about the environment. Based on sensor data, it recognises the robot's state, the objects, and the environment.

(iii) A Control Subsystem The control subsystem influences the robot's motion to achieve a given task using the information provided by the recognition subsystem.

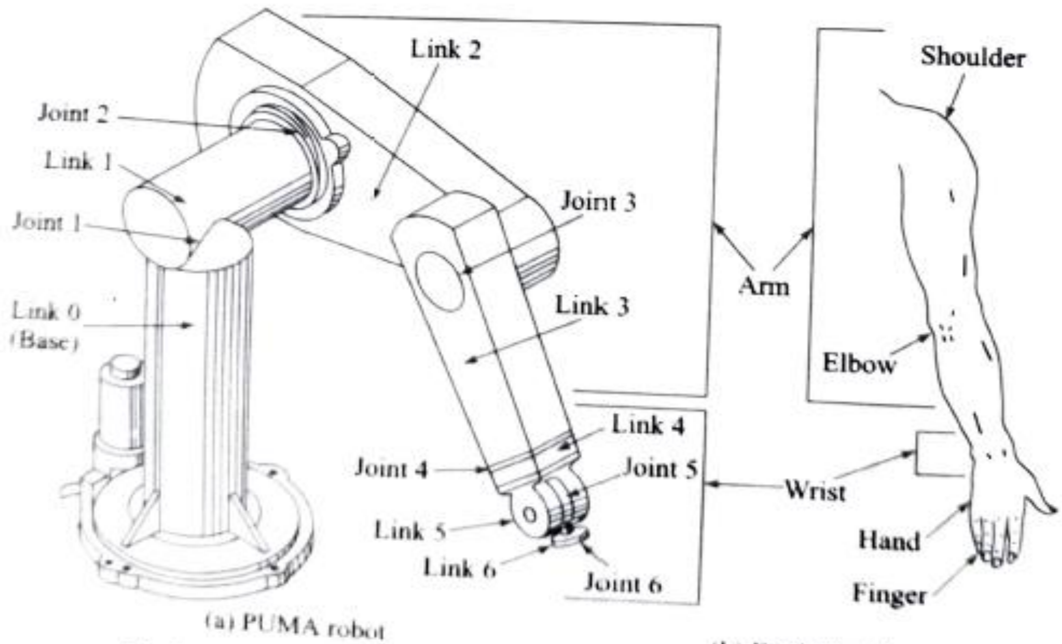


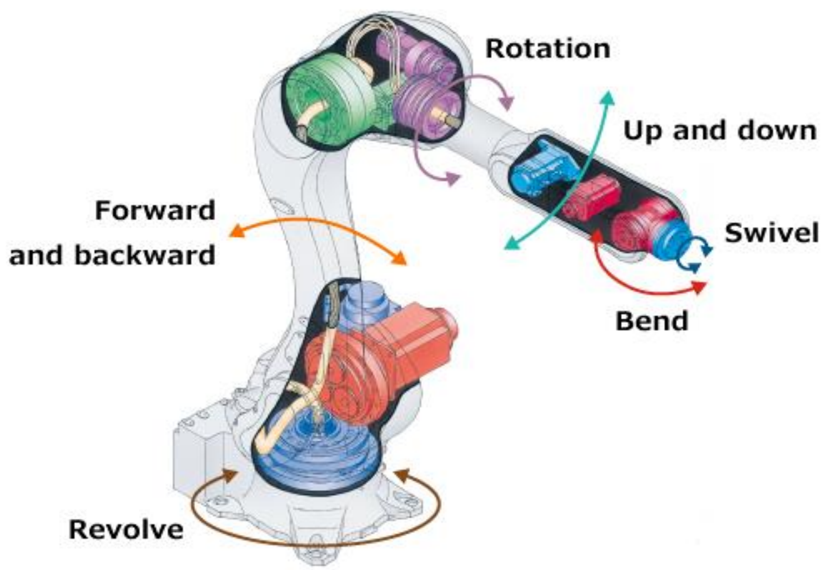
Fig. 2.2 A robot manipulator and its equivalent human parts

SPAITAL RESOLUTION-ACCURACY AND REPETABILITY

- Three terms used to define precision in robotics, similar to numerical control precision:
- **CONTROL RESOLUTION** -capability of robot's positioning system to divide the motion range of each joint into closely spaced points
- **ACCURACY** -capability to position the robot's wrist at a desired location in the work space, given the limits of the robot's control resolution

- **REPEATABILITY** -capability to position the wrist at a previously taught point in the work space.

MOTORS IN A ROBOTIC ARM



SERVO MOTOR WHICH USED IN A INDUSTRIAL ROBOT

Construction of a standard servo motor

RESOLUTION

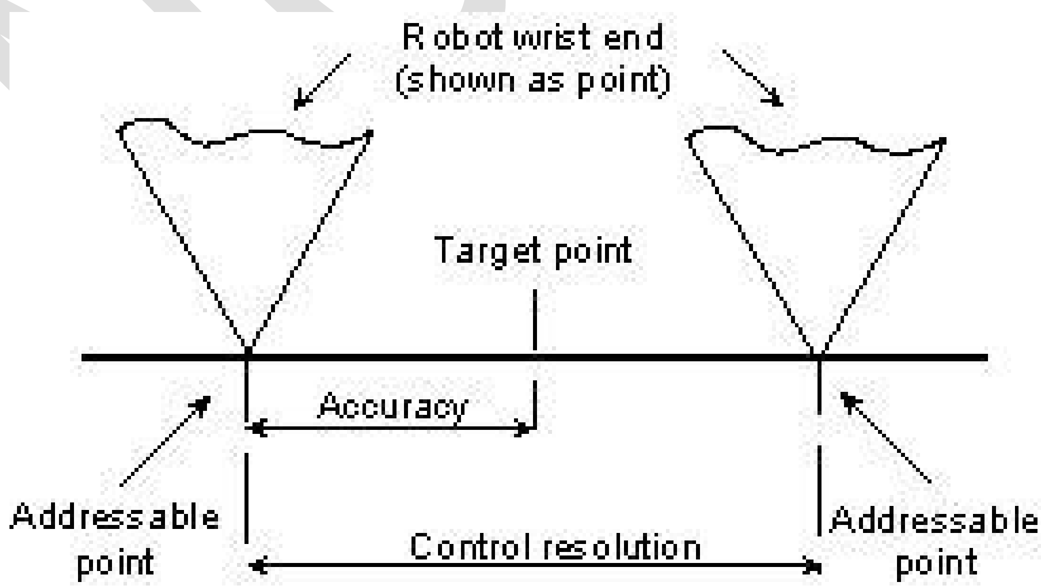
- The resolution of a robot is a feature determined by the design of the control unit and is mainly dependent on the position feedback sensor.
- It is important to distinguish the programming resolution from the control resolution.
- The programming resolution is the smallest allowable position increment in robot programs and is referred to as the basic resolution unit (BRU).
- For IRB2000 ABB robot it is approximately 0,125 mm on linear axis.
- The control resolution is the smallest change in position that the feedback device can sense.

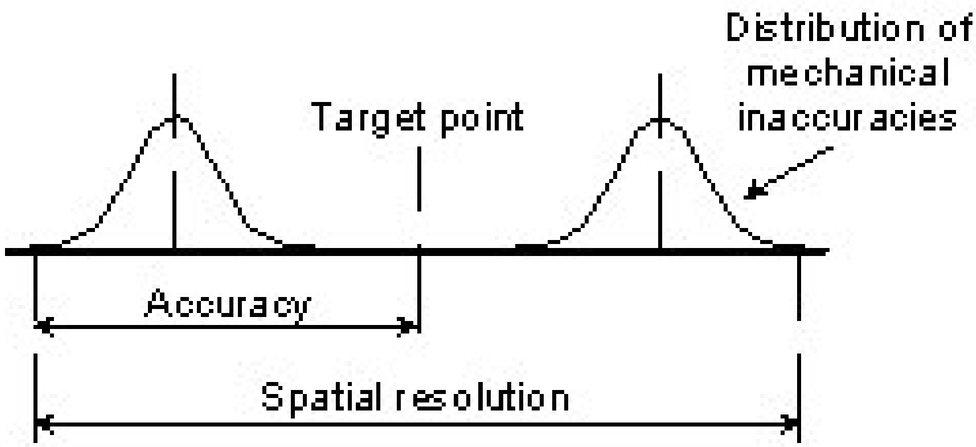
FOR EXAMPLE

- Assume that an optical encoder which emits 1000 pulses per revolution of the shaft is directly attached to a rotary axis.
- This encoder will emit one pulse for each of 0.36° of angular displacement of the shaft.
- The unit 0.36° is the control resolution of this axis of motion.
- Angular increments smaller than 0.36° cannot be detected. Best performance is obtained when programming resolution is equal to control resolution.
- In this case both resolutions can be replaced with one term: the system resolution.

ACCURACY

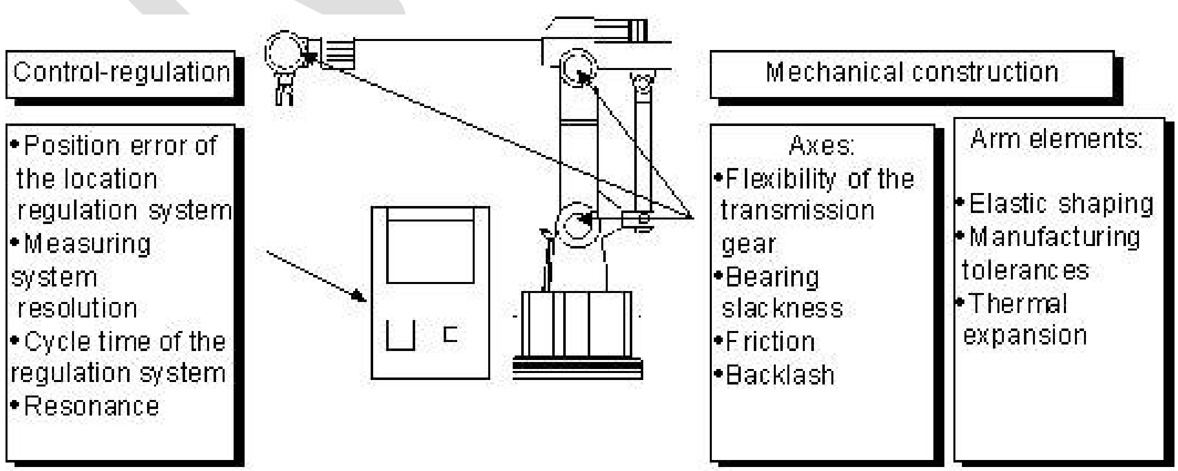
- Accuracy refers to a robot's ability to position its wrist end at a desired target point within the work volume, and it is defined in terms of spatial resolution.





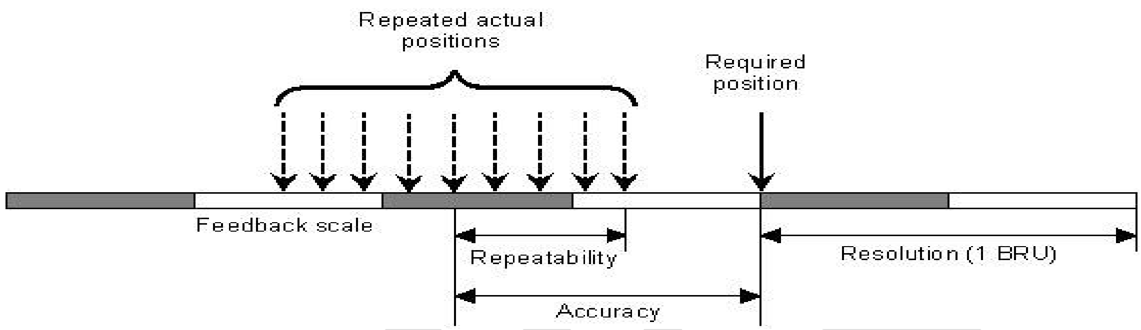
FACTORS AFFECTING ACCURACY

- At first accuracy depends on robot technology and how closely the control increments can be defined for each of the joint motions, excluding for the moment the mechanical inaccuracy which include the robot manufacture quality
- The final accuracy of a robotic system depends on its mechanical inaccuracies, the computer control algorithms, and the system resolution.
- The mechanical inaccuracies are caused mainly by backlash in the manipulators joints and bending of the links. The backlash exists in gear mechanisms, in lead screws, and in actuators of hydraulic drives.
- The minimization of the link bending is the main design requirement for the link, as any deflection of the link due to the load at the robot's end causes positional errors.
- A higher rigidity of the links, however, should not be achieved by a substantial increase in their mass. A larger mass causes an increase in the time response of the arm.
- Control algorithms might cause position errors due to round-off errors in the computer.
- Computer round-off errors might be significant if a robot controller uses scaled integer representation of Cartesian and angular coordinates



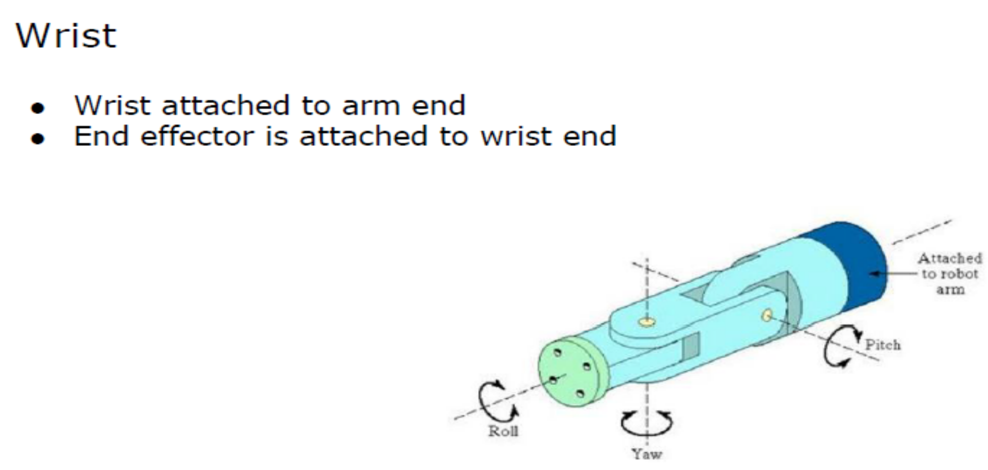
REPEATABILITY

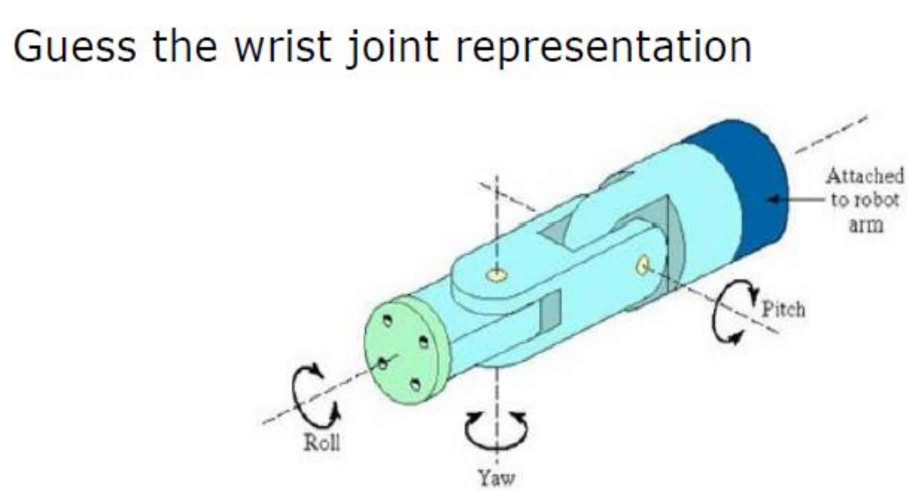
- Repeatability is a statistical term associated with accuracy, it describes how a point is repeated
- If a robot joint is instructed to move by the same angle from a certain point a number of times, all with equal environmental conditions, it will be found that the resultant motions lead to differing displacements.



- Although a target is always missed by a large margin, if the same error is repeated, then we say that the repeatability is high and the accuracy is poor.
- Repeatability does not describe the error with respect to absolute coordinates.
- System repeatability is the positional deviation from the average of displacements.
- For example, +-0,2 mm indicates that any point might be as much as 0,2 mm beyond or short of the center of the repeatability pattern.
- Most robot manufacturers provide a numerical value for the repeatability rather than the accuracy of their robots.
- The reason is that the accuracy depends upon the particular load that the gripper carries.
- A heavier weight causes larger deflections of the robot links and larger load on the joints, which degrade the accuracy, while the repeatability value, however, is almost independent of the gripper load.

WRIST CONFIGURATION

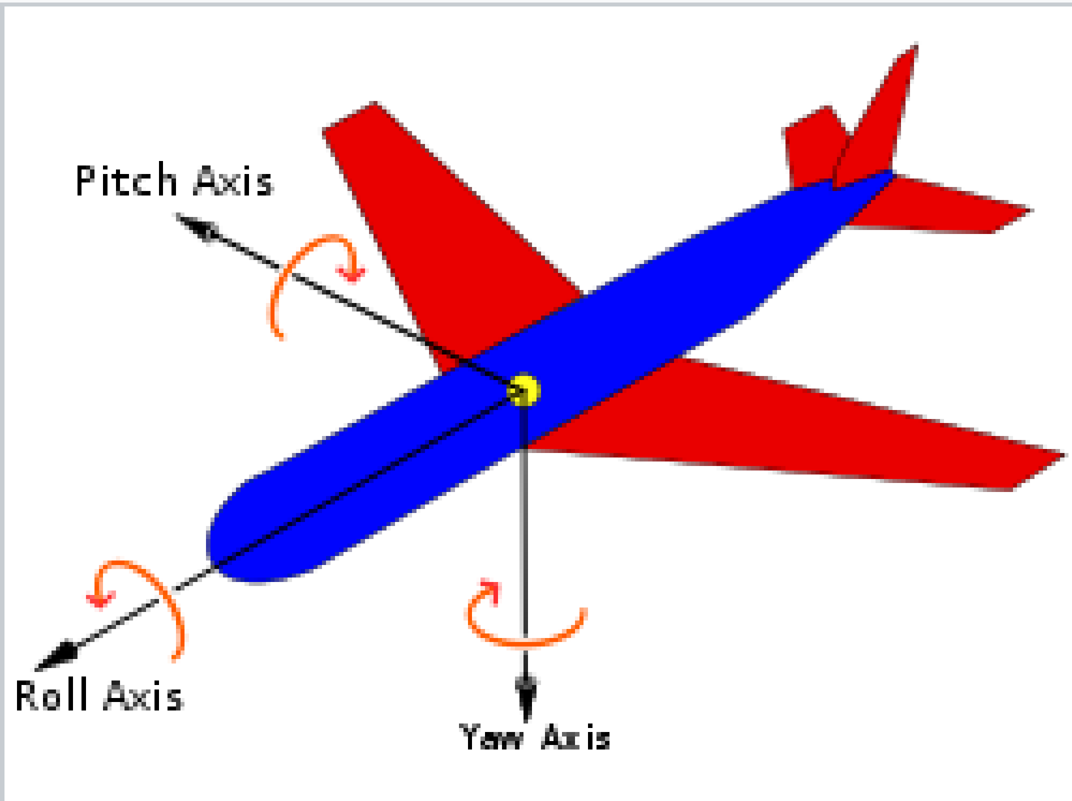




MOTION-ROLL-YAW-PITCH

- Pitch, yaw and roll are the three dimensions of movement when an object moves through a medium.
- The terms may be used to describe an aero plane's movements through the air. They are also applied to fish moving through water, and spacecraft moving through space.
- There are in fact six degrees of freedom of a rigid body moving in three-dimensional space.

- As the movement along each of the three axes is independent of each other and independent of the rotation about any of these axes, the motion has six degrees of freedom (see diagram).
- **PITCH**: nose up or tail up
- **YAW** : nose moves from side to side
- **ROLL** : a circular (clockwise or anticlockwise) movement of the body as it moves forward

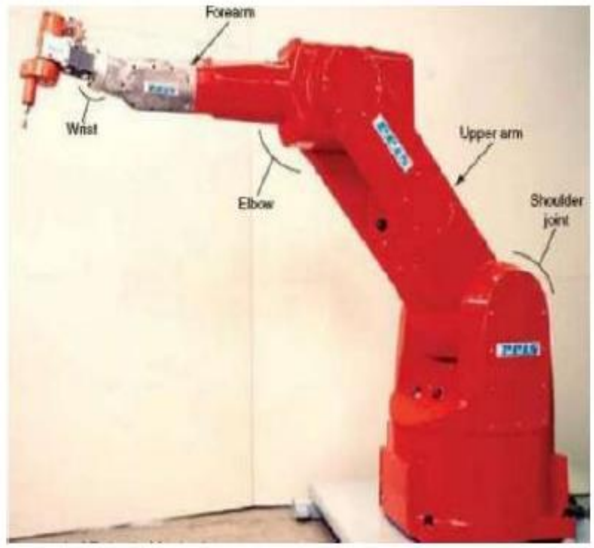


The position of all three axes, with the right-hand rule for describing the angle of its rotations

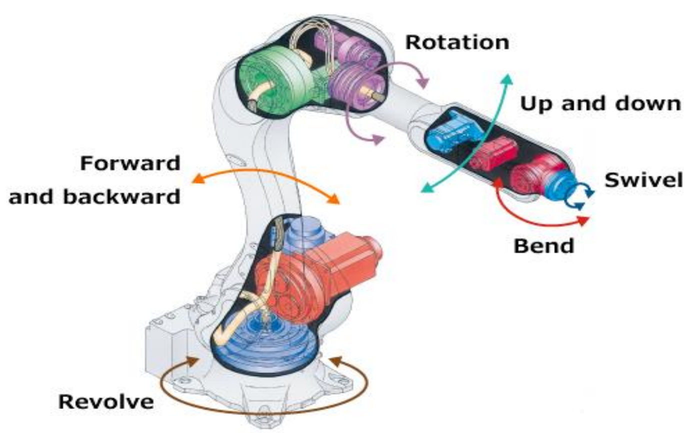
MODULE 2

DRIVES

Manipulator Vs Human Arm



- 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.
- 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, pressurized fluid or the electricity, based on which they are classified as follow



BASIC PNEUMATIC SYSTEM

- Pneumatic systems use pressurized air to make things move. Basic pneumatic system consists of an air generating unit and an air-consuming unit.
- Air compressed in compressor is not ready for use as such, air has to be filtered, moisture present in air has to be dried, and for different applications in plant pressure of air has to be varied.
- Several other treatments are given to the air before it reaches finally to the Actuators

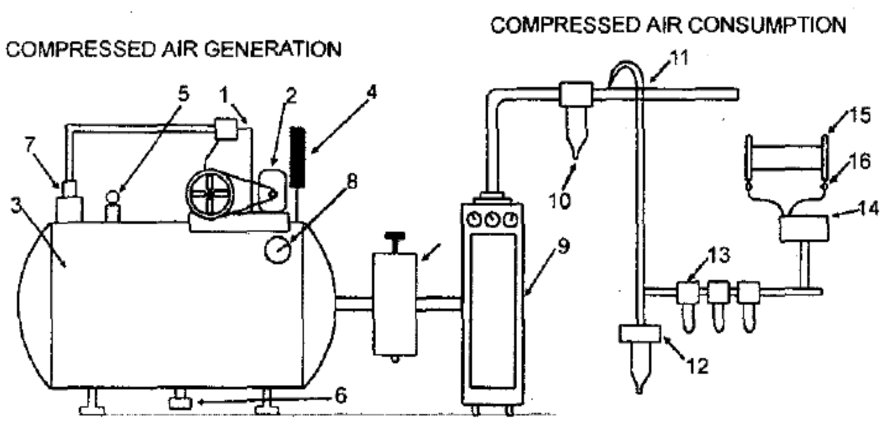


Fig. 2.1. Basic Pneumatic System

1. Compressor
2. Electric motor
3. Air receiver
4. Pressure switch
5. Safety valve
6. Auto drain
7. Check valve
8. Pressure gauge
9. Air dryer
10. After filter
11. Tapping
12. Auto Drain
13. Air service unit
14. Direction control valve
15. Actuator
16. Speed controller.

HYDRAULIC MOTOR

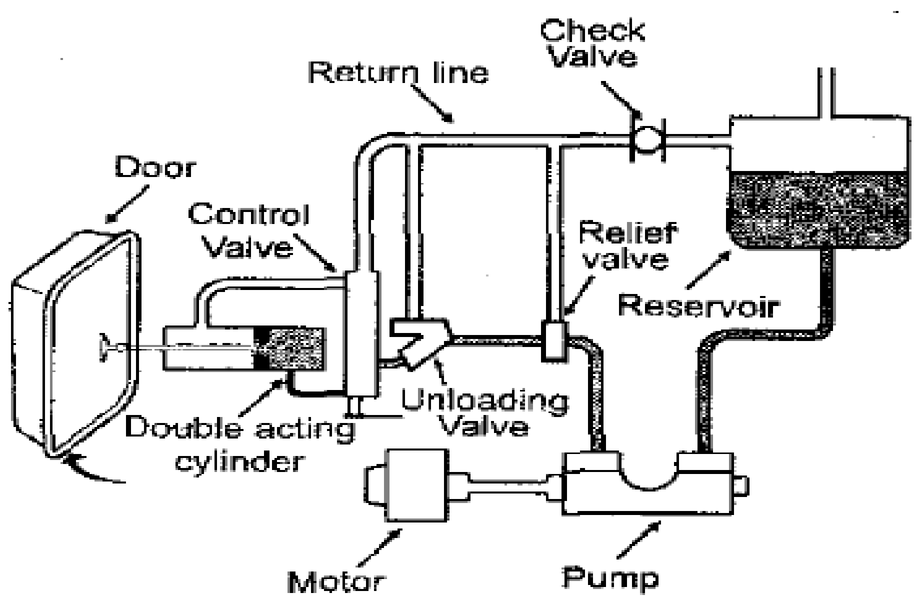
- Electric Motor Electric motor is used to drive the compressor Hydraulic Pump.
- Hydraulic pumps convert mechanical energy from a prime mover (engine or electric motor) into hydraulic (pressure) energy. The pressure energy is used then to operate an actuator Pumps push on a hydraulic fluid and create flow.
- Strainers and Filters. To keep hydraulic components performing correctly, the hydraulic liquid must be kept as clean as possible.
- Foreign matter and tiny metal particles from normal wear of valves, pumps, and other

components are going to enter a system.

- Strainers, filters, and magnetic plugs are used to remove foreign particles from a hydraulic liquid and are effective as safeguards against contamination Strainers.
- A strainer is the primary filtering system that removes large particles of foreign matter from a hydraulic liquid.
- Even though its screening action is not as good as a filter's, a strainer offers less resistance to flow.

ADVANTAGES

- Through the use of simple devices, an operator can readily start, stop, speed up, slow down, and control large forces with very close and precise tolerance.
- High power output from a compact actuator.
- Hydraulic power systems can multiply forces simply and efficiently from a fraction of an ounce to several hundred tons of output.
- Force can be transmitted over distances and around corners with small losses of efficiency.
- There is no need for complex systems of gears, cams, or levers to obtain a large mechanical advantage



A typical Hydraulic power system includes the following components:

1. Electric motor
2. Hydraulic pump
3. Filter
4. Pressure gauge
5. Pressure Regulator/Unloading valve
6. Pressure relief valve
7. Direction control valve
8. Hydraulic actuator
9. Load
10. Check valve
11. Reservoir
12. Manifolds, hose, tube, fittings, couplings, etc.

DISADVANTAGES

- System components must be engineered to minimize or preclude fluid leakage.
- Protection against rust, corrosion, dirt, oil deterioration, and other adverse environment is very important.
- Maintenance of precision parts when they are exposed to bad climates and dirty-atmospheres.
- Fire hazard if leak occurs.
- Adequate oil filtration must be maintained

APPLICATION OF HYDRAULIC ACTUATORS

- Used to drive the spray coating robots
- Used in heavy part loading robots
- Useful in material handling robot system
- Used to drive the joints of assembly (heavy) robots
- Useful in producing translator motion in Cartesian robot
- Useful in robots operating in hazardous, sparking environments.
- Useful in gripper mechanisms

DC SERVO MOTOR

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

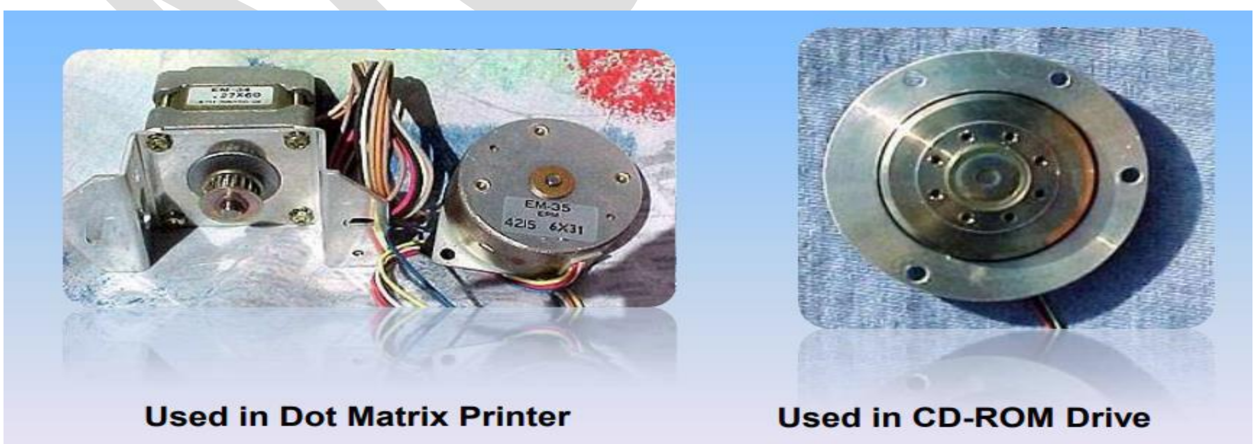
- Rotor, stator, brush and commutator assembly. The rotor has got windings of armature and the stator has got the magnet. The brush and the commutator assemblies switch the current to the armature maintaining an opposed field in the magnets
- Types of electric drive

THE MOST COMMONLY

1. **DC SERVO MOTOR**
2. **AC SERVO MOTOR**
3. **STEPPER MOTOR**

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.

STEPPER MOTOR-OPERATION



Used in Dot Matrix Printer　　Used in CD-ROM Drive

- A stepper motor is a special electrical machine which rotates in discrete angular steps in response to a programmed sequence of input electrical pulses.

WORKING PRINCIPLE

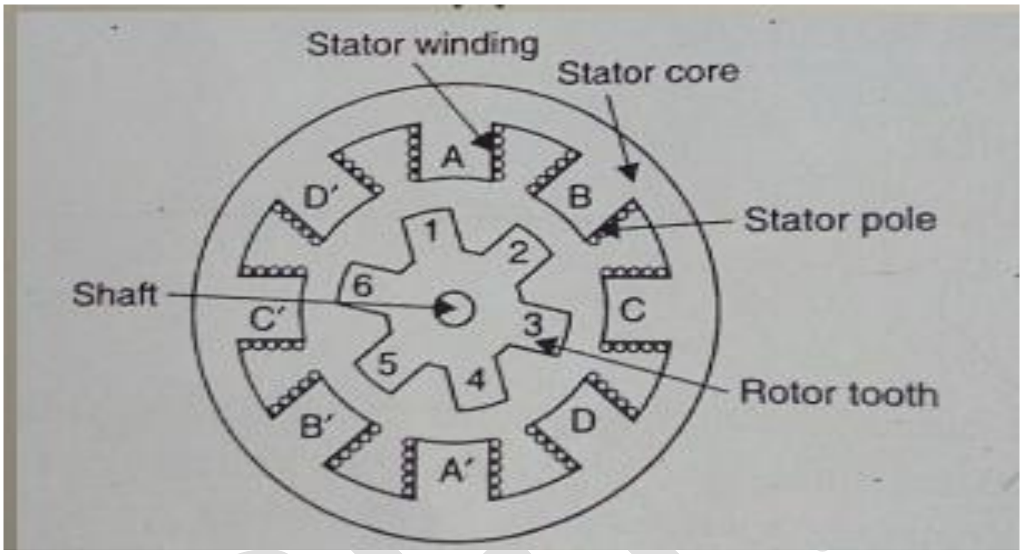
- A magnetic interaction takes place between the rotor and the stator, which make rotor move.

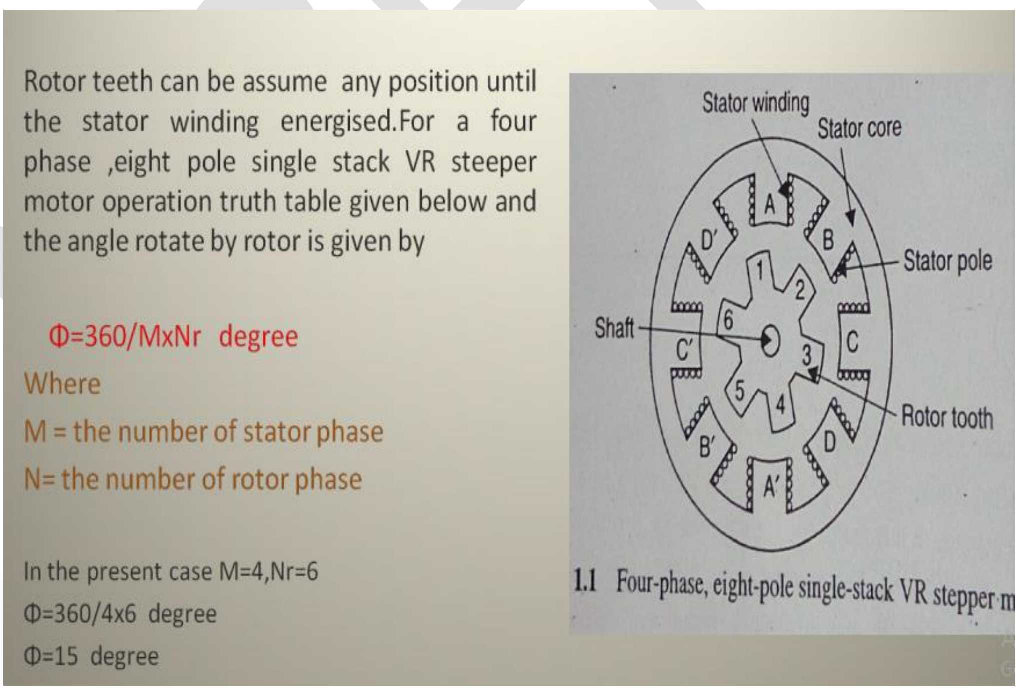
CONSTRUCTION

- The stator has windings
- The rotor is of salient structure without any windings

VARIABLE RELUCTANCE MOTOR

- Variable reluctance stepper motor works on the principle that a magnetic material placed in magnetic field experience a force to align minimum reluctance path





Switching sequence

Phase	S-1	S-2	S-3	S-4	Angle (Deg)
A	1	0	0	0	0
B	0	1	0	0	15
C	0	0	1	0	30
D	0	0	0	1	45
A	1	0	0	0	60

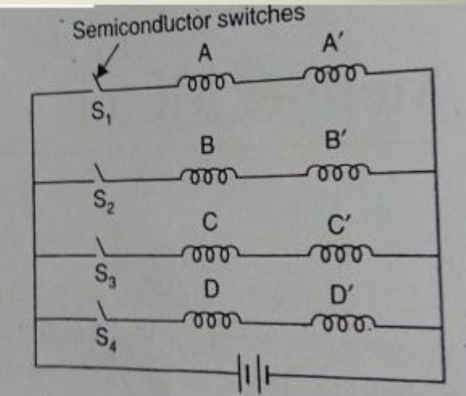


Fig. 1.2 Switching circuit

Rotor position for phase excitation

Fig. 1.3 Rotor position when phase A is excited

Fig. 1.4 Rotor position when phase B is energised

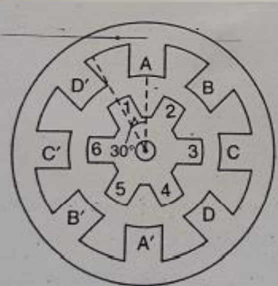


Fig. 1.5 Position of rotor after switching phase C

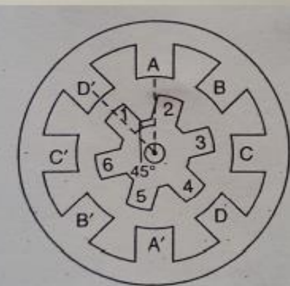
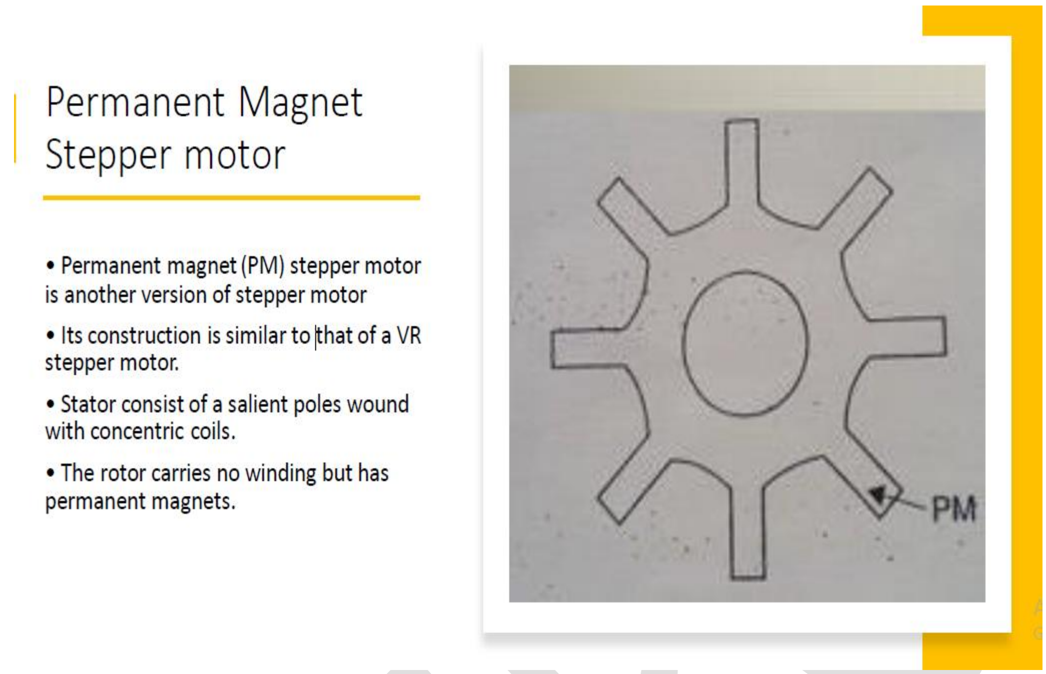
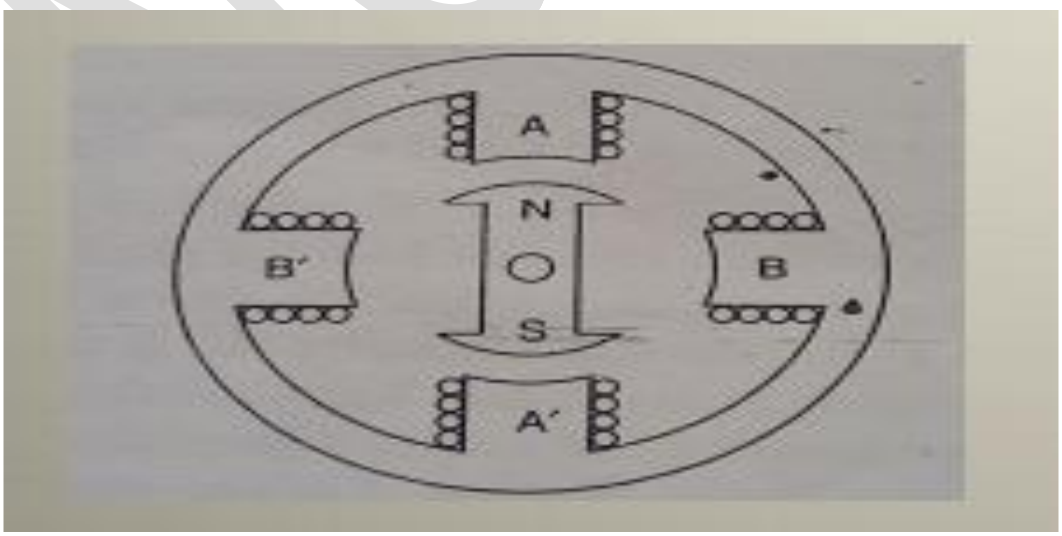


Fig. 1.6 Rotor position after switching phase D



- Due to the difficulty in manufacturing small PMs, the number of poles in the rotor is limited and the step size is relatively large in the range
- To study the principle of operation of PM stepper motor, a two phase motor is considered.
- It has four stator poles and two rotor poles.
- The stator has winding on its poles.
- When a phase is energized, it sets up a magnetic flux and rotor will position to lock its N pole and S pole to stator S pole and N pole respectively.



POWER TRANSMISSION SYSTEM

- As the term conveys, these elements transmit motion from the motors and actuators to the actual links of the manipulator.
- For electric motors these elements together with the electric motor form an actuator. Typical transmission elements are

GEAR TRANSMISSION

- Of all mechanical transmissions, the various types of gears, as shown in Fig. 2.6, are amongst the most reliable and long-lasting, although their backlash must be carefully taken into account during the design stage.

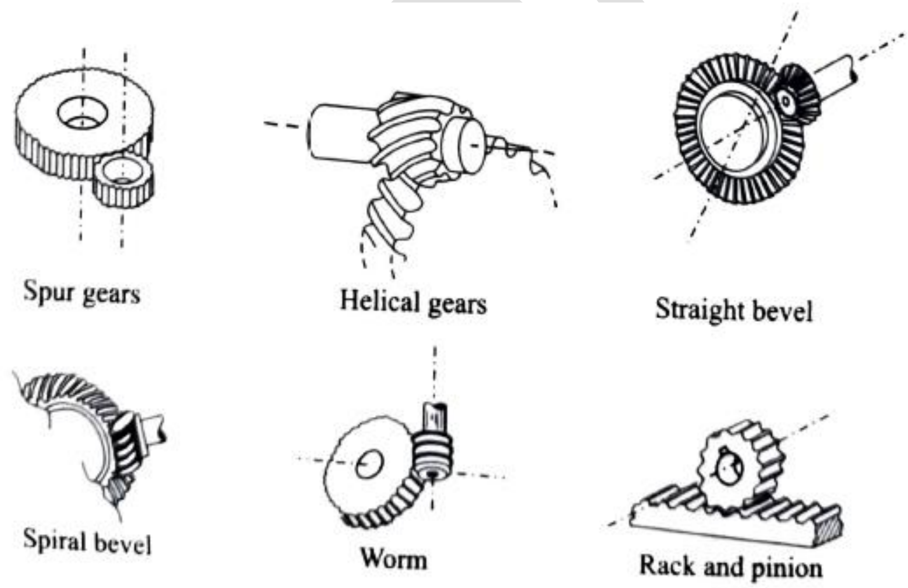


Fig. 2.6 Gears

BELT DRIVES

- Belt drives are widely used in robotics,
- Particularly, the synchronous belt, as shown in Fig. 2.5(a). However, their life cycle is short as they rely on belt tension to produce a grip over the pulley.
- Alternatively, chains, as shown in Fig. 2.5(b), are generally cheaper. They have a higher load capacity and service life as compared to belt drives but lower in comparison to gears.

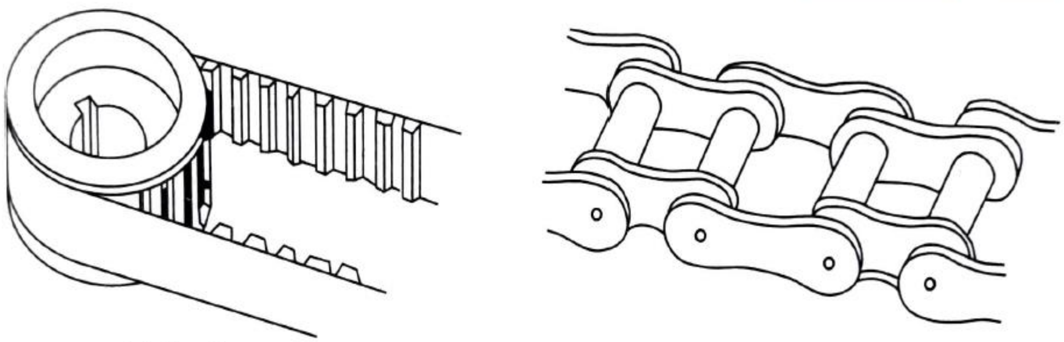


Fig. 2.5 Belt and chain drives

LINKS

- In order to reduce the weight and excess flexibility of above transmission elements. Link mechanisms of are employed how a ball screw with a four-bar link arrangement is used to transmit motion.
- A series links, generally rigid, coupled by joint that allow relative motions between any two links, form a mechanism.

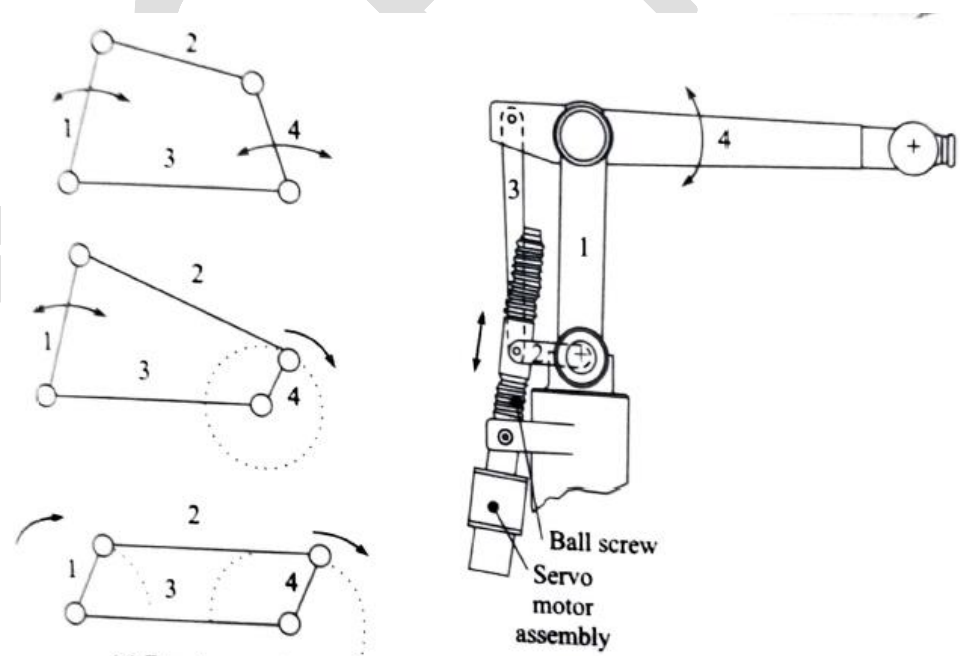
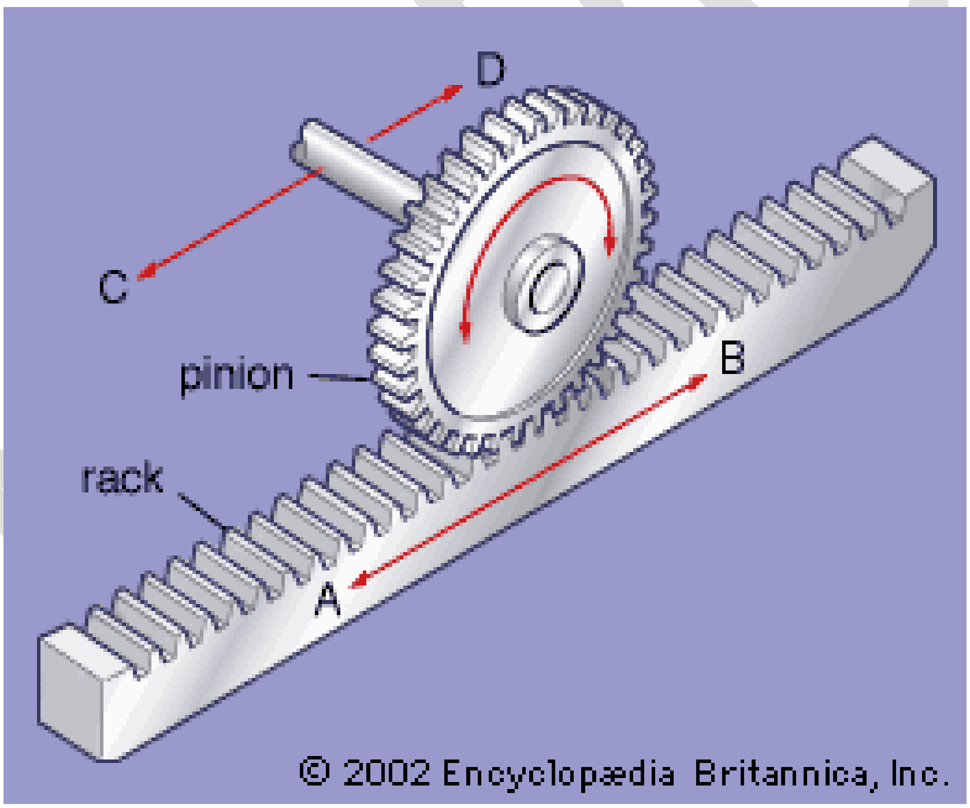


Fig. 2.7 Mechanisms and their use in robot manipulator

ROTARY TO LINEAR MOTION CONVERSION

RACK AND PINION DRIVES

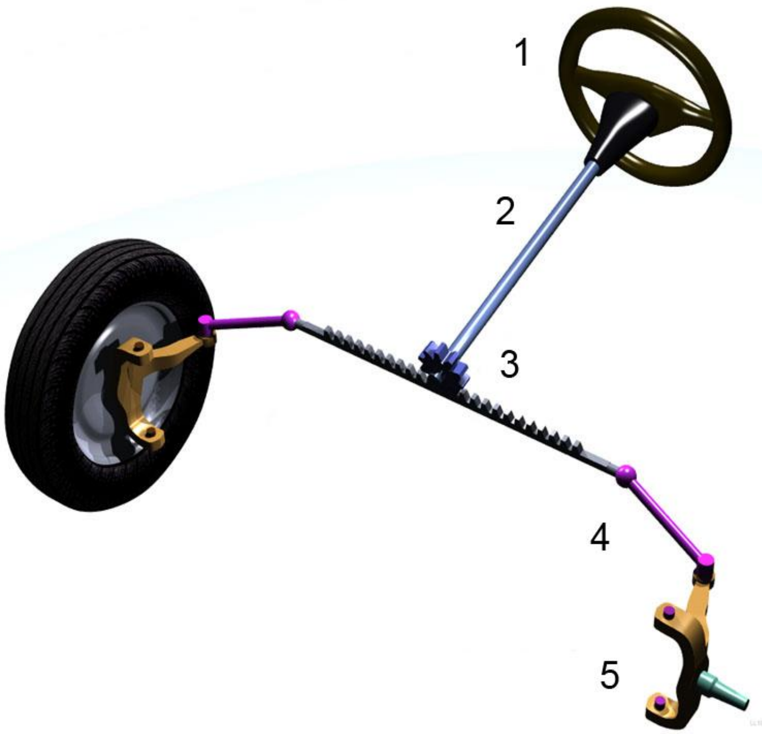
- A rack and pinion is a type of linear actuator that comprises a circular gear (the *pinion*) engaging a linear gear (the *rack*), which operate to translate rotational motion into linear motion.
- Driving the pinion into rotation causes the rack to be driven linearly.
- Driving the rack linearly will cause the pinion to be driven into a rotation. A rack and pinion drive can use both straight and helical gears.
- Helical gears are preferred due to their quieter operation and higher load bearing capacity.
- The maximum force that can be transmitted in a rack and pinion mechanism is determined by the tooth pitch and the size of the pinion.



APPLICATION

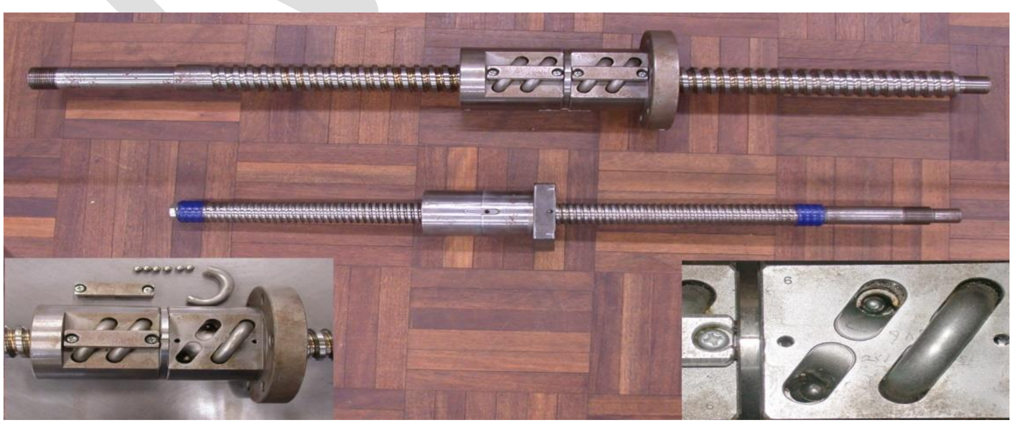
- Rack and pinion combinations are often used as part of a simple linear actuator, where the rotation of a shaft powered by hand or by a motor is converted to linear motion.
- The rack carries the full load of the actuator directly and so the driving pinion is usually small, so that the gear ratio reduces the torque required.
- This force, thus torque, may still be substantial and so it is common for there to be a reduction gear immediately before this by either a gear or worm gear reduction.

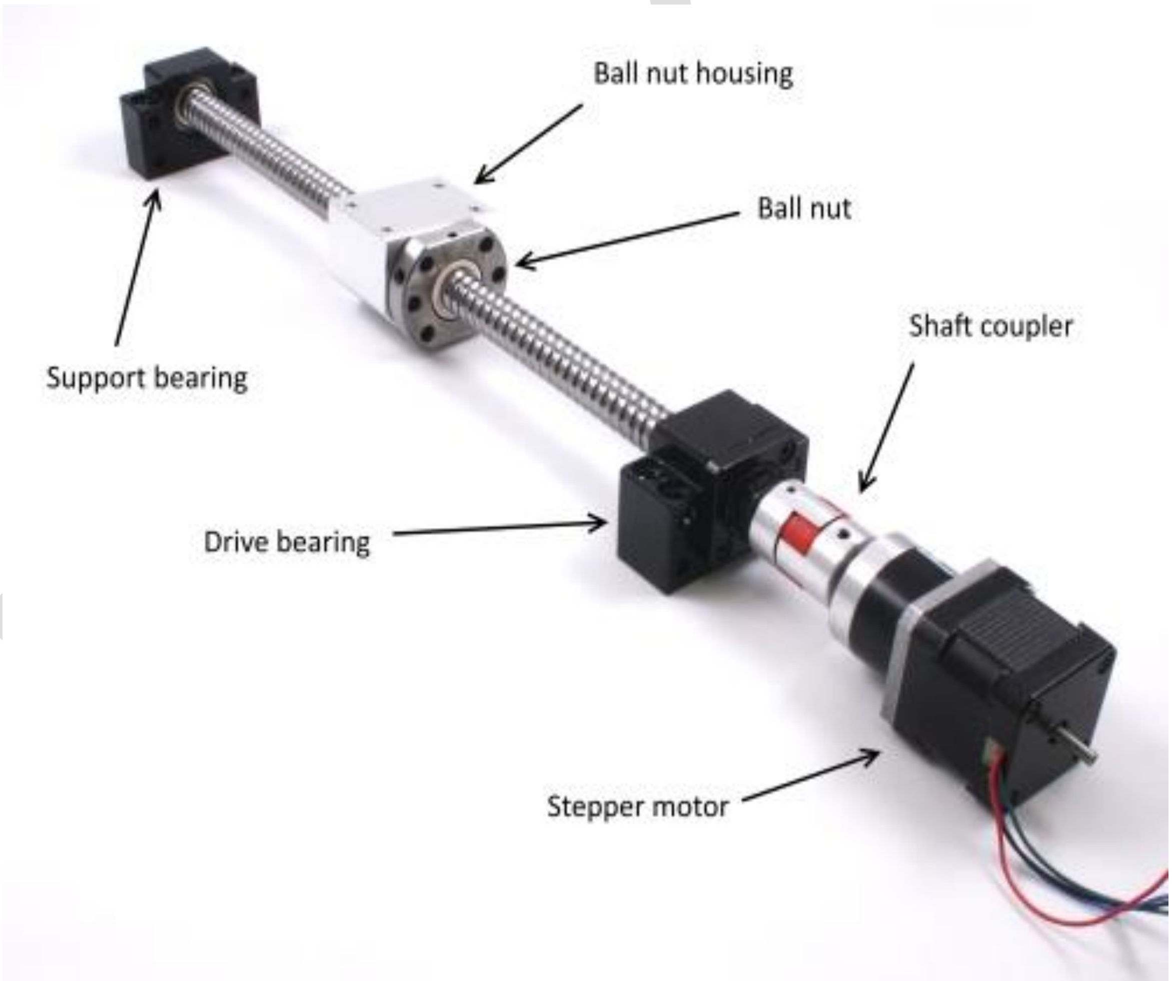
- **STAIR LIFTS**
- **STEERING**
- **STAIR LIFTS**
- **STEERING**


1
2
3
4
5

- A rack and pinion is commonly found in the steering mechanism of cars or other wheeled, steered vehicles.
- Rack and pinion provides less mechanical advantage than other mechanisms such as recirculating ball, but less backlash and greater feedback, or steering "feel".
- The mechanism may be power-assisted, usually by hydraulic or electrical means.
- A rack and pinion with two racks and one pinion is used in actuators. An example is pneumatic rack and pinion actuators that can be used to control valves in pipeline transport.

BALL BEARING SCREWS



- A ball screw is a mechanical linear actuator that translates rotational motion to linear motion with little friction.
- A threaded shaft provides a helical raceway for ball bearings which act as a precision screw.
- As well as being able to apply or withstand high thrust loads, they can do so with minimum internal friction. They are made to close tolerances and are therefore suitable for use in situations in which high precision is necessary.
- The ball assembly acts as the nut while the threaded shaft is the screw.
- In contrast to conventional leads crews, ball screws tend to be rather bulky, due to the need to have a mechanism to re-circulate the balls.
- 

APPLICATIONS

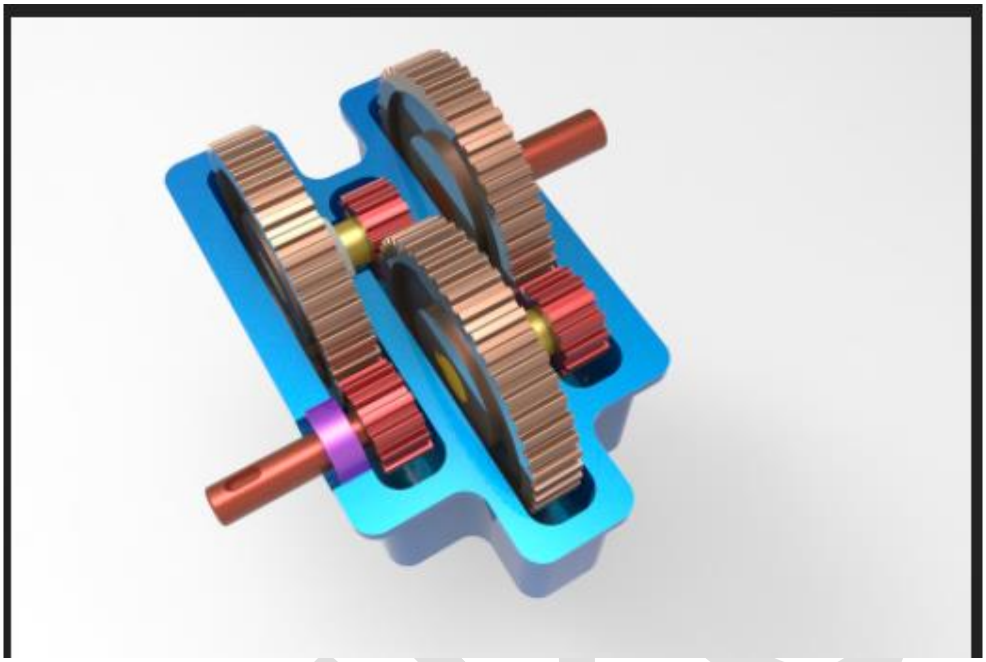
- All screws are used in aircraft and missiles to move control surfaces, especially for electric fly by wire, and in automobile power steering to translate rotary motion from an electric motor to axial motion of the steering rack.
- They are also used in machine tools, robots and precision assembly equipment. High precision ball screws are used in steppers for semiconductor manufacturing.
- Lack of sliding friction between the nut and screw lends itself to extended lifespan of the screw assembly (especially in no-backlash systems), reducing downtime for maintenance and parts replacement, while also decreasing demand for lubrication.
- This combined with their overall performance benefits and reduced power requirements, may offset the initial costs of using ball screws.

SPEED REDUCER

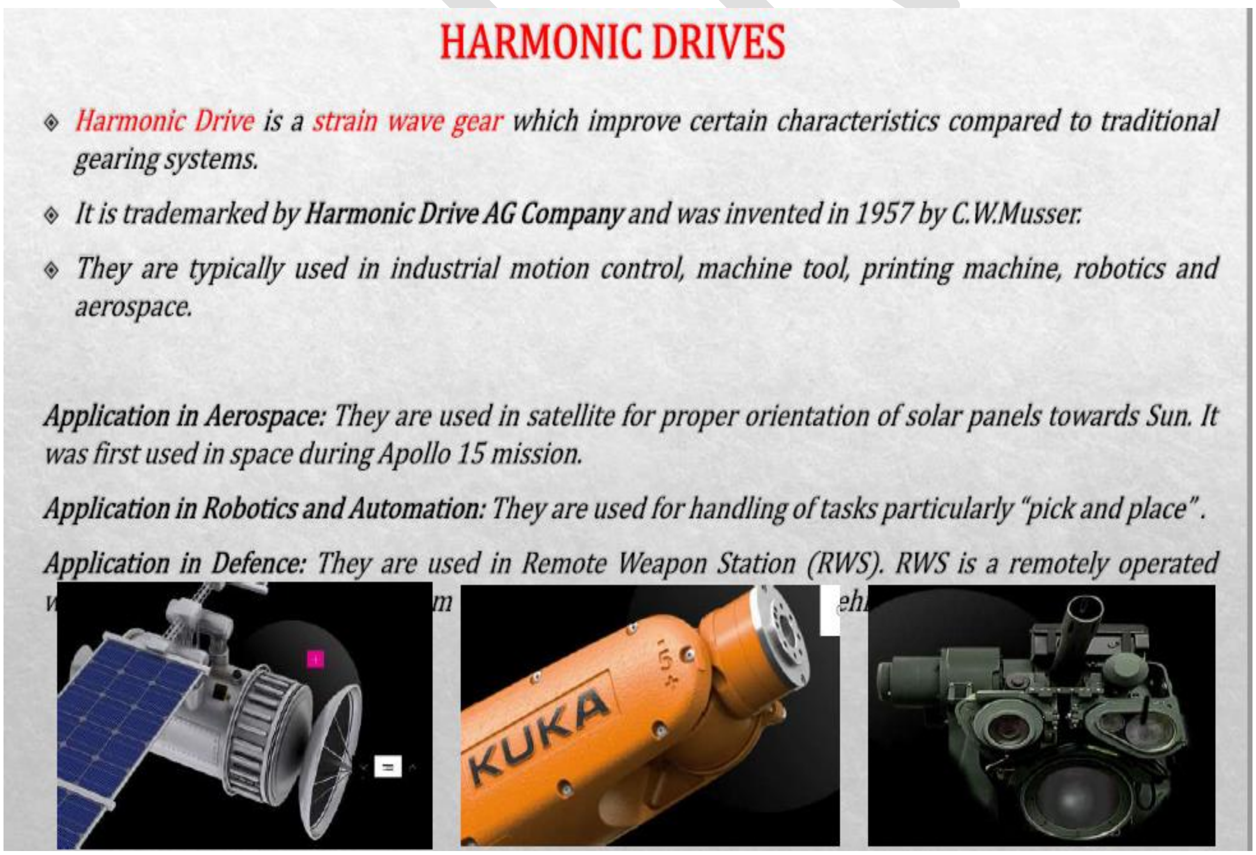
- Speed reducers are mechanical devices generally used for two purposes.
- The primary use is to multiply the amount of torque Speed reducers are mechanical devices generally used for two purposes.
- The primary use is to multiply the amount of torque generated by an input power source to increase the amount of usable work.
- They also reduce the input power source speed to achieve desired output speeds.
- The wide variety of mechanical speed reducing devices includes pulleys, sprockets, gears, and friction drives.
- There are also electrical products that can change the motor speed**.**
- This discussion will focus on enclosed-drive speed reducers, also known as gear drives and gearboxes, which have two main configurations

1. **IN-LINE**
2. **RIGHT ANGLE.**

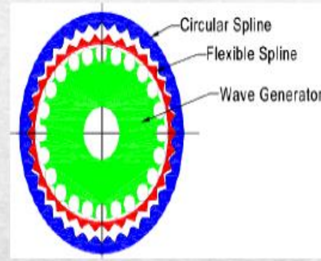
- Each can be achieved using different types of gearing. In-line models are commonly made up of helical or spur gears, planetary gears, or harmonic wave generators.
- Planetary designs generally provide the highest torque in the smallest package.
- Cycloidal and harmonic drives offer compact designs in higher ratios, while helical and spur reducers are generally the most economical. All are fairly efficient.
- Right angle designs are typically made with worm gearing or bevel gearing, though hybrid drives are also available.
- Worm gears are perhaps the most cost effective reduction solution



HARMONIC DRIVES



- ***Strain Wave Gearing*** *is a special type of mechanical gear system whose theory is based on elastic dynamics and utilizes flexibility of metals.*
- *The three basic components:*
  1. ***Wave Generator (Input)***
  2. ***Flex Spline (Output)***
  3. ***Circular Spline***
- ***Wave Generator*** *is made of two separate parts:*
  1. ***Elliptical disk called wave generator plug***
  2. ***Outer ball bearing***



Flex Spline

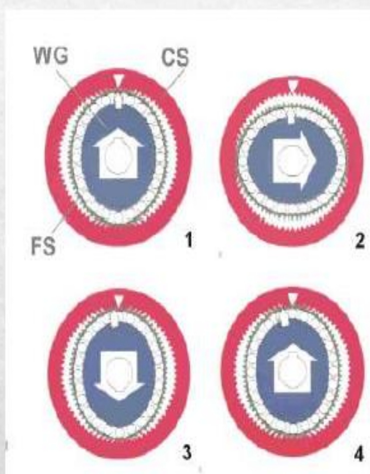
- ***Flex Spline*** *is like shallow cup. The sides of the spline are very thin but the bottom is thick and rigid.*
- *Teeth are positioned radially around the outside of the flex spline.*
- *The flex spline fits tightly over the wave generator, so that when the wave generator plug is rotated, the flex spline deforms to the shape of a rotating ellipse.*

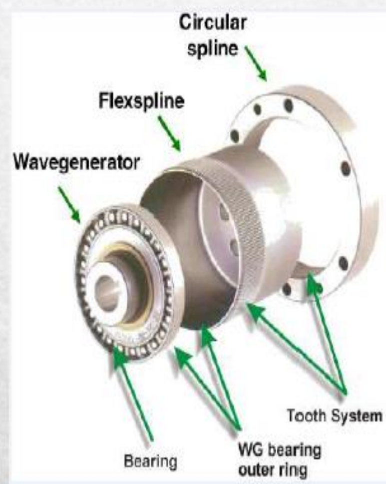
Circular Spline

- *The* ***circular spline*** *is a rigid circular ring with teeth on the inside.*
- *The flex spline and wave generator are placed inside the circular spline, meshing the teeth of the flex spline and the circular spline.*
- *Because the flex spline has an elliptical shape, its teeth only actually mesh with the teeth of the circular spline in two regions on opposite sides of the flex spline, along the major axis of the ellipse.*

Working

- *Assume that the wave generator is the input rotation.*
- *As the wave generator plug rotates, the flex spline teeth which are meshed with those of the circular spline change.*
- *The major axis of the flex spline actually rotates with wave generator, so the points where the teeth mesh revolve around the centre point at the same rate as the wave generator.*
- *The key to the design of the strain wave gear is that there are fewer teeth (for example two fewer) on the flex spline than there are on the circular spline.*
- *This means that for every full rotation of the wave generator, the flex spline would be required to rotate a slight amount (two teeth, for example) backward relative to the circular spline.*
- *Thus the rotation action of the wave generator results in a much slower rotation of the flex spline in the opposite direction.*





For strain wave gearing mechanism the gearing reduction ratio can be calculated as follows:

$$\text{Reduction Ratio} = \frac{(\text{Flex Spline Teeth} - \text{Circular Spline Teeth})}{\text{Flex spline Teeth}}$$

For example, if there are 202 teeth on the circular spline and 200 on the flex spline, the reduction ratio is (200 − 202)/200 = −0.01
Thus the flex spline spins at 1/100 the speed of the wave generator plug and in the opposite direction.


N-HDF Pancake Style Component Sets
N-HDA Heavy Duty Pancake Style (with hubs) Component Sets
N-HDB Back-To-Back Pancake Style Component Sets
N-HDC Cup Style Component Sets
• Low Backlash
• High Ratio
• Compact Design
• High Torque-to-Weight Ratio
• High Positional Accuracy

MODULE 3

ROBOT END EFFECTORS

- An end effector is a device that attaches to the wrist of the robot arm and enables the general-purpose robot to perform specific task.
- It is sometimes referred to as the robot's "hand." Most production machines require special purpose fixtures and tools designed for a particular operation.
- The end effector is part of that special-purpose tooling for a robot.
- Usually, end effectors must be custom engineered for the particular task which is to be performed.
- This can be accomplished either by designing and fabricating the device from scratch, or by purchasing a commercially available device and adapting it to the application**.**
- Most robot manufacturers have special engineering groups whose function is to design end effectors and to provide consultation services to their customers.
- Also, there are a growing number Of robot systems firms which perform some or all of the engineering work to install robot systems.

TYPES OF END EFFECTORS

- There is a wide assortment of end effectors required to perform the variant of different work functions.

The various types can be divided into two main categories:

1. **Grippers**
2. **Tools**

- Grippers are end effectors used to grasp and hold objects.
- The object is generally working parts that are to be moved applications include machine loading and unloading.
- Pickings parts from a conveyor and arranging parts onto a pallet. In addition to work parts, other objects handled by robot grippers include cartons, bottles, raw materials, and tools.
- We tend to think of grippers as mechanical grasping devices, but there are alternative ways of holding objects involving the use of magnets, suction cups, or other means.

Grippers can be classified as:

1. **single grippers**
2. **double grippers**

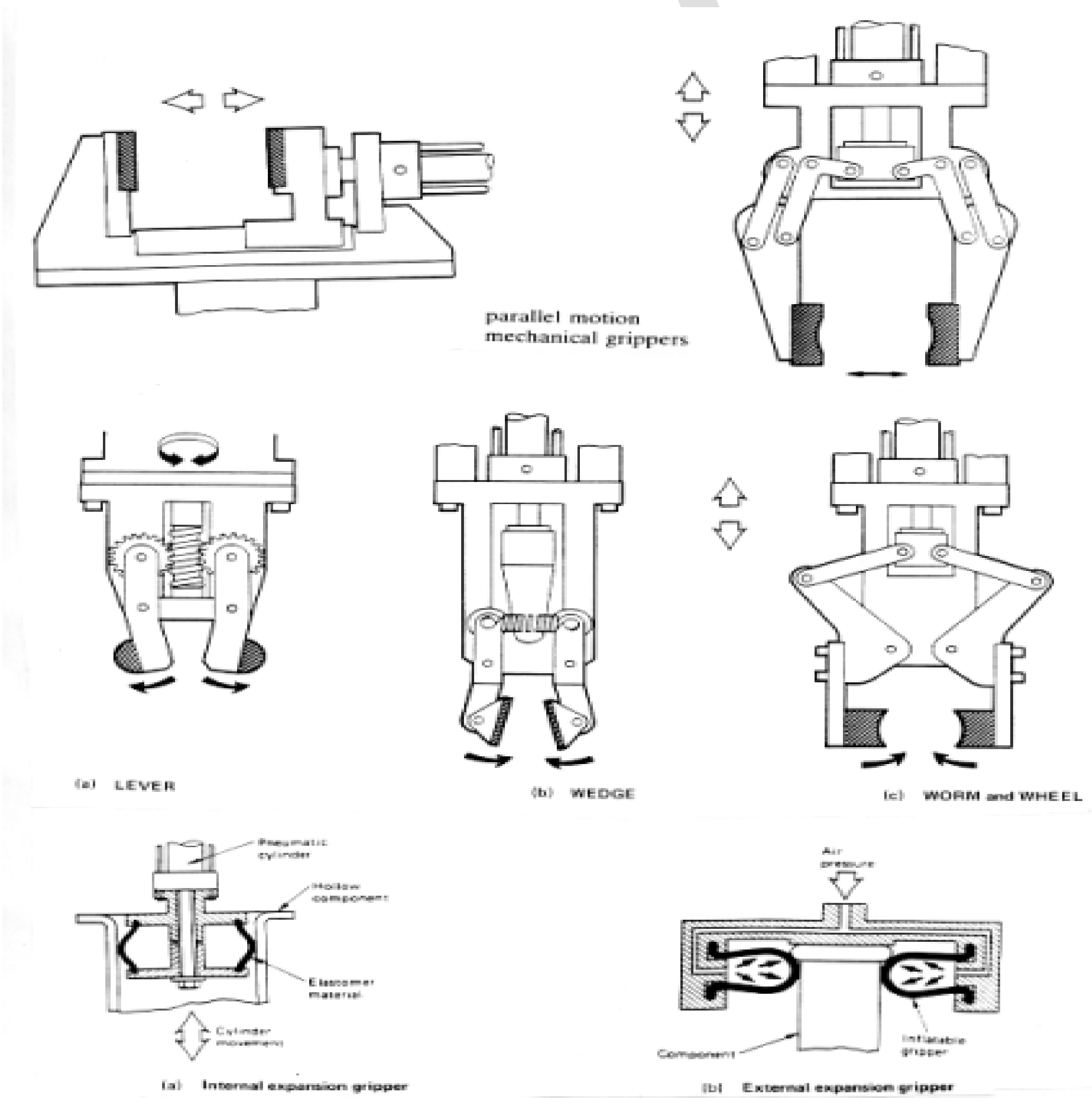
- Although this classification applies best to mechanical grippers.
- The single gripper is distinguished by the fact that only one grasping device is mounted on the robot's wrist.
- A double gripper has two gripping devices attached to the wrist and is used to handle two separate objects. The two gripping devices can be actuated independently.
- The double gripper is especially useful in machine loading and unloading applications.
- Another way of classifying grippers depends on whether the part is grasped on its exterior surface or its internal surface, for example, a ring shaped part.

1. The first type is called an **external gripper**
2. the second type is referred to as an **internal gripper**

- It was mentioned above that grippers are sometimes used to hold tools rather than work parts.
- The reason for using a gripper instead of attaching the tool directly to the robot's wrist is typically because the job requires several tools to he manipulated by the robot during the work cycle.

Tools

- Tools are end effectors designed to perform work on the part rather than to merely grasp it.
- By definition, the tool-type end effector is attached to the robot's wrist.
- One of the most common applications of industrial robots is spot welding, in which the welding electrodes constitute the end effector of the robot.
- Other examples of robot applications in which tools are used as end effectors include spray painting and arc welding.



MECHANICAL GRIPPER

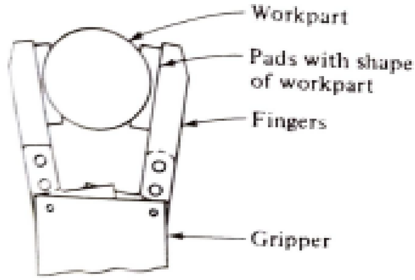
- A mechanical gripper is an end effector that uses mechanical fingers actuated by a mechanism to grasp an object.
- The fingers, sometimes called jaws, are the appendages of the gripper that actually make contact with the object.
- The fingers are either attached to the mechanism or are an integral part of the mechanism. If the fingers are of the attachable type, then they can be detached and replaced.
- The use of replaceable fingers allows for wear and interchangeability.
- Different sets of fingers for use with the same gripper mechanism can be designed to accommodate different part models. An example of this interchangeability feature is illustrated in Fig. 5-1,
- The function of the gripper mechanism is to translate some form of power input into the grasping action of the fingers against the part.
- The power input is supplied from the robot and can be pneumatic, electric, mechanical, or hydraulic

Two ways to of holding an object using a gripper

1. **The first is by Physical constrain of the part within fingers of a gripper**
2. **The second way of holding the part Is by friction between the fingers and the work part**

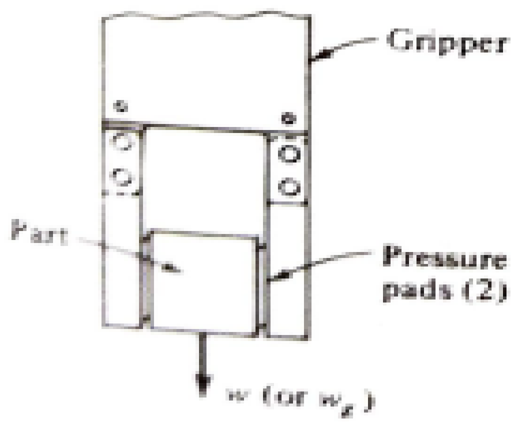
The first is by Physical constrain of the part within fingers of a gripper

- In this approach, the grippers enclose the part to some extent, thereby constraining the motion of the part.
- This is usually accomplished by designing the contacting Surface of the gripper fingers to be in the approximate shape of the part geometry.



The second way of holding the part is by friction between the fingers and the work part

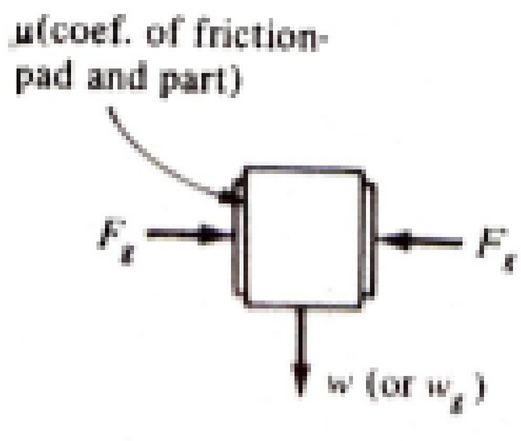
- With this approach, the fingers must apply a force that is sufficient for friction to retain the part against gravity, acceleration, and any other force that might arise during the holding portion of the work cycle.
- The fingers, or the pads attached to the fingers which make contact with the part, are generally fabricated out of a material that is relatively soft.
- This tends to increase the coefficient of friction between the part and the contacting finger surface.
- It also serves to protect the part surface from scratching or other damage



(b)

- The friction method of holding the part results in a less complicated and therefore less expensive gripper design, and it tends to be readily adaptable to greater variety of work parts.
- However, there is a problem with the friction method that is avoided with the physical constriction method.
- If a force of sufficient magnitude is applied against the part in a direction parallel to the friction surfaces of the fingers the part might slip out of the gripper.
- To resist this slippage, the gripper must be designed to exert a force that depends on the weight of the part, the coefficient of friction between the part surface and the finger

surface, the acceleration (or deceleration part.



(a)

$$\mu n_f F_g = w \qquad (5\text{-}1)$$

where μ = coefficient of friction of the finger contact surface against the part surface

n_f = number of contacting fingers

F_g = gripper force

w = weight of the part or object being gripped

TYPES OF GRIPPER MECHANISMS

- There are various ways of classifying mechanical grippers and their actuating mechanisms. One method is according to the type of finger movement used by the gripper.
- In this classification, the grippers can actuate the opening and closing of the fingers by one of the following motions

1) **Pivoting movement**

2) Linear or translational movement

- In the pivoting movement, the fingers rotate about fixed pivot points on the Gripper to open and close. The motion is usually accomplished by some kind of linkage mechanism.
- In the linear movement, the fingers open and close by moving in parallel to each other.

This is accomplished by means of guide rails that each finger base slides along a guide rail during actuation.

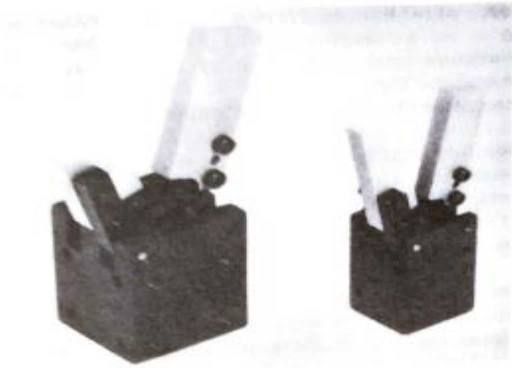


Figure 5-4 Mechanical gripper finger with pivoting movement (Photo courtesy of Phd, Inc.)

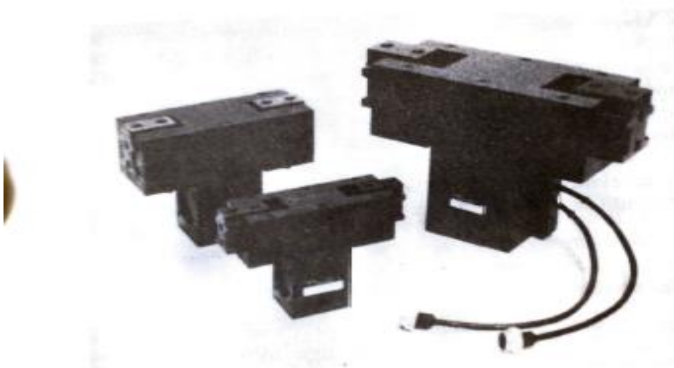


Figure 5-5 Mechanical gripper finger with linear movement using guide rails (Photo courtesy of Phd, Inc.)

- Mechanical grippers can also be classed according to the type of kinematic device used to actuate the finger movement. In this classification we have the following types

1. **Linkage actuation**
2. **Gear-and-rack actuation**
3. **Cam actuation**
4. **Screw actuation**
5. **Rope-and-pulley actuation**
6. **Miscellaneous**

LINKAGE ACTUATION

- The linkage category covers a wide range of design possibilities to actuate the opening and closing of the gripper.
- The design of the linkage determines how the input force F_a to the gripper is converted into the gripping force F_g applied by the fingers.
- The linkage configuration also determines other operational features such as how
- Wide the gripper fingers will open and how quickly the gripper will actuate.

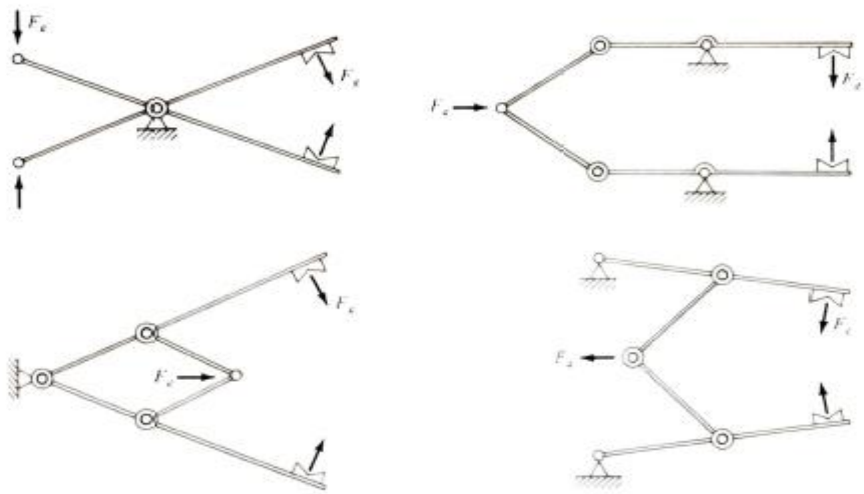


Figure 5-6 Some possible linkages for robot grippers.

•

GEAR-AND-RACK ACTUATION

- The rack gear would be attached to a piston or some other mechanism that would provide a linear motion.
- Movement of the rack would drive two partial pinion gears, and these would in turn close the fingers

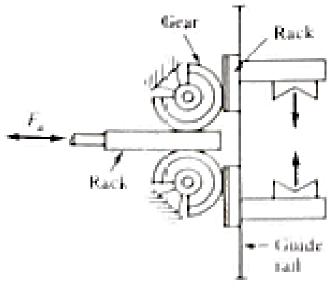


Figure 5-7 Gear-and-rack method of actuating the gripper.

CAM ACTUATION

- A cam-and-follower arrangement, often using spring-loaded follower, can provide the opening and closing action of the gripper.
- For example, movement of the cam in one direction would force the gripper to open, while movement of the cam in the opposite direction would cause the spring to force the gripper to close.
- The advantage of this arrangement is that the spring action would accommodate different sized parts.
- This might be desirable, for example, in a machining operation where a single gripper is used to handle the raw work part and the finished part.
- The finished part might be significantly smaller after machining.

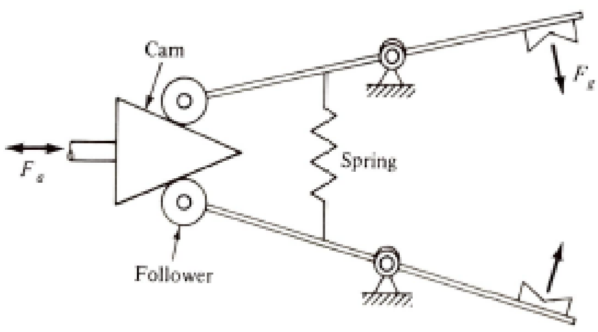


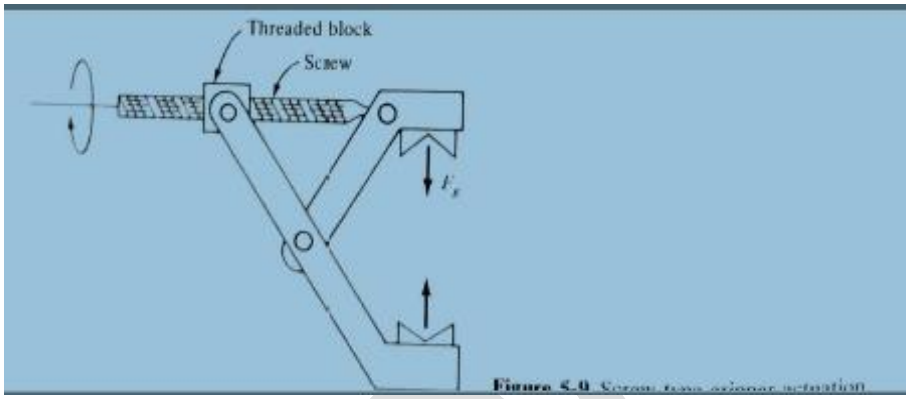
Figure 5-8 Cam-actuated gripper.

SCREW ACTUATION

- The screw is turned by a motor, usually accompanied by a speed reduction mechanism.
- When the screw is rotated in one direction, this causes a threaded block to be translated in one direction.
- When the screw is rotated in the opposite direction, the threaded block moves in the

opposite direction.

- The threaded block is, in turn, connected to the gripper fingers to cause the corresponding opening and closing action



ROPE-AND-PULLEY ACTUATION

- Rope-and-pulley mechanisms can be designed to open and close a mechanical gripper.
- Because of the nature of these mechanisms, some form of tension device must be used to oppose the motion of the rope or cord in the pulley system.
- For example, the pulley system might operate in one direction to open the gripper, and the tension device would take up the slack in the rope and close the gripper when the pulley system operates in the opposite direction

OTHER TYPES OF GRIPPERS

In addition to mechanical grippers there are a variety of other devices that can be designed to lift and hold objects. Included among these other types of

Grippers are the following:

1. Vacuum cups
2. Magnetic grippers
3. Adhesive grippers
4. Hooks, scoops, and other miscellaneous devices

VACUUM CUPS

- Vacuum cups, also called suction cups, can be used as gripper devices for handling certain types of objects.
- The usual requirements on the objects to be handled are that they be flat, smooth, and clean, conditions necessary to form a satisfactory vacuum between the object and the suction cup.
- An example of a vacuum cup used to lift flat glass is pictured in Fig. 5-13. The suction

cups used in this type of robot gripper are typically made of elastic material such as rubber or soft plastic.

- An exception would be when the object to be handled is composed of a soft material. In this case, the suction Cup would be made of a hard substance. The shape of the vacuum cup, as Shown in the figure, is usually round.
- Some means of removing the air between ne cup and the part surface to create the vacuum is required. The vacuum pump and the venturi are two common devices used for this purpose. The vacuum pump is a piston-operated or vane-driven device powered by an electric motor.
- It is capable of creating a relatively high vacuum. The venturi simpler device as pictured in Fig. 5-14 and can be driven by means of and can be driven by means of shop air pressure." Its initial cost is less than that of a vacuum pump and it is relatively reliable because of its simplicity. However, the overall reliability of the vacuum system is dependent on the source of air pressure

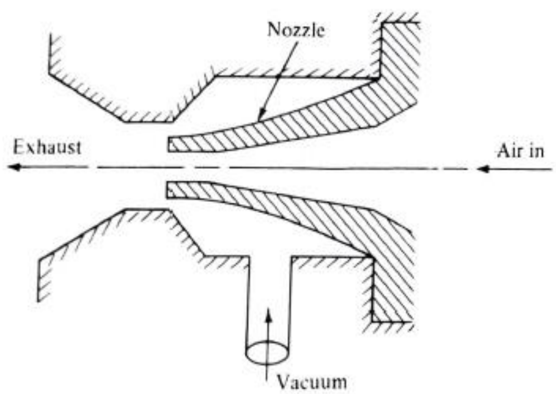


Figure 5-14 Venturi device used to operate a suction cup.

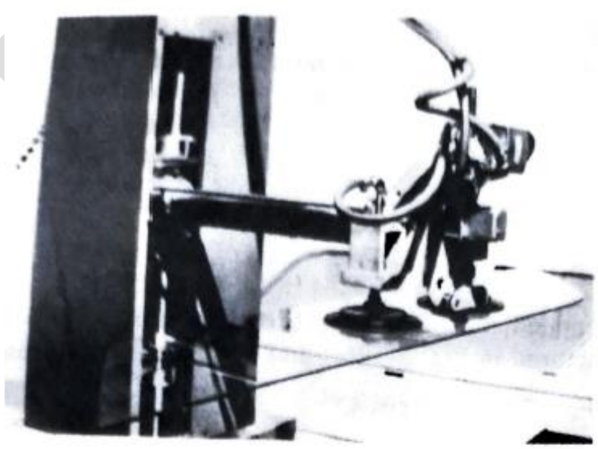


Figure 5-13 Vacuum cup gripper lifting glass plates (Photo courtesy of Prab Conveyors, Inc.)

MAGNETIC GRIPPERS

- Magnetic grippers can be a very feasible means of handling ferrous materials.
- The stainless steel plate in Example 5-3 would not be an appropriate application for a magnetic gripper because 18-8 stainless steel is not attracted by a magnet. Other steels. However, including certain types of stainless steel would be suitable candidates for this means of handling, especially when the materials are handled in sheet or plate form In general, magnetic grippers offer the following advantages in robotic handling applications:
- Pickup times are very fast.
- Variations in part size can be tolerated. The gripper does not have to be designed for one particular work part. They have the ability to handle metal parts with holes (not possible with vacuum grippers). They require only one surface for gripping.

- Disadvantages with magnetic grippers include the residual magnetism remaining in the work piece which may cause a problem in subsequent handling, and the possible side slippage and other errors which limit the precision of this means of handling.
- Another potential disadvantage of a magnetic gripper is the problem of picking up only one sheet from a stack. The magnetic attraction tends to penetrate beyond the top sheet in the stack, resulting in the possibility that more than a single sheet will be lifted by the magnet.
- This problem can be confronted in several ways. First, magnetic grippers can be designed to limit the effective penetration to the desired depth, which would correspond to the thickness of the top sheet. Second, the stacking device used to hold the sheets can be designed to separate the sheets for pickup by the robot.
- One such type of stacking device is called a *fanner," and it makes use of a magnetic field to induce a charge in the ferrous sheets in the stack. Each sheet toward the top of the stack is given a magnetic charge. Causing them to possess the same polarity and repel each other.
- The sheet most affected is the one at the top of the stack. It tends to rise above the remainder of the stack, thus facilitating pickup by the robot gripper.

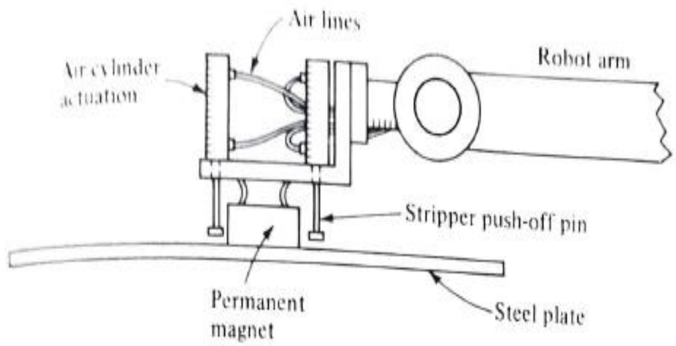


Figure 5-15 Stripper device operated by air cylinders used with a permanent magnet gripper.

- Magnetic grippers can be divided into two categories, those using electromagnets, and those using permanent magnets. Electromagnetic grippers are easier to control, but require a source of dc power and an appropriate controller unit.
- As with any other robotic-gripping device, the part must be released at the end of the handling electromagnet than cycle. This is easier to accomplish with an with a permanent magnet.
- When the part is to be released, the controller unit reverses the polarity at a reduced power level before switching off the electromagnet. This procedure acts to cancel the residual magnetism in the work piece and ensures a positive release of the part.
- Permanent magnets have the advantage of not requiring an external power source to operate the magnet. However, there is a loss of control that accompanies this apparent advantage.
- For example, when the part is to be released at the end of the handling cycle, some means of separating the part from the magnet must be provided. The device which accomplishes this is called a stripper or stripping device.
- Its function is to mechanically detach the part from the magnet. One possible stripper design is illustrated in Fig. 5-15.
- Permanent magnets are often considered for handling tasks in hazardous environments requiring explosion proof apparatus. The fact that no electrical circuit is needed.
- To operate the magnet reduces the danger of sparks which might cause ignition in such an environment.

ADHESIVE GRIPPERS

- Gripper designs in which an adhesive substance performs the grasping action can be used to handle fabrics and other lightweight materials. The requirements on the items to be handled are that they must be gripped on one side only and that other forms of grasping such as a vacuum or magnet are not appropriate. One of the potential limitations of an adhesive gripper is that the adhesive substance loses its tackiness on repeated usage.
- Consequently, its reliability as a gripping device is diminished with each successive operation cycle. To overcome this limitation, the adhesive material is loaded in the form of a continuous ribbon into a feeding mechanism that is attached to the robot Wrist. The feeding mechanism operates in a manner similar to a typewriter ribbon mechanism.

HOOKS, SCOOPS, AND OTHER MISCELLANEOUS DEVICES

- A Variety of other devices can be used to grip parts or materials in robotics applications. Hooks can be used as end effectors to handle containers of parts and to load and unload parts hanging from overhead conveyors.
- Obviously the items to be handled by a hook must have some sort of handle to enable the hook to hold it. Scoops and ladles can be used to handle certain materials in liquid or powder form.
- Chemicals in liquid or powder form, food materials, granula substances, and molten metals are all examples of materials that can be handled by a robot using this method of holding.

- One of its limitations is that the amount of material being scooped by the robot is sometimes difficult to control. Spillage during the handling cycle is also a problem.
- Other types of grippers include inflatable devices, in which an inflatable bladder or diaphragm is expanded to grasp the object.
- The inflatable bladder is fabricated out of rubber or other elastic material which makes t appropriate for gripping fragile objects.
- The gripper applies a uniform grasping pressure against the surface of the object rather than a concentrated force typical of a mechanical gripper.
- An example of the inflatable bladder type gripper is shown in Fig. 5-16. Part (a) of the figure shows the bladder fully expanded. Part (b) shows the bladder used to grasp the inside diameter of a bottle.

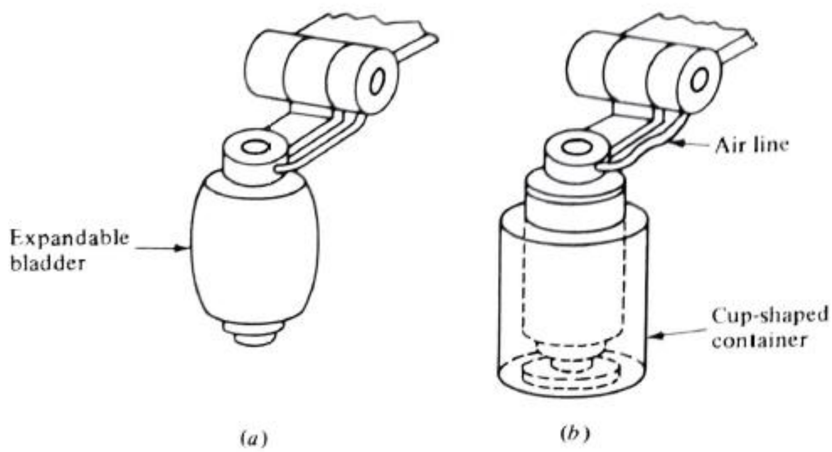


Figure 5-16 Expansion bladder used to grasp inside of a cup-shaped container.

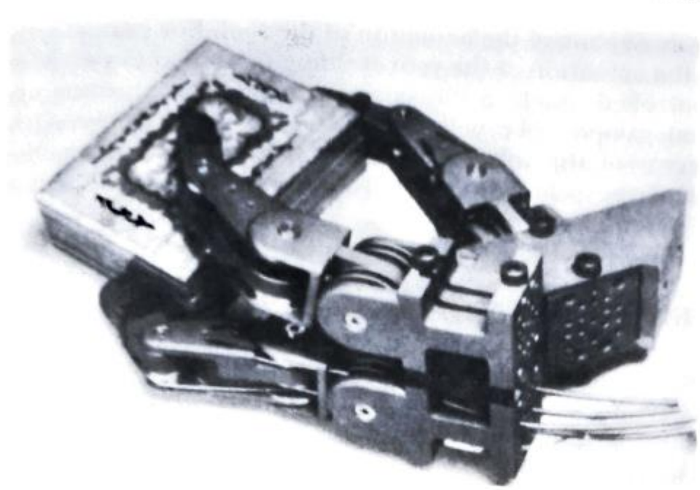


Figure 5-17 The Stanford/JPL three-fingered anthropomorphic hand. (Photo courtesy of Salisbury Robotics, Inc.)

THE ROBOT/END EFFECTOR INTERFACE

An important aspect of the end effector applications engineering involves the interfacing of the end effector with the robot. This interface must accomplish at least some of the following functions:

1. **Physical support of the end effector during the work cycle must be provided.**
2. **Power to actuate the end effector must be supplied through the interface.**
3. **Control signals to actuate the end effector must be provided. This is often accomplished by controlling the actuating power**.

Feedback signals must sometimes be transmitted back through the interface to the robot controller. In addition, certain other general-design objectives should be met. These include high reliability of the interface, protection against the environment, and overload protection in case of disturbances and unexpected events during the work cycle.

PHYSICAL SUPPORT OF THE END EFFECTOR

The physical support of the end effector is achieved by the mechanical connection between the end effector and the robot wrist. This mechanical connection often consists of a faceplate at the end of the wrist to which the end effector is bolted. In other cases, a more complicated wrist socket is used. Ideally, there should be three characteristics taken into consideration in the design of the mechanical connection strength, compliance, and overload protection. The strength of the mechanical connection refers to its ability to withstand the forces associated with the operation of the end effector. These forces include the weight of the end effector; the weight of the objects being held by the end effector if it is a gripper, acceleration and deceleration forces, and any applied forces during the work cycle (e.g., thrust forces during a drilling operation). The wrist socket must provide sufficient strength and rigidity to support the end effector against these various forces.

The second consideration in the design of the mechanical connection is compliance. Compliance refers to the wrist socket's ability to yield elastically when subjected to a force. In effect, it is the opposite of rigidity. In some applications, it is desirable to design the mechanical interface so that it will yield during the work cycle.

A good example of this is found in robot work. Certain assembly operations require the insertion of objects in to a hole where there is very little clearance between the hole and the object to he inserted. If an attempt is made to insert the object off center, it is likely that the object will bind against the sides of the hole. Human assembly workers can make adjustments in the position of the object as it enters the hole using hand eye coordination and their sense of "touch." Robots have difficulty with this kind of insertion task because of limitations on their accuracy. To overcome these limitations, remote center compliance (RCC) devices have been designed to provide high lateral compliance for centering the object relative to the hole in response to sideways forces encountered during insertion.

We will discuss the RCC device in Chap. Fifteen on assembly and Inspection applications. The third factor which must be considered relative to the mechanical interface between the robot wrist and the end effector is overload protection. An overload results when some unexpected event happens to the end effector such as a part becoming stuck in a die, or a tool getting caught in a moving conveyor. Whatever the cause, the consequences involve possible damage to the end effector or maybe even the robot itself. Overload protection is intended to eliminate or reduce

this potential damage. The protection can be provided either by means of a breakaway feature in the wrist socket or by using sensors to indicate that an unusual event has occurred so as to somehow take preventive action to reduce further overloading of the end effector.
A breakaway feature is a mechanical device that will either break or yield when subjected to a high force. Such a device is generally designed to accomplish its breakaway function when the force loading exceeds a certain specific level. A shear pin is an example of a device that is designed to fail if subjected to a shear force above a certain value. It is relatively inexpensive and its purpose as a component in the mechanical interface is to be sacrificed in order to save the end effector and the robot.
The disadvantage of a device that breaks is that it must be replaced and this generally involves downtime and the attention of a human operator. Some mechanical devices are designed to yield or give under unexpected load rather than fail. Examples of these devices include spring-loaded detents and other mechanisms used to hold structural components in place during normal operation. When abnormal conditions are encountered, these mechanisms snap out of position to release the structural components. Although more complicated than shear pins and other similar devices that fail, their advantage is that they can be reused and in some cases reset by the robot without human assistance.

POWER AND SIGNAL TRANSMISSION
End effectors require power to operate. 1hey also require control signals regulate their operation. The principal methods to transmitting power control signals to the end effector are: Power and Signal Transmission and

1. Pneumatic
2. Electric
3. Hydraulic
4. Mechanical

The method of providing the power to the end effector must be compatible with the capabilities of the robot system. For example, it makes sense to use a pneumatically operated gripper if the robot has incorporated into its arm design the facility to transmit air pressure to the end effector.

The control signals to regulate the end effector are often provided simply by controlling the transmission of the actuating power. The operation of a pneumatic gripper is generally accomplished in this manner. Air pressure is supplied to either open the gripper or to close it. In some applications, greater control is required to operate the end effector. For example, the gripper might possess range of open/close positions and there is the need to exercise control over these positions. In more complicated cases, feedback signals from sensors in the end effector are required to operate the device. These feedback signals might indicate how much force is being applied to the object held in the gripper, or they might show whether an arc-welding operation was following the seam properly. In the paragraphs below, we will explore the four methods of power and signal transmission to the end effector.

Pneumatic power using shop air pressure is one of the most common methods of operating mechanical grippers. Actuation of the gripper s co trolled by regulating the incoming air pressure. A piston device is typically used to actuate the gripper. Two air lines feed into opposite ends of the piston.

One to open the gripper and the other to close it. This arrangement can be accomplished with a single shop airline by providing a pneumatic valve switch the air pressure from one line to the other. A schematic diagram o piston is illustrated in Fig. 5-18. When air of pressure enters the left portion the piston chamber the piston ram is extended, and when air is forced in the opposite end of the chamber, the piston ram is retracted. The force sup by the piston on the extension stroke is equal to the air pressure multiplied by the area of the piston diameter.

Another use of pneumatic power in end effector design is for vacuum cup grippers. When a venturi device is used to provide the vacuum, the device can be actuated by shop air pressure. Otherwise, some means of developing and controlling the vacuum must be provided to operate the suction cup gripping device. A second method of power transmission to the end effector is electrical Pneumatic actuation of the gripper is generally limited to two positions, open and closed. The use of an electric motor can allow the designer to exercise a greater degree of control over the actuation of the gripper and of the holding force applied. Instead of merely two positions, the gripper can be controlled to any number of partially closed positions. This feature allows the gripper to be used to handle a variety of objects of different sizes, a likely requirement in assembly operations.

By incorporating force sensors into the gripper fingers, a feedback control system can be built into the gripper to regulate the holding force applied by the fingers rather than their position. This would be useful, for example, if the objects being grasped are delicate or if the objects vary in size and the proper finger positions for gripping are not known. Other uses of electric power for end effectors include electromagnet grippers, spot-welding and arc-welding tools, and powered spindle tools used as robot end effectors. Hydraulic and mechanical power transmission is less common means of actuating the end effector in current practice. Hydraulic actuation of the gripper has the potential to provide very high holding forces, but its disadvantage is the risk of oil leaks. Mechanical power transmission would involve an arrangement in which a motor (e.g., pneumatic, electric, hydraulic, etc.) is mounted on the robot arm and connected mechanically to the gripper, perhaps by means of a flexible cable or the use of pulleys. The possible advantage of this arrangement is a reduction of the weight and mass at the robot's wrist.

MODULE 4

TRANSDUCERS AND SENSORS

- A transducer is a device that converts one type of physical variable (e.g. force, pressure, temperature, velocity, flow rate, etc.) into another form. Common conversion is to electrical voltage, and the reason for making the conversion is that the converted signal is more convenient to use and evaluate a sensor is a transducer that is used to make a measurement of a physical variable of interest.
- Some of the common sensors and transducers include strain gauges (used to measure force and pressure), thermocouples (temperatures), speedometers (velocity), and Pitot tubes (flow rates).
- Any sensor or transducer requires calibration in order to be useful as a measuring device. Calibration is the procedure by which the relationship Between the measured variable and the converted output signal is established Transducers and sensors can be classified into two basic types depending on the form of the converted signal. The two types are

1. **Analog transducers**
2. **Digital transducers**

- Analog transducers provide a continuous analog signal such as electric voltage or current. This signal can then he interpreted as the value of the physical variable that is being measured.
- Digital transducers produce a digital input signal. Either in the form of a set of parallel status bits or a series of pulses that can be counted. In either form. The digital signal represents the value of the measured variable.
- Digital transducers are becoming more popular because of the ease with which they can be read as separate me assuring instruments. In addition. they offer the advantage in automation and process control that they are generally more compatible with the digital computer than analog-based sensors.

SENSORS IN ROBOTCS

The sensors used in robotics include a wide range of devices which can be divided into the following general categories:

1. **Tactile sensors**
2. **Proximity and range sensors**
3. **Miscellaneous sensors and sensor-based systems**
4. **Machine vision systems**

TACTILE SENSORS

- Tactile sensors are devices which indicate contact between themselves and some other solid object. Tactile sensing devices can be divided into two classes: touch sensors and force sensors. Touch sensors provide a binary output signal which indicates whether or not contact has been made with the object.

- Force sensors (also sometimes called stress sensors) indicate not only that contact has been made with the object but also the magnitude of the contact force between the two objects.

TOUCH SENSORS

- Touch sensors are used to indicate that contact has been made between two objects without regard to the magnitude of the contacting force. Included within this category are simple devices such as limit switches, micro switches. and the like. The simpler devices are frequently used in the design of interlock systems in robotics. For example, they can be used to indicate the presence or absence of parts in a fixture or at the pickup point along a conveyor.
- Another use for a touch-sensing device would be as part of an inspection probe which is manipulated by the robot to measure dimensions on a work part. A robot with degrees of freedom would be capable of accessing surfaces on the part that would be difficult for a three-axis coordinate measuring machine, the - E system normally considered for such an inspection task fortunately the robot's accuracy would be a limiting factor in contact inspection work

FORCE SENSORS

- Capacity to measure forces permits the robot to perform a number of tasks include the capability to grasp parts of different sizes in materials handling, machine loading, and assembly work, apply1ng the appropriate level of force for the given part. In assembly applications, force sensing could be used to determine if screws have become cross-threaded or if parts are jammed.

- Force sensing in robotics can be accomplished in several ways. A commonly used technique is a "force-sensing wrist." This consists of a special load-cell mounted between the gripper and the wrist. Another technique is to measure the torque being exerted by each joint.
- This is usually accomplished by sensing motor current for each of the joint motors. Finally, a third technique is to form an array of force-sensing elements so that the shape and other information about the contact surface can be determined. We discuss these three possibilities in the paragraphs that follow.

FORCE-SENSING WRIST

- The purpose of a force-sensing wrist is to provide information about the three components of force (F,, Fy, and F.) and the three moments (M,, M,, and M,) being applied at the end-of-the-arm. One possible construction of a force-sensing wrist is illustrated in Fig. 6-1. The device
- Consists of a metal bracket fastened to a rigid frame. The frame is mounted to the wrist of the robot and the tool is mounted to the center of the bracket. The figure shows how the sensors might react to a moment applied to the bracket due to forces and moments on the tool.

- Since the forces are usually applied to the wrist in combinations it is necessary to first resolve the forces and moments into their six components. This kind of computation can be carried out by the robot controller (if it has the required computational capability) or by a specialized amplifier designed for this purpose.
- Based on these calculations, the robot controller can obtain the required information of the forces and moments being applied at the wrist. This information could be used for a number of applications.
- As an example, an insertion operation (e.g., inserting a peg into a hole in an assembly application) requires that there are no side forces being applied to the peg. Another example is where the robot's end effector is required to follow along an edge or contour of an irregular surface.
- This is called force accommodation. With this technique, certain forces are set equal to zero while others are set equal to specific values. Using force accommodation, one could command the robot to follow the edge or contour by maintaining a fixed velocity in one direction and fixed forces in other directions.

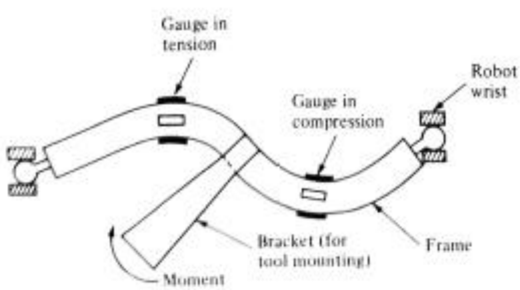


Figure 6-1 Possible configuration of sensing device used for a force sensing wrist, showing deflection (exaggerated) due to a moment about one of the axes.

The robot equipped with a force-sensing wrist plus the proper computing capacity could be programmed to accomplish these kinds of applications. The procedure would begin by deciding on the desired force to be applied in each axis direction. The controller would perform the following sequence of operations, with the resulting offset force calculated as illustrated in Fig. 6-2:

1. Measure the forces at the wrist in each axis direction.
2. Calculate the force offsets required. The force offset in each direction is determined by subtracting the desired force from the measured force.
3. Calculate the torques to be applied by each axis to generate the desired force offsets at the wrist. These are moment calculations which take into account the combined effects of the various joints and links of the robot.
4. Then the robot must provide the torques calculated in step 3 so that the desired forces are applied in each direction.

- Force-sensing wrists are usually very rigid devices so that they will not deflect undesirably while under load. When designing a force-sensing wrist there are several problems that may be encountered. The end-of-the-arm is often in a relatively hostile environment. This means that the device must be sufficiently rugged to withstand the environment.

- For example, it must be Capable of tolerating an occasional crash of the robot arm. At the same time the device must be sensitive cough to detect small forces. This design problem is usually solved by using over travel limits. An over travel limit is physical stop designed to prevent the force sensor from deflecting so far that it would be damaged.

JOINT SENSING

- If the robot uses dc servomotors then the torque being exerted by the motors is proportional to the current flowing through the armature. A simple way to measure this current is to measure the voltage drop across a small precision resistor in series with the motor and power amplifier. This simplicity makes this technique attractive
- However. Measuring the joint torque has several disadvantages. First, measurements are made in joint space, while the forces of interest are applied by the tool and would be more useful if made in tool space.
- The measurements therefore not only reflect the forces being applied at the tool, but also the forces and torques required to accelerate the links of the arm and to overcome the friction and transmission losses of the joints. In fact, if the joint friction is relatively high (and it usually is), it will mask out the small forces being applied at the tool tip. One area where joint torque sensing shows promise of working well is with direct-drive robots.
- Direct-drive robots are a relatively new innovation in which the drive motors are located at the joints of the manipulator. In torque sensing, this configuration reduces the friction and transmission losses, and the problems of torque measurement which accompany these losses are thereby reduced.

TACTILE ARRAY SENSORS

Tactile array sensor is a special type of force sensor composed of a matrix of force-sensing elements. The force data provided by this type of device may be combined with pattern recognition techniques to describe a number of characteristics about the impression contacting the array sensor surface. Among these characteristics are:

(1) The presence of an object
(2) The object's contact area, shape, location, and orientation,
(3) The pressure and pressure distribution, and
(4) Force magnitude and location.

Tactile array sensors can be mounted in the fingers of the robot gripper or attached to a Work table as a flat touch surface. Figures 6-3 and 6-4 illustrate these two possible mountings for the sensor device.

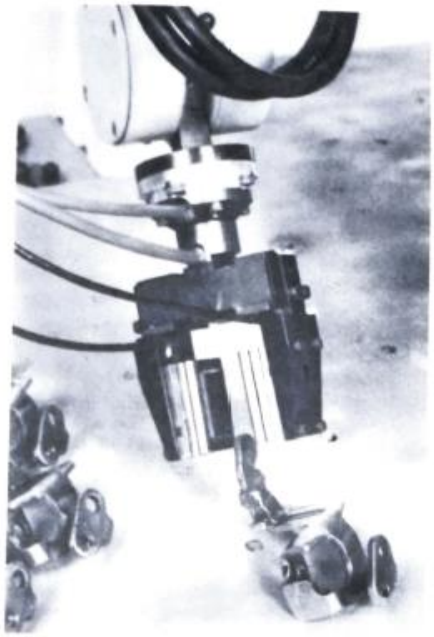


Figure 6-3 Tactile array sensor device mounted in a mechanical gripper. (Photo courtesy of Lord Corporation.)

Figure 6-4 Tactile array sensor mounted on a flat work surface. (Photo courtesy of Lord Corporation.)

PROXIMITY AND RANGE SENSORS

- Proximity sensors are devices that indicate when one object is close to another object. How close the object must be in order to activate the sensor is dependent on the particular device. The distances can be anywhere between several millimeters and several fact.
- Some of these sensors can also be used to measure the distance between the object and the sensor, and these devices are called range sensors. Proximity and range sensors would typically be located on the wrist or end effector since these are the moving parts of the robot.
- One practical use of a proximity sensor in robotics would be to detect the presence or absence of a work part or other object. Another important application is for sensing human beings in the robot work cell. Range sensors would be useful for determining the location of an object (e.g., the work part) in relation to the robot. variety of technologies are available for designing proximity and range sensors.
- These technologies include optical devices, acoustics, electrical field techniques (e.g., eddy currents and magnetic fields), and others. We will survey only a few of the possibilities in the following paragraphs.
- Optical proximity sensors can be designed using either visible or invisible (infrared) light sources. Infrared sensors may be active or passive.
- The active sensors send out an infrared beam and respond to the reflection of the beam against a target. The infrared-reflectance sensor using an incandescent light source is a common device that is commercially available.
- The active infrared sensor can be used to indicate not only whether or not a part is present, but also the position of the part. By timing the interval from when the signal is send the echo is received, a measurement of the distance between the object and the sensor can be made.
- This feature is especially useful for locomotion and guidance systems. Passive infrared sensors are simply devices which detect the presence of infrared radiation in the environment. They are often utilized in security systems to detect the presence of bodies giving off heat within the range of the sensor. These sensor systems are effective at covering large areas in building interiors.
- Another optical approach for proximity sensing involves the use of a collimated light beam and a linear array of light sensors. By reflecting the light beam off the surface of the object, the location of the object can be determined from the position of its reflected beam on the sensor array.
- This scheme is illustrated in Fig. 6-7. The formula for the distance between the object and the sensor is given as follows.

$$x = 0.5y \tan(A)$$

where x = the distance of the object from the sensor

y= the lateral distance between the light source and the reflected light beam against the linear array. This distance corresponds to number of elements contained within the reflected beam in the sensor array

A = the angle between the object and the sensor array as illustrated in Fig. 6-7

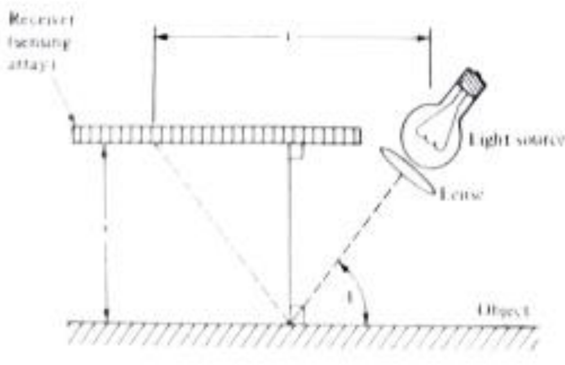


Figure 6-7 Scheme for a proximity sensor using reflected light against a sensor array

- Use of this device in the configuration shown relies on the fact that the surface of the object must be parallel to the sensing array. Acoustical devices can be used as proximity sensors. Ultrasonic frequencies (above 20,000 Hz) are often used in these devices because the sound is beyond the range of human hearing.
- One type of acoustical proximity sensor uses a cylindrical open-ended chamber with an acoustic emitter at the closed end of the chamber. The emitter sets up a pattern of standing waves in the cavity which is altered by the presence of an object near the open end.
- A microphone located in the wall of the chamber is used to sense the change in the sound pattern. This kind of device can also be used as a range sensor. Proximity and range sensors based on the use of electrical fields are commercially available.
- Two of the types in this category and eddy-current sensors and magnetic field sensors.
- Eddy-current devices create a primary alternating magnetic field in the small region near the probe. This field induces eddy currents in an object placed in the region so long as the object is made of a conductive material.
- These eddy currents produce their own magnetic field which interacts with the primary field to change its flux density. The probe detects the change in the flux density and this indicates the presence of the object.
- Magnetic field proximity sensors are relatively simple and can be made using a reed switch and a permanent magnet.
- The magnet can be made a part of the object being detected or it can be part of the sensor device. In either case, the device can be designated so that the presence of the object in the region of the sensor completes the magnetic circuit and activates the reed switch.
- This type of proximity sensor design is attractive because of its relative simplicity and because no external power supply is required for its operation.

MISCELLANEOUS SENSORS AND SENSOR-BASED SYSTEMS

- The miscellaneous category covers the remaining types of sensors and transducers that might be used for interlocks and other purposes in robotic work cells. This category includes devices with the capability to sense variables Such as temperature, pressure, fluid flow, and electrical properties. Many of the common transducers and sensors used for these variables are list.

- An area of robotics research that might be included in this chapter is are listed in robotics for oral communication of instructions to the robot. Voice sensing relies on the techniques of speech recognition to analyze spoken words uttered by a human and compare those words with a set of stored word patterns. When the spoken word matches the stored word pattern, this indicates that the robot should perform some particular actions which correspond to the word or series of words.

USES OF SENSORS IN ROBOTICS

The major uses of sensors in industrial robotics and other automated manufacturing systems can be divided into four basic categories:

(1) Safety monitoring
(2) Interlocks in work cell control
(3) Part inspection for quality control
(4) Determining positions and related information about objects in the robot Cell

- One of the important applications of sensor technology in automated manufacturing operations is safety or hazard monitoring which concerns the protection of human workers who work in the vicinity of the robot or other equipment.
- The second major use of sensor technology in robotics interlocks is to implement in work cell control. As mentioned in Chap. Two, interlocks are used to coordinate the sequence of activities of the different pieces of equipment in the work cell the execution of the robot program, there are certain elements of the work cycle whose completion must be verified before proceeding with the next element in the cycle.
- Sensors, often very simple devices, are utilized to provide this kind of verification. We will discuss interlocks and their uses in Chap. Eleven on work cell control.
- The third category is quality control. Sensors can be used to determine a variety of part quality characteristics. Traditionally, quality control has been performed using manual inspection techniques on a statistical sampling basis.
- The use of sensors permits the inspection operation to be performed automatically on a 100 percent basis, in which every part is inspected. The limitation on the use of automate inspection is that the sensor system can only inspect for a limited range ol part characteristics and defects.
- For example, a sensor probe designed to measure part length cannot detect flaws in the part surface Many applications of automated inspection are accomplished without the use robotics. The reason for including this category in our discussion of robotic sensors Is that robots are, in fact, often used to implement automatic inspection systems by means off sensors.
- The fourth major use of sensors in robotics is to determine the positions and other information about various objects in the work cell (e.g. Work Paris, fixtures. people. equipment, etc.).
- In addition to positional data about a particular object. Other information required to properly execute the work we might include the object's orientation, color, size and other characteristics.

- Visa sensors can be classified as external non-contact type, as indicated in Fig. 41 However they are treated here in a separate section due to their complexity. Which requires detailed treatment typical components of a vision system used as security alarm are shown in Fig 4.15 Vision systems are successfully used with robots to look around and find the parts for picking and placing them at appropriate locations earlier fixtures were used with robots for the accurate positioning of the objects Such fixtures are very expensive.
- Other tasks of vision systems sees with robots include determination of the configuration of the objects, moon of the objects. Reconstruction of the 3D geometry of the objects from their 2D images for measurements, and building up of the maps of the environment for the robot's navigation Vision systems provide information that is difficult, or possible. to obtain in other ways. Their coverage is from few millimeters to tens of meters with either narrow or wide angle, depending upon the system needs and design.

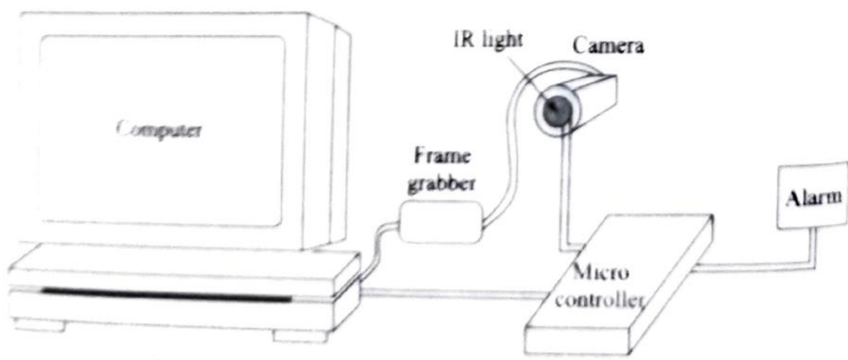


Fig. 4.15 Hardware components of a vision system

CAMERA SYSTEMS

- Early vision systems employed the Vidicons camera, which were bulky vacuum tube devices. Vidicons are also more sensitive to the electromagnetic noise interference and require high power.
- Their chief advantages are higher resolution and better light sensitivity. To reduce size, most current systems use solid state cameras, based on the charged coupled devices (CCDs) or the charge injection device (CID) techniques. Solid state cameras are smaller, more rugged, last longer, and have less inherent image distortion than vidicon cameras. They are also slightly more costly, but prices are coming down.
- Manufacturers often recommend operating the sensors with appropriate filters to eliminate IR wavelengths. Both the CCDs and CID chips use large transfer techniques to capture an image. In a CCD camera, light impinges on the optical equivalent of a random access memory (RAM) chip. The light is absorbed in a silicon-substrate, with the charge build-up being proportional to the amount of light reaching the array. Once sufficient amount of energy has been received to provide a picture, the charges are read out through the built-in control registers.

- Some CCD chips use an interline charge transfer technique. Others use frame transfer approach, which is more flexible for varying the integration period. A type of electronic device can adjust the sensitivity of the camera towards light, by controlling the amount of voltage across the elements and the length of time that the array is attached to charge.
- The CID camera works on a similar principle. A CID chip is a metal oxide semi-conductor (MOS) based device with multiple gates similar to CCDs. The video signal is the result of a current pulse from a recombination of carriers. CIDs produce a better image (less distortion) and use a different read out technique than CCDs which require a separate scanning address unit.
- CIDs are therefore more expensive than CCDs. The principle difference between a CCD and a CID camera is the method of generating the video signal. In CCDs, the charge must be shifted out of the array by switching voltages between even and odd gates. The resultant flow of the current creates an analog signal. In the CID, each element is discharged and the resultant is used directly.
- The amount of charge stored is a linear function of both the object intensity and the length of time the camera is exposed to.

STEPS IN VISION SENSING

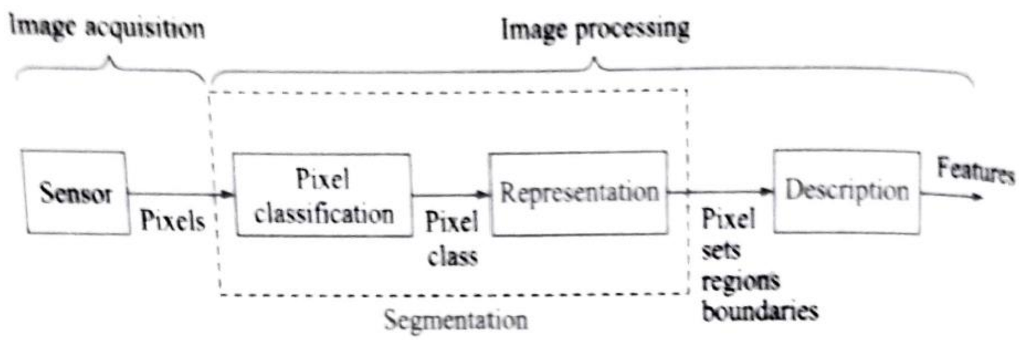


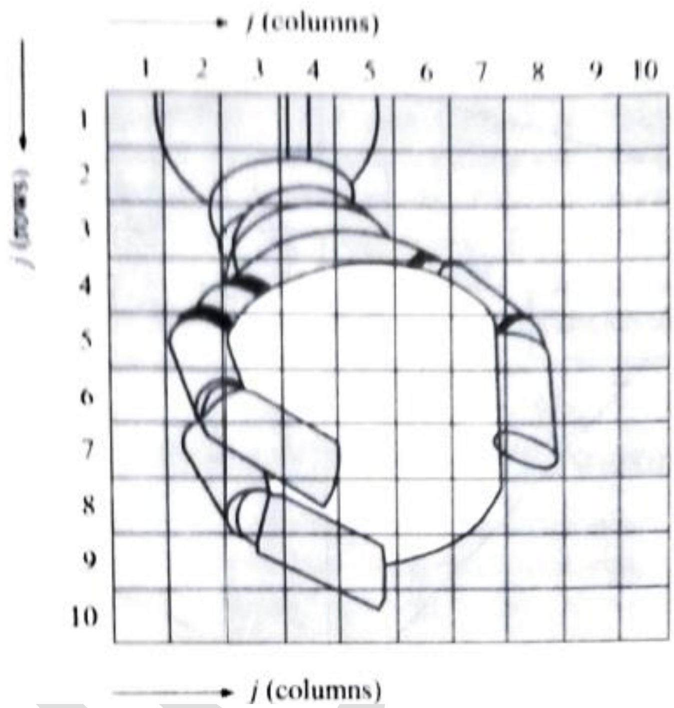
Fig. 4.16 Visual sensing

IMAGE ACQUISITION

- In image acquisition, an image is obtained and digitized for further processing. As shown in Fig. 4.17. The first step in digitization is to partition the image into cells (pixels) addressed by rows and columns. An exaggerated image is shown on the left. Each pixel is assigned a number based on its light intensity or image brightness.
- Although image acquisition is primarily a hardware function. Software can be used to control light intensity. Lens opening focus, camera angle. Synchronization. Field of view, read times and other functions. Image acquisition has four principle elements
- Namely. A light source, either controlled or ambient a lens that focuses reflected light from the object on to the image sensor an image sensor, which converts the light image into a stored electrical image electronics to read the sensed image from the image sensing element and alter processing transmit the image information to a computer for further processing The computer then handles the rest of the steps. I.e. Image analysis and pattern recognition.

IMAGE PROCESSING

- Image processing examines the digitized data to locate and recognize an object within the image field. Different approaches can used. Most image analysis techniques include segmentation. Parameter extracts and pattern recognition. Segmentation breaks the scene into several pieces d segments and allows the desired object to be isolated; if multiple objects of interest are present, segmentation separates them in the image. Parameter extraction the looks at segmented objects and determines the key feature such as size.



j (columns) → ; i (rows) ↓

	1	2	3	4	5	6	7	8	9	10
1	45	78	35	34	41	40	74	121	126	128
2	42	67	12	27	31	44	66	115	129	124
3	40	63	28	25	20	27	59	109	117	126
4	62	74	49	110	136	145	138	102	112	115
5	124	103	77	226	238	243	240	104	109	191
6	127	117	69	109	221	230	225	109	101	107
7	130	127	66	78	118	210	205	93	85	103
8	134	134	85	73	129	175	190	125	99	100
9	138	136	133	199	80	94	98	104	105	108
10	139	136	133	129	126	122	112	119	139	171

Fig. 4.17 Digitised picture

MODULE 5

For the purpose of controlling a robot, it is necessary to know the relationships between the joint motions (input) and the end-effector motions (output), because the joint motions control the end-effector movements. Thus, the study of kinematics is important, where transformations between the coordinate frames attached to different robot links of the robot need to be performed.

LINKS AND JOINTS

- The individual bodies that make up a robot are called links." Here, unless otherwise Stated, all links are assumed to be rigid, i.e. the distance between any two points within the body does not change while it is moving. A rigid body in the three dimensional Cartesian space has six DOF this implies that the position of the body can be described by three translational, and the orientation by three rotational coordinates.
- For convenience, certain non-rigid bodies, such as chains, cables, or belts which when serve the same function as the rigid bodies, may be considered as links Prom the kinematic point of view, two or more members when connected either without any elative motion between them are considered as a single link.
- For example. An assembly of two gears connected by a common shaft is treated as single link.
- Links of a robot are coupled by kinematic pairs or joints. A joint couples two Links and provides the physical constraints on the relative motion between the links.it is not a physical entity but just a concept that allows one to specify how one link moves with respect to another one.
- For example. A hinge joint of a door allows it to move relative to the fixed wall about an axis. No other motion is possible. The type of a relative motion permitted by a joint is governed by the form of the contact surface between the members.
- Which can be a surface, a line, or a point? Accordingly. They are termed as either "lower or "higher' pair joint. If two mating links are in surface contact. The joint is referred to as a lower pair joint.
- On the contrary. If the links are in line or point contact, the joint is called higher pair joint. As per the definition, the hinge joint of the door is a lower pair joint, whereas a ball rolling on a plane makes a higher pair joint. Frequently used lower and higher pairs are listed in Table 5.1

REVOLUTE JOINT, R

- A revolute joint, known also as a "turning pair' or a hinge' or a 'pin joint,' permits two paired links to rotate with respect to each other about the axis of the joint, say, Z, as shown in Fig. 5.1. Hence. a revolute joint imposes five constraints, i.e. it prohibits one of the links to translate with respect to the other one along the three perpendicular axes, X, Y, Z, along with the rotation about two axes, X and Y. This joint has one-degree-of-freedom (DOF)

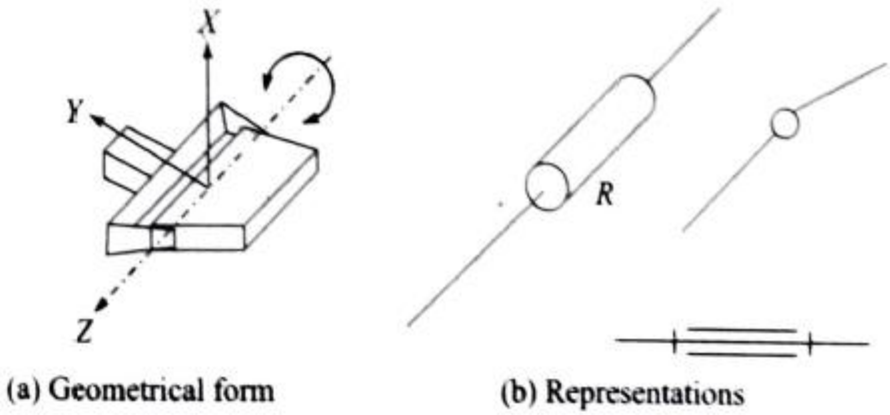


Fig. 5.1 A revolute joint

PRISNMATIC JOINT, P A

- The 'prismatic joint' or a 'sliding pair' allows two paired links to slide with respect to each other along its axis, as shown in Fig. 5.2. It also imposes five constraints and hence, has one-DOF.

HELICAL JOINT, H

- As shown in Fig. 5.3, a helical joint allows two paired Links to rotate about and translate at the same time along the axis of the joint. The translation is however, not independent. It is related to the rotation by the pitch of the screw. Thus, the helical joint also has five constraints, and accordingly one-DOF

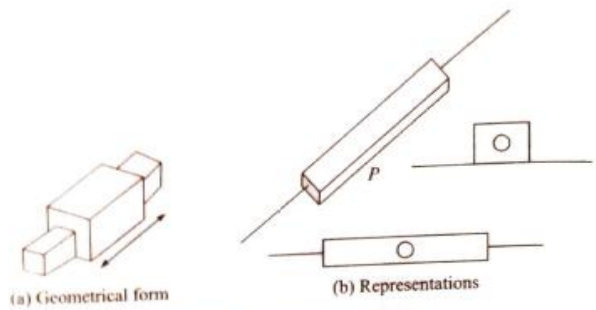


Fig. 5.2 A prismatic joint

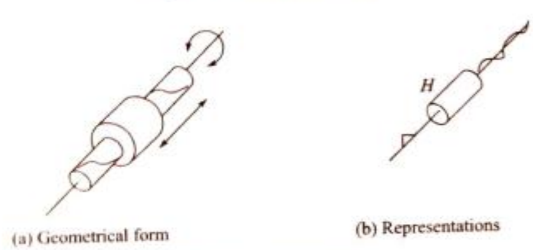
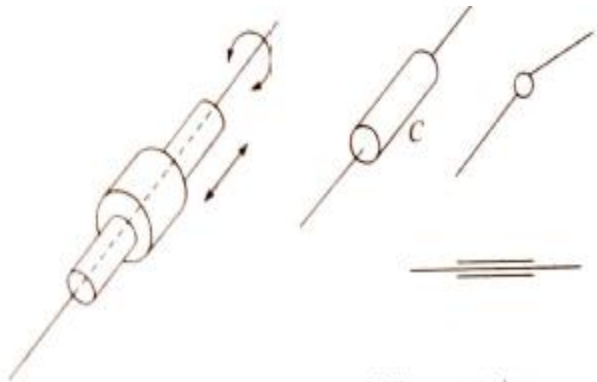


Fig. 5.3 A helical joint

CYLINDRICAL JOINT C

- It permits rotation about and independent translation along the axis of the joint, as shown in Fig. 5.4. Hence, a cylindrical joint imposes four constraints on the paired links, and has two-DOF.



(a) Geometrical form (b) Representations

Fig. 5.4 A cylindrical joint

SPHERICAL JOINT S

It allows one of the coupled links to rotate freely in all possible orientations with respect to the other one about the center of a sphere. N elative translation is permitted. Hence, it imposes three constraints and so it has three-DOF.

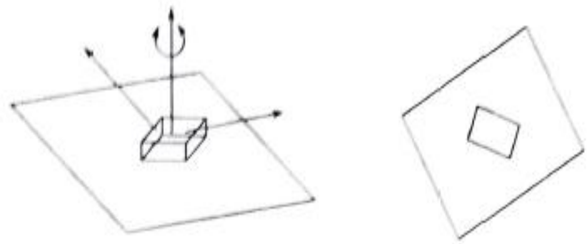
Transformations

(a) Geometrical form (b) Representation

Fig. 5.5 A spherical joint

PLANAR JOINT, L

This three-DOF joint allows two translations along the two independent axis of the plane of contact and one rotation about the axis normal to the plane, Fig. 5.6.



(a) Geometrical form (b) Representation

Fig. 5.6 A planar joint

Table 5.1 summarizes the basic lower pair joints, where all the joints have surface contact between the interconnecting links. Another commonly used lower pair joint in robotics is the two-DOF 'universal joint', as shown in Fig. 5.7. This is the combination of two intersecting revolute joints. Examples of higher pair joints robots are 'gears' and 'cams with roller followers', where they make line contacts.

Table 5.1 Lower pair joints

Name	*Symbol*	*Geometric Form and Representations*	*DOF*	*Common Surface*
Revolute	*R*	Fig. 5.1	1	Cylinder
Prismatic	*P*	Fig. 5.2	1	Prism
Helical	*H*	Fig. 5.3	1	Screw
Cylindrical	*C*	Fig. 5.4	2	Cylinder
Spherical	*S*	Fig. 5.5	3	Sphere
Planar	*L*	Fig. 5.6	3	Plane

KINEMATIC CHAIN

Kinematic chain is a series of links connected by joints. When each and every link in a kinematic chain is coupled to, at most two other links the chain is referred to as a simple kinematic chain'. A simple kinematic chain can be either 'closed' or 'open'. It is closed if each and every link is coupled to two other links as shown in Fig. 5.8. A kinematic chain is open if it contains exactly two links namely the end ones that are coupled to only one link. A robotic manipulator shown in Fig. 5.9 falls in this category.

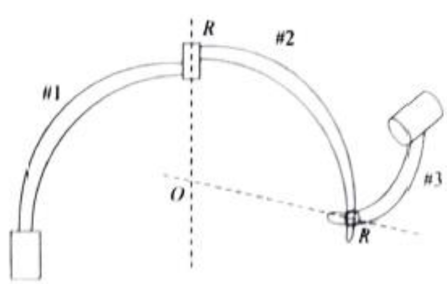


Fig. 5.7 A universal joint

DEGREE OF FREEDOM

- Formally, the degree of freedom (DOF) of a mechanical system is defined as the number of independent coordinates or minimum coordinates required to fully describe its pose or configuration. Thus, a rigid body moving in the three dimensional Cartesian space has six-DOF, three each for position and orientation.
- Several methodologies exist to determine the DOF. One such method was given by Grubler in 1917 for planar mechanisms, which was later generalized by Kutzbach in 1929 for spatial mechanisms. Together they are known as the Grubler Kutzbach criterion, which is described below:

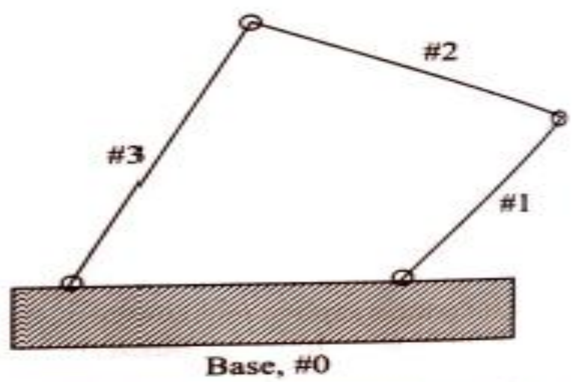


Fig. 5.8 A four-bar mechanism

Assume,

- s: dimension of working space (For planar, $s = 3$; spatial, $s = 6$);
- r: number of rigid bodies or links in the system;
- p: number of kinematic pairs or joints in the system;
- c_i: number of constraints imposed by each joint;
- c: total number of constraints imposed by p joints;
- n_i: relative degree of freedom of each joint;
- n: degree of freedom of the whole system.

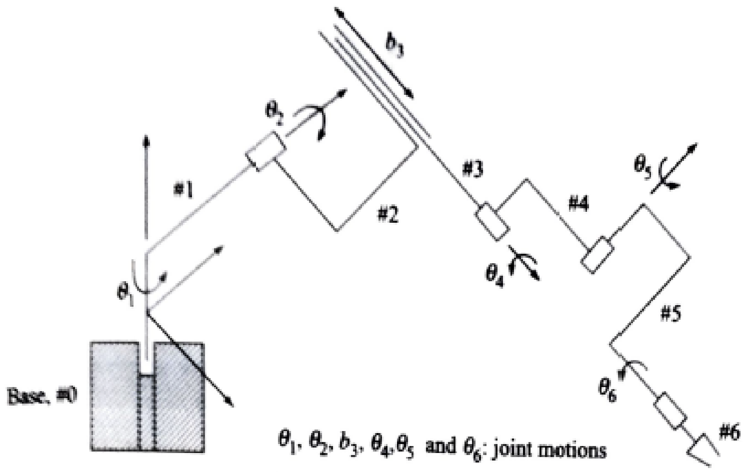


Fig. 5.9 A robot manipulator

The DOF of the whole system—n, is then determined from the total DOF associated with all the moving links minus the total number of constraints imposed by all the joints, i.e.

$$n = s\,(r - 1) - c \qquad (5.1)$$

where $c \equiv \sum_{i=1}^{p} c_i$.

Note that −1 in eq. (5.1) corresponds to the fixed link of the system which has a zero DOF. Moreover, for the coupled links, the sum of the number of constraints imposed by each joint—c_i, and the relative degree of freedom permitted by that joint—n_i, is equal to the dimension of the working space s, i.e.,

$$s = c_i + n_i$$

Hence, the total number of constraints imposed by all the joints can be re-written as

$$c = \sum_{i=1}^{p} c_i = \sum_{i=1}^{p} (s - n_i) = sp - \sum_{i=1}^{p} n_i \qquad (5.2)$$

Upon substitution of eq. (5.2) into eq. (5.1), one obtains the DOF—n, as

$$n = s(r - p - 1) + \sum_{i}^{p} n_i \qquad (5.3)$$

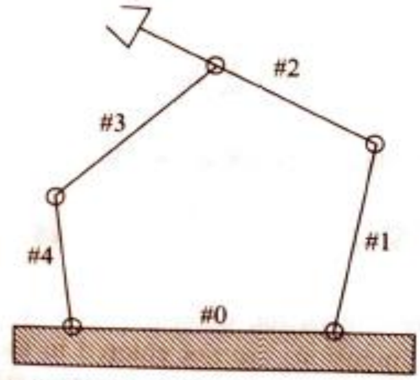


Fig. 5.10 A five-bar mechanism

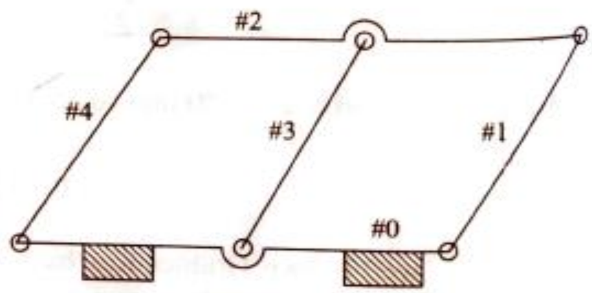


Fig. 5.11 A double parallelogram mechanism

POSE OF A RIGID BODY

- Rigid body motion in the three-dimensional Cartesian space comprises translation and rotation. Whereas translation is defined by using the three Cartesian coordinates, the rotation Difference between Configurations needs three angular coordinates.
- Hence, the rigid body motion can be defined completely by using all the six coordinates. In the study of the kinematics of robot manipulators, one con saintly deals with the position and orientation of several bodies in space. The bodies of interest include the links of the manipulator, tools, and work piece. To identify the position and orientation of a body, i.e. its 'pose' or "configuration', a fixed reference coordinate system is established, which is called the 'fixed frame.' Next, a Cartesian coordinate system attached to the moving body is employed to describe its pose.
- The pose or the position and orientation of a rigid body with respect to the reference coordinate system are known from the six independent parameters. As shown in Fig. 5.12, let X-Y-Z-coordinate system be the 'fixed reference frame'. The U-V-W-coordinate system is attached to the moving body and referred as the 'moving frame. Clearly, the pose or configuration of the rigid body is known if the pose of the moving frame with respect to the fixed frame is known. This pose is determined from the 'position' of any point on it, say, the origin 0, or point P, and the 'orientation' of the moving frame with respect to the fixed frame.

****** NOTES IN THE END******

MODULE 6

A robot today can do much more than merely move its arm through a series of points in space. Current technology robots can accept input from sensors and other devices. They can send signals to pieces of equipment operating with them in the cell. They can make decisions. They can communicate with computers to receive instructions and to report production data and problems. All of these capabilities require programming.

METHODS OF ROBOT PROGRAMMING

- Robot programming is accomplished in several ways. Consistent with current industrial practice we divide the programming methods into two basic types:

1. Lead through methods
2. Textual robot languages

- The lead through methods requires the programmer to move the manipulator through the desired motion path and that the path is committed to memory by the robot controller.
- The lead through methods is sometimes referred to as "teach-by-showing" methods. Chronologically, the lead through methods represents the first real robot programming methods used in industry.
- They had their beginnings in the early 1960s when robots were first being used Tor industrial applications.
- Robot programming with textual languages is accomplished somewhat like computer programming. The programmer types in the program on a CRT (cathode ray tube) monitor using a high-level English-like language.
- The procedure is usually augmented by using lead through techniques to teach the robot the locations of points in the workspace. The textual languages started to be developed in the 1970s, with the first commercial language appearing around 1979.
- In addition to the lead through and textual language programming, another method of programming is used for simple. Low-technology robots. We referred to these types of machines in Chap.Two as limited sequence robots which are controlled by means of mechanical stops and limit switches to define the end points of their joint motions.
- The setting of these stops and switches might be called a programming method. We prefer to think of this kind of programming as a manual setup procedure.
- In this chapter we discuss the lead through methods. We also examine the basic features and capabilities of these programming methods. What functions must a typical robot be able to do, and how is it taught to do these functions using lead through programming.

LEADTHROUGH PROGRAMMING METHODS

- In lead through programming, the robot is moved through the desired motion path in order to record the path into the controller memory. There are two ways of accomplishing lead through programming:

- Powered lead through
- Manual lead through

- The powered lead through method makes use of a teach pendant to control the various joint motors, and to power drive the robot arm and wrist through a series of points in space. Each point is recorded into memory for subsequent playback during the work cycle.
- The teach pendant is usually a small handheld control box with combinations of toggle switches, dials, and buttons to regulate the robot's physical movements and programming capabilities. Among the various robot programming methods, the powered lead through method is probably the most common today.
- It is largely limited to point-to point motions rather than continuous movement because of the difficulty in using the teach pendant to regulate complex geometric motions in space. A large number of industrial robot applications consist of point-to-point movements of the manipulator. These include part transfer tasks, machine loading and unloading, and spot welding.
- The manual lead through method (also sometimes called the "walkthrough method) is more readily used for continuous-path programming where the motion cycle involves smooth complex curvilinear movements of the robot arm.
- The most common example of this kind of robot application is spray painting, in which the robot wrist, with the spray painting gun attached as the end effector, must execute a smooth, regular motion pattern in order to apply the paint evenly over the entire surface to be coated Continuous are welding is another example in which continuous-path programming is required and this is sometimes accomplished with the manual lead through method.
- In the manual lead through method the programmer physically grasps the robot arm (and end effector) and manually moves it through the desired motion cycle. If the robot is large and awkward to physically move.
- A special programming apparatus is often substituted for the actual robot. This apparatus has basically the same geometry as the robot but it is easier to manipulate during programming. A teach button is often located near the wrist of the robot (or the special programming apparatus) which is depressed during those movements of the manipulator that will become part of the programmed cycle.
- This allows the programmer the ability to make extraneous moves of the arm without their being included in the final program. The motion cycle is divided into hundreds or even thousands of individual closely spaced points along the path and these points are recorded into the control.
- The control systems for both lead through procedures operate in either of two modes: teach mode or run mode. The teach mode is used to program the robot and the run mode is used to execute the program.
- The two lead through methods are relatively simple procedures that have been developed and enhanced over the last 20 years to teach robots to perform simple, repetitive operations in factory environments. Requirements of the programmers are relatively modest and these procedures can be readily applied in the plant.

A ROBOT PROGRAM AS A PATH IN SPACE

- This and the following sections of this chapter will examine the programming issues involved in the use of the lead through methods, with emphasis on the powered lead through approach. Let us begin our discussion with our previous definition of a robot program as a path in space.

- The locus of points along the path defines the sequence of positions through which the robot will move its wrist. In most applications, an end effector is attached to the wrist, and the program can be considered to be the path in space through which the end effector is to be moved by the robot.
- Since the robot consists of several joints (axes) linked together. The definition of the path in space in effect requires that the robot move its axes through various positions in order to follow that path. For a robot with six axes, each point in the path consists of six coordinate values.
- Each coordinate value corresponds to the position of one joint. As discussed in Chap. Two. There are four basic robot anatomies: polar, cylindrical, Cartesian, and jointed arm. Each one has three axes associated with the arm and body configuration and two or three additional joints associated with the wrist.

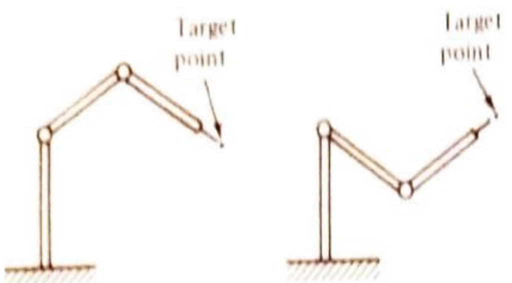


Figure 8-1 Two alternative axis configurations with end effector located at desired target point.

- Let us consider the problem of defining a sequence of points in space. We will assume that these points are defined by specifying the joint coordinates as described above, although this method of specification will not affect the issues we are discussing here. For the sake of simplicity, let us assume that we are programming a point-to-point Cartesian robot with only two axes, and only two addressable points for each axis.
- An addressable point is one of the available Points (as determined by the control resolution) that can be specified in the program so that the robot can be commanded to go to that point. Figure 8-2 shows the four possible points in the robot's rectangular workspace. A program For this robot to start in the lower left-hand corner and traverse the perimeter of the rectangle could be written as follows:

Example 8-1

Step	Move	Comments
1	1,1	Move to lower left corner
2	2,1	Move to lower right corner
3	2,2	Move to upper right corner
4	1,2	Move to upper left corner
5	1,1	Move back to start position

- The point designations correspond to the x, y coordinate positions in the Cartesian axis system, as illustrated in the figure. In our example, using a robot with two orthogonal slides and only two addressable points per axis, the definition of points in space corresponds exactly with joint coordinate values. Using the same robot, let us consider its behavior when performing the following program:

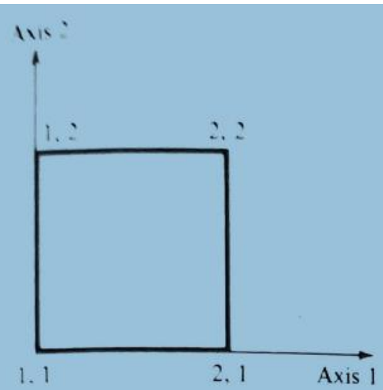


Figure 8-2 Robot workspace for Example 8-1

Example 8-2

Step	Move	Comments
1	1,1	Move to lower left corner
2	2,1	Move to lower right corner
3	1,2	Move to upper left corner
4	1,1	Move back to start position

- The second program is the same as the first, except that the point in the upper right corner (2,2) has not been listed. Before explaining the implications of this missing point, let us recall that in Example 8-1, the move from one point to the next required only one joint to be moved while the other joint position remained unchanged.
- In this second program, the move from point 2, 1 to point 1, 2 require both joints to be moved.
- The question that arises is: what path will the robot follow in getting from the first point to the second certainly one possibility is that both axes will move at the same time, and the robot will therefore trace a path along the diagonal line between the two points. The other possibility is that the robot will move only one axis at a time and trace out a path along the border of the rectangle, either through point.
- The question of which path the robot will take between two programmed points is not a trivial one. It is important for the programmer to know the answer in order to plan out the motion path correctly. Unfortunately, there is no general rule that all robots follow.

Limited-sequence non servo robots. Which are programmed using manual setup procedures rather than lead through methods, can usually move both joints at the same time.

- The path that is followed involves a slew motion (as described in Chap. Four) which is along the diagonal in our illustration. Other limited sequence robots.

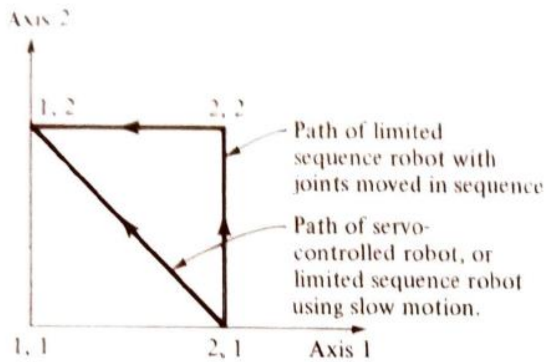


Figure 8-3 Likely path followed by the robot in Example 8-2 when operating at high speed. The arm trajectory misses the unprogrammed points.

- Move their joints in sequence rather than simultaneously Usually, these robots that move one axis at a time do so by moving the lower numbered axes first. Thus, the path through point 2, 2 is most likely in this example.
- However, there are no industry standards on this issue, and the programmer must make this kind of determination either from the user's manual or by experimentation with the actual robot. Servo controlled robots, which are programmed by lead through and textual language methods, tend to actuate all axes simultaneously.
- Hence, with servo control, the robot would likely move approximately along the diagonal path between points 2, 1 and 1, 2. The differences between the paths for example 8-2 are illustrated in fig. 8-3. As illustrated by the preceding discussion of example 8-2, it is possible for the programmer to make certain types of robots pass through points without actually including the points in the program.
- The key phrase is "pass through." these are not addressable points in the program and the robot will not actually stop at them in the sense of an addressable point.

METHODS OF DEFINING POSITIONS IN SPACE

Irrespective of robot configuration, there are several methods that can be used by the programmer during the teach mode to actuate the robot arm and wrist, we list the following three methods:

1. **Joint movements**
2. **x-y-z coordinate motions (also called world coordinates)**
3. **Tool coordinate motions**

- The first method is the most basic and involves the movement of each joint, usually by means of a teach pendant. The teach pendant has a set of toggle switches (or similar control devices) to operate each joint in either of its two directions until the end effector has been positioned to the desired point.

- This method of teaching points is often referred to as the joint mode. Successive positioning of the robot arm in this way to define a sequence of points can be a very tedious and time-consuming way of programming the robot.
- To overcome this disadvantage. Many robots can be the teach mode to controlled during move in x-y-z coordinate motions. Called the world coordinate system, allows the wrist location to be defined using the conventional Cartesian coordinate system with origin at some location in the body of the robot.
- In the case of the Cartesian coordinate robot, this method is virtually equivalent to the joint mode of programming. For polar. Cylindrical. And jointed-arm robots, the controller must solve a set of mathematical equations to convert the rotational joint motions of the robot into the Cartesian coordinate system.
- These conversions are carried out in such a way that the programmer does not have to be concerned with the substantial computations that are being performed by the controller. To the programmer.
- The wrist (or end effector) is being moved in motions that are parallel to the x, y and axes. The two or three additional joints which constitute the wrist assembly are almost always rotational, and while programming is being done in the x-y-z system to move the arm and body joints. The wrist is usually being maintained by the controller in a constant orientation. The x-y-z method of defining points in space is illustrated in Fig. 8-4 for a jointed-arm robot.

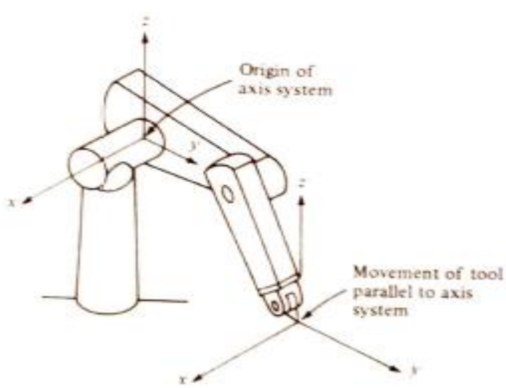


Figure 8-4 World mode or X-Y-Z method of defining points in space.

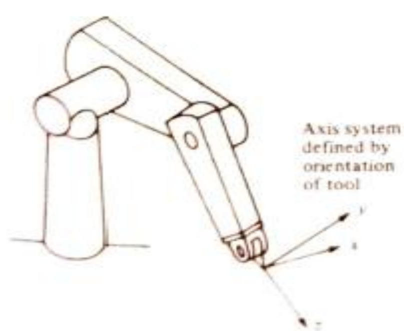


Figure 8-5 Tool mode of defining points in space

- Some robots have the capability for tool coordinate motions to be defined for the robot. This is a Cartesian coordinate system in which the origin is located at some point on the wrist and the XY plane is oriented parallel to the faceplate of the wrist. Accordingly, the z axis is perpendicular to the faceplate and pointing in the same direction as a tool or other end effector attached to the faceplate.
- Hence, this method of moving the robot could be used to provide a driving motion of the tool. Again, a significant amount of com mutational effort must be accomplished by the controller in order to permit the programmer to use tool motions for defining motions and points. Figure 8-5 shows the tool coordinate system.

REASONS FOR DEFINING POINTS

The preceding examples and discussion are intended to argue that there are some good reasons for defining points in space in a robot program, rather than relying on the robot to pass through an undefined point or to actuate a certain axis before it actuates another axis. The two main reasons for defining points in a program are:

- To define a working position for the end effector
- To avoid obstacles
- The first category is the most straightforward. This is the case where the robot is programmed to pick up a part at a given location or to perform a spot-welding operation at a specified location. Each location is a defined point in the program.
- This category also includes safe positions that are required in the work cycle. For example, it might be necessary to define a safe, remote point in the workspace from which the robot would start the work cycle.
- The second category is used to define one or more points in space for the robot to follow which ensures that it will not collide with other objects located in the work cell. Machines, conveyors, and other pieces of equipment in the work volume are examples of these obstacles. By defining a path of points around these obstacles, the collisions can be prevented.

SPEED CONTROL

- Most robots allow for their motion speed to be regulated during the program execution. A dial or group of dials on the teach pendant are used to set the speed for different portions of the program. It is considered good practice to operate the robot at a relatively slow speed when the end effector is operating close to obstacles in the work cell, and at higher speeds when moving over large distances where there are no obstacles.
- This gives rise to the notion of "freeways" within the cell. These are possible pathways in the robot cell which are free of obstructions and therefore permit operation at the higher velocities.
- The speed is not typically given as a linear velocity at the tip of the end effector for robots programmed by lead through methods. There are several reasons for this. First, the robot's linear speed at the end effector depends on how many axes are moving at one time and which axes they are. Second, the speed of the robot depends on its current axis

configuration. For example, the top speed of a polar coordinate robot will be much greater with its arm fully extended than with the arm in the fully retracted position. Finally, the speed of the robot will be affected by the load it is carrying due to the force of acceleration and deceleration.

- All of these reasons lead to considerable computational complexities when the control computer is programmed to determine wrist end velocity in the next chapter.
- We will be able to define the speed explicitly using the textual languages so that the wrist or even the end effector velocity can be programmed in more conventional units (e.g.. millimeters per second or inches per second). This capability is not available with all computer-controlled robots because of the reasons mentioned above.

MOTION INTERPOLATION

Suppose we were programming a two-axis servo controlled Cartesian robot with eight addressable points for each axis. Accordingly, there would be a total of 64 addressable points that we can use in any program that might be written. The work volume is illustrated in Fig. 8-6. Assuming the axis sizes to be the same as our previous limited sequence robot, a program for the robot to perform the same work cycle as Example 8-1 would be as follows:

Example 8-3

Step	Move
1	1,1
2	8,1
3	8,8
4	1,8
5	1,1

- If we were to remove step 3 in this program (similar to Example 8-2), our servo controlled robot would execute step 4 by tracing a path along the diagonal line from point 8, 1 to point 1, 8. This process is referred to as Interpolation.
- This internal algorithm followed by the robot controller to get between the two points is somewhat more complicated than it appears from our Simple illustration. Also, as indicated in Chap. Four, there are different interpolation schemes that can be specified by the robot to get from one point another. Before discussing these differences, let us describe the most basic Interpolation process, called joint interpolation.

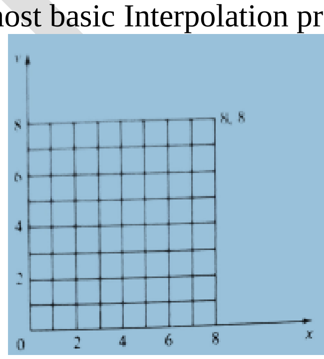


Figure 8-6 Robot work space with 8 × 8 addressable points.

- In joint interpolation, the controller determines how far each joint must move to get from the first point defined in the program to the next. It then selects the joint that requires the longest time.

- This determines the time it will take to complete the move (at a specified speed). Based on the known move time, and the amount of the movement required for the other axes, the controller subdivides the move into smaller increments so that all joints start and stop their motions at the same time.
- Consider, for example, the move from point 1,1 to point 7,4 in the grid of fig. 8-6. Linear joint 1 must move six increments (grid locations) and joint 2 must move three increments. To determine the joint interpolated path, the controller would determine a set of intermediate addressable points along the path between 1,1 and 7,4 which would be followed by the robot. The following program illustrates the process.

Example 8-4

Step	Move	Comments
1	1,1	User specified starting point
2	2,2	Internally generated interpolation point
3	3,2	Internally generated interpolation point
4	4,3	Internally generated interpolation point
5	5,3	Internally generated interpolation point
6	6,4	Internally generated interpolation point
7	7,4	User specified end point

- The reader should note that the controller alternatively moves both axes, and just one axis. Also, for each move requiring actuation of both axes, the two axes start and stop together.
- This kind of actuation causes the robot to take a path as illustrated in Fig. 8-7. The controller does the equivalent of constructing a hypothetically perfect path between the two points specified in the program, and then generates the internal points as close to that line as possible.
- The resulting path is not a straight line, but is rather an approximation. The controller approximates the perfect path as best it can within the limitations imposed by the control resolution of the robot (the available addressable points in the work volume). In our case. With only 64 addressable points in the grid, the approximation is very rough. With a much number of addressable larger points and a denser grid. The approximation would be better.
- The reader might have noticed that the interpolation procedure used above created a straight line approximation. This is usually referred to as straight line interpolation. Yet we have described it as joint interpolation.
- Because we are dealing with a Cartesian robot in the above illustration which has only linear axes. Joint interpolation and straight line interpolation are the same. For other robots with a combination of rotational and linear joints (cylindrical and polar configurations), or all rotational joints jointed arm configuration), straight line interpolation produces a path that is different from joint interpolation.
- For joint interpolation, the algorithm is outlined in the preceding discussion. In Straight line interpolation, the robot controller computes the straight line path between two points and develops the sequence of addressable points along the path for the robot to pass

through. As indicated the procedure is identical to the example given in Example 8-4.

- Consider a robot that has one rotational axis (axis 1) and one linear (axis 2), where each axis has eight addressable points. This creates a total of 64 addressable points which form the grid shown in Fig. 8-8. The grid is polar rather than rectilinear.
- During an interpolation procedure this has the effect of creating moves of different lengths (from the viewpoint of Euclidean geometry).
- For example, compare the move from 1,I to 3,2 with the move room 1,7 to 3,8.
- The addressability of a robot with rotational axes is not uniform in Euclidean space. Moves that are made close to the axis of rotation safe significantly smaller than moves that are far from the rotation joint.
- This change in robot configuration has implications for the interpolation schemes used by the controller. Although the descriptions given above still apply for one interpolation and straight line interpolation, it is clear that the paths taken by the robot will be affected by the change in anatomy.
- The incremental hives executed by the robot consist of combinations of rotational ovens Along axis

1. and linear moves along axis
2. we leave the visualization of

- Movements as irregular smooth motions and an interpolation process are involved in order to achieve them. To approximate the irregular smooth being taught by the programmer, the motion path is divided into a sequence closely spaced points that are recorded into the controller memory.
- These positions constitute the nearest addressable points to the path followed during programming. The interpolated path may consist of thousands of individual points that the robot must play back during subsequent program execution.

WAIT, SIGNAL, AND DELAY COMMANDS

- Robots usually work with something in their work space. In the simplest case, it may be a part that the robot will pick up, move, and drop off during execution of its work cycle.
- In more complex cases, the robot will work with other pieces of equipment in the work cell, and the activities of the various equipment must be coordinated.
- For the moment, let us introduce the kinds of basic programming commands that must be employed in work cell control. Nearly all industrial robots can be instructed to send signals or wait for signals during execution of the program.
- These signals are sometimes called interlocks, and their various applications in work cell control will be discussed in Chap. Eleven. The most common form of interlock signal is to actuate the robot's end effector. In the case of a gripper, the signal is to open or close the gripper.
- Signals of this type are usually binary; that is, the signal is on-off or high-level-low-level. Binary signals are not readily capable of including any complex information such as force sensor measurements. The binary signals used for the robot gripper are typically implemented by using one or more dedicated lines. Air pressure is commonly used to

actuate the gripper.

- A binary valve to actuate the gripper is controlled by means of two interlock signals, one to open the gripper and the other to close it. In some cases, feedback signals can be used to verify that the actuation of the gripper had occurred, and interlocks could be designed to provide this feedback data.
- In addition to control of the gripper, robots are typically coordinated with other devices in the cell also. For example, let us consider a robot whose task is to unload a press. It is important to inhibit the robot from having its gripper enter the press before the press is open, and even more obvious, it is important that the robot remove its hand from the press before the press closes.
- To accomplish this coordination, we introduce two commands that can be used during the program. The first command is.

SIGNAL M

- Which instructs the robot controller to output a signal through line M (where M IS one of several output lines available to the controller). The second command is which indicates that the robot should wait at its current location until it receives a signal on line N (where N is one of several input lines available to the robot controller)

WAIT N

- Let us suppose that the two-axis robot of Fig. 8-2 is to be used to perform the unloading of the press in our example. The layout of the work cell is illustrated in Fig. 8-9, which is similar to Fig. 8-6. The platen of the press (where the parts are to be picked up) is located at 8,8.
- The robot must drop the parts in a tote pan located at 1,8. One of the columns of the press is in the Way of an easy straight line move from 8,8 to 1,8. Therefore, the robot must move its arm around the near side of the column in order to avoid colliding with it.
- This is accomplished by making use of points 8,1 and 1.1. Point 8,1 will be our position to wait for the press to open before entering the press to remove the part, and the robot will be started from point 1.1, a point in space known to be safe in the application.
- We will use controller ports I to 10 as output (SIGNAL) lines and ports 11 through 20 as input (WAIT) lines.
- Specifically, output line 4 will be used to actuate (SIGNAL) the press, and output lines 5 and 6 will be used to close and open the gripper, respectively. Input line 11 will be used to receive the signal from the press indicating that it has opened (WAIT). The following is our program to accomplish the press unloading task (the sequence begins with the gripper in the open position).
- Each step in the program is executed in sequence, which means that the SIGNAL and WAIT commands are not executed until the robot has moved to the point indicated in the previous step.
- The operation of the gripper was assumed to take place instantaneously so that its actuation would be completed before the next step in the program was started. Some grippers use a feedback loop to ensure that the actuation has occurred before the program is permitted to execute the next step.

- A WAIT instruction can be programmed to accomplish this feedback. One of the exercises at the end of the chapter deals with this problem.

Example 8-5

Step	Move or signal	Comments
0	1,1	Start at home position
1	8,1	Move to wait position
2	WAIT 11	Wait for press to open
3	8,8	Move to pickup point
4	SIGNAL 5	Signal gripper to close
5	8,1	Move to safe position
6	SIGNAL 4	Signal press to actuate
7	1,1	Move around press column
8	1,8	Move to tote pan
9	SIGNAL 6	Signal gripper to open
10	1,1	Move to safe position

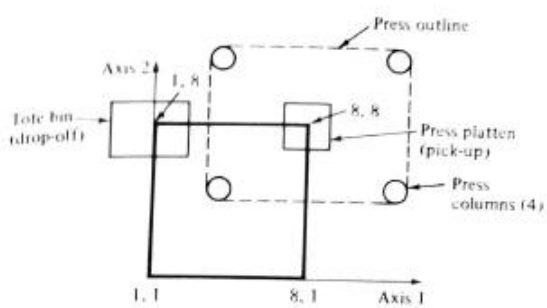


Figure 8-9 Robot work space for press unloading operation of Example 8-5.

- An alternative way to address this problem is to cause the robot to delay before proceeding to the next step. In this case, the robot would be programmed to wait for a specified amount of time to ensure that the operation had taken place. The form of the command for this second case has a length of time as its argument rather than an input line. The command

DELAY X SEC

- Indicates that the robot should wait X seconds before proceeding to the next step in the program. Below, we show a modified version of Example 8-5, using time as the mean for assuring that the gripper is either opened or closed.
- The reader is cautioned that our programs above are written to look like computer programs. This is for convenience in our explanation of the programming principles. The actual teaching of the moves and signals is accomplished by leading the arm through the motion path and entering the no motion instructions at the control panel or with the teach pendant.

Example 8-6

Step	Move or signal	Comments
0	1,1	Start at home position
1	8,1	Move to wait position
2	WAIT 11	Wait for press to open
3	8,8	Move to pickup point
4	SIGNAL 5	Signal gripper to close
5	DELAY 1 SEC	Wait for gripper to close
6	8,1	Move to safe position
7	SIGNAL 4	Signal press that hand is clear
8	1,1	Move around press column
9	1,8	Move to tote pan
10	SIGNAL 6	Signal hand to open
11	DELAY 1 SEC	Wait for gripper to open
12	1,1	Move to home position

APPENDIX

MEDICAL ROBOTS: CURRENT SYSTEMS AND RESEARCH DIRECTIONS

First used medically in 1985, robots now make an impact in laparoscopy, neurosurgery, orthopedic surgery, emergency response, and various other medical disciplines. This paper provides a review of medical robot history and surveys the capabilities of current medical robot systems, primarily focusing on commercially available systems while covering a few prominent research projects. By examining robotic systems across time and disciplines, trends are discernible that imply future capabilities of medical robots, for example, increased usage of intraoperative images, improved robot arm design, and haptic feedback to guide the surgeon.

Medical robotics is causing a paradigm shift in therapy. The most widespread surgical robot, Intuitive Surgical's da Vinci system, has been discussed in over 4,000 peer-reviewed publications, was cleared by the United States' Food and Drug Administration (FDA) for multiple categories of operations, and was used in 80% of radical prostatectomies performed in the U.S. for 2008, just nine years after the system went on the market. The rapid growth in medical robotics is driven by a combination of technological improvements (motors, materials, and control theory), advances in medical imaging (higher resolutions, magnetic resonance imaging, and 3D ultrasound), and an increase in surgeon/patient acceptance of both laparoscopic procedures and robotic assistance. New uses for medical robots are created regularly, as in the initial stages of any technology-driven revolution.

In 1979, the Robot Institute of America, an industrial trade group, defined a robot as "a reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or other specialized devices through various programmed motions for the performance of a variety of tasks." Such a definition leaves out tools with a single task (e.g., stapler), anything that cannot move (e.g., image analysis algorithms), and nonprogrammable mechanisms (e.g., purely manual laparoscopic tools). As a result, robots are generally indicated for tasks requiring programmable motions, particularly where those motions should be quick, strong, precise, accurate, untiring, and/or via complex articulations. The downsides generally include high expense, space needs, and extensive user training requirements. The greatest impact of medical robots has been in surgeries, both radiosurgery and tissue manipulation in the operating room, which are improved by precise and accurate motions of the necessary tools. Through robot assistance, surgical outcomes can be improved, patient trauma can be reduced, and hospital stays can be shortened, though the effects of robot assistance on long-term results are still under investigation.

Medical robots have been reviewed in various papers since the 1990s. Many such reviews are domain-specific, for example, focusing on surgical robots, urological robots, spine robots, and so forth [8–13]. For an overview of the basic science behind medical robots (e.g., kinematics, degrees of freedom, ergonomics, and telesurgery) along with a discussion of urologic robotic systems, see Challacombe and Stoianovici . Similarly focused on surgery, Kenngott et al. provide a recent Medline metareview on the outcomes of laparoscopic robot-assisted surgeries (urologic, gynecologic, and abdominal) while Gomes covers market drivers and roadblocks [16], and Okamura et al. explore big picture issues like societal drivers, quantitative diagnosis, and system adaptation/learning . The most recent coverage of medical robots across various domains was by Najarian et al. and the articles collected by Rosen et al.

This paper provides an overview of the impact of robots in multiple medical domains. This work builds on top of the aforementioned papers by providing an updated review of various robotic systems, covering system improvements (technical and regulatory) and changes in manufacturers due to corporate buyouts. Furthermore, to the author's knowledge this work covers more breadth in the medical domains benefiting from robot assistance than any other single paper, and thus provides a big picture view of how robots are improving the medical field. Though primarily focused on commercially available medical robotic systems and the history that describes their evolution, this paper also covers multiple next-generation systems and discusses their potential impacts on the future of the medical field.

NEUROLOGICAL

Brain surgery involves accessing a buried target surrounded by delicate tissue, a task that benefits from the ability for robots to make precise and accurate motions based on medical images . Thus, the first published account investigating the use of a robot in human surgery was in 1985 for brain biopsy using a computed tomography (CT) image and a stereotactic frame. In that work, an industrial robot defined the trajectory for a biopsy by keeping the probe oriented toward the biopsy target even as the surgeon manipulated the approach. This orientation was determined by registering a preoperative CT with the robot via fiducially on a stereotactic frame attached to the patient's skull. That project was discontinued after the robot company was bought out, due to safety concerns of the new owning company, which specified that the robot arm (54 kg and capable of making 0.5 m/s movements) was only designed to operate when separated by a barrier from people. Then in 1991, the Minerva robot (University of Lausanne, Switzerland) was designed to direct tools into the brain under real-time CT guidance. Real-time image guidance allows tracking of targets even as the brain tissue swells, sags, or shifts due to the operation. Minerva was discontinued in 1993 due to the limitation of single-dimensional incursions and its need for real-time CT.

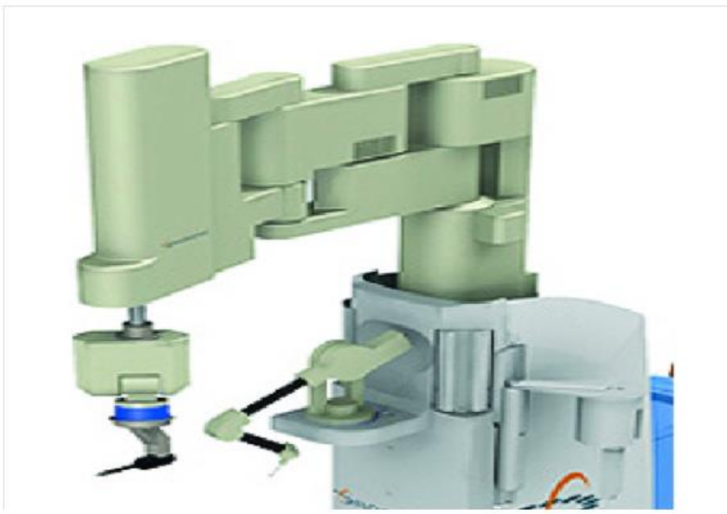
The currently available neurosurgery robots exhibit a purpose similar to historical systems, namely, image-guided positioning/orientation of cannulae or other tools (Figure 1). The NeuroMate (by Renishaw, previously by Integrated Surgical Systems, previously by Innovative Medical Machines International) has a Conformity Europeans (CE) mark and is currently used in the process for FDA clearance (the previous generation was granted FDA clearance in 1997) [24]. In addition to biopsy, the system is marketed for deep brain stimulation, stereotactic electroencephalography, trans cranial magnetic stimulation, radiosurgery, and neuro-endoscopy. Li et al. report in-use accuracy as sub millimeter for a frame-based configuration, the same level of application accuracy as bone-screw markers with infrared tracking, and an accuracy of 1.95 mm for the frameless configuration.

Another robotic system, Pathfinder (Prosurgics, formerly Armstrong Healthcare Ltd.), has been cleared by the FDA for neurosurgery (2004) . Using the system, the surgeon specifies a target and trajectory on a pre-operative medical image, and the robot guides the instrument into position with sub millimeter accuracy . Reported uses of the system include guiding needles for biopsy and guiding drills to make burr holes.

Renaissance (Mazor Robotics, the first generation system was named Spine Assist) has FDA clearance (2011) and CE mark for spinal surgery, and a CE mark for brain operations (2011) . The device consists of a robot the size of a soda can that mounts directly onto the spine and provides tool guidance based on planning software for various procedures including deformity corrections, biopsies, minimally invasive surgeries, and electrode placement procedures. Renaissance includes an add-on for existing fluoroscopy C-arms that provides 3D images for intraoperative verification of implant placement. Studies show increased implant accuracy and provide evidence that the Renaissance/Spine Assist may allow significantly more implants to be placed percutaneous.

ORTHOPEDICS

The expected benefit of robot assistance in orthopedics is accurate and precise bone resection [31, 32]. Through good bone resection, robotic systems (Figure 2) can improve alignment of implant with bone and increase the contact area between implant and bone, both of which may improve functional outcomes and implant longevity . Orthopedic robots have so far targeted the hip and knee for replacements or resurfacing (the exception being the Renaissance system in Section 2 and its use on the spine). Initial systems required the bones to be fixed in place, and all systems use bone screws or pins to localize the surgical site.



The initial robot assistance for orthopedics came via Robodoc (Curexo Technology Corp, originally by Integrated Surgical Systems), first used in 1992 for total hip replacement.. Robodoc has received a CE mark (1996), and FDA clearance for total hip replacement (1998) and total knee replacement (2009) [34]. The robot is used in conjunction with Ortho Doc, a surgical planner, with which the surgeon plans bone milling is based on preoperative CT. During the procedure, the patient’s leg is clamped to the robot’s pedestal, and a second clamp locates the femoral head to automatically halt the robot if the leg moves. The Robodoc then performs the milling automatically based on the surgical plan. Many initial attempts in surgical robotics involved such autonomous motions, which generated concerns about patient and doctor safety. To address those concerns, Robodoc has force sensing on all axes, as well as a six-axis force sensor at the wrist. The force sensing is used for safety monitoring, to allow the surgeon to manually direct the robot arm and to vary the velocity of tool motion as a function of the forces experienced during the milling operation.

Though no longer for sale, CASPAR (Computer Assisted Surgical Planning and Robotics) was another robotic system for knee and hip surgery, introduced in 1997 by OrtoMaquet, acquired by Getinge in 2000, acquired and discontinued by Universal Robot Systems (URS) in 2001. The robot was a direct competitor to Robodoc. It automatically performed bone drilling from a preoperative plan based on CT data.

In 2008, the RIO robotic arm (MAKO Surgical Corp, previous generation called the Tactile Guidance System) was released and received FDA clearance. The RIO is used for implantation of medial and lateral unicondylar knee components, as well as for patellofemoral arthroplasty As part of the trend away from autonomous robot motions, both the RIO and the surgeon simultaneously hold the surgical tool, with which the surgeon moves about the surgical site. The arm is designed to be low friction and low inertia, so that the surgeon can easily move the tool, back driving the arm's joint motors in the process.. The arm's purpose is to act as a haptic device during the milling procedure, resisting motions outside of the planned cutting envelope by pushing back on the surgeon's hand. Unlike other orthopedic systems, the RIO does not require the bone to be fixed in place, instead relying on a camera system to track bone pins and tools intraoperative and instantaneously registering the planned cutting envelope to the patient in the operating room. With this configuration, the system has promise for use as a surgical training tool.

Further reducing robotic influence on the cutting tool, the iBlock (Praxim Inc., an Orthopaedic Synergy Inc. company, previous generation the Praxiteles, FDA clearance 2010) is an automated cutting guide for total knee replacement . The iBlock is mounted directly to the bone, preventing any relative motion between the robot and the bone and aligns a cutting guide that the surgeon uses to manually perform planar cuts based on a preoperative plan. Koulalis et al. report reduced surgical time and increased cut accuracy compared with freehand navigation of cutting blocks.

The Navio PFS (Blue Belt Technologies, CE mark 2012) does not require a CT scan for unicondylar knee replacement, instead it uses intraoperative planning. The drill tool is tracked during the procedure, and the drill bit is retracted when it would leave the planned cutting volume. Limited information is available on the system due to its recent development.

The Stanmore Sculptor (Stanmore Implants, previous generation the Acrobot Sculptor by Acrobot Company Ltd.) is a synergistic system similar to the RIO, with active constraints to keep the surgeon in the planned workspace. The company's "Savile Row" system tailors a personalized unicondylar knee implant to the patient, incorporates the 3D model of that implant into the surgical planning interface, and uses active constraints with the Stanmore Sculptor to ensure proper preparation of the bone surface. The system does not currently have FDA clearance, but has been in use in Europe since 2004.

GENERAL LAPAROSCOPY

Prior to the 1980s, surgical procedures were performed through sizable incisions through which the surgeon could directly access the surgical site. In the late 1980s, camera technology had improved sufficiently for laparoscopy (a.k.a. minimally invasive surgery), in which one or more small incisions are used to access the surgical site with tools and camera. Laparoscopy significantly reduces patient trauma in comparison with traditional “open” procedures, thereby reducing morbidity and length of hospital stay, but at the cost of increased complexity of the surgical task. Compared with open surgery, in laparoscopy the surgeon’s feedback from the surgical site is impaired (reduced visibility and cannot manually palpate the tissue) and tool control is reduced (“mirror-image” motions due to fulcrum effect and loss of degrees of freedom in tool orientation).

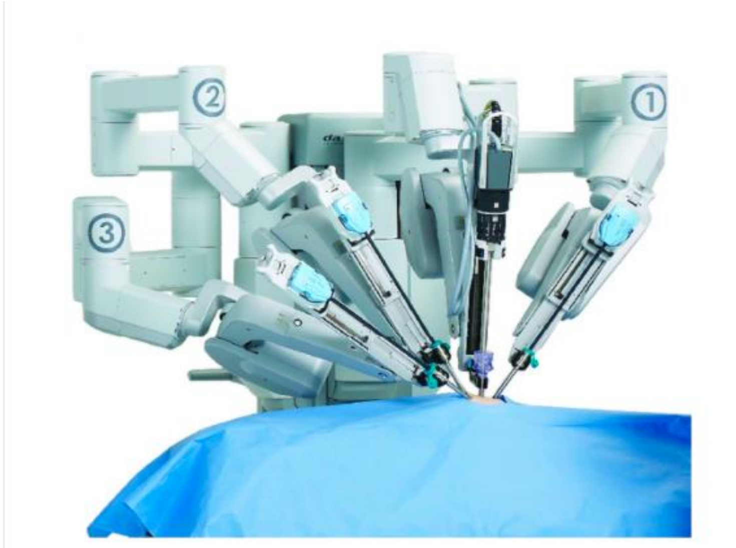
Robot assistance for soft-tissue surgery was first done in 1988 using an industrial robot to actively remove soft tissue during transurethral resection of the prostate. As with neurosurgery, the researchers deemed use of an industrial robot in the operating room to be unsafe. The experience provided the impetus for a research system, Probot, with the same purpose.

ZEUS

Commercial robotic systems for laparoscopy started with Computer Motion’s Aesop (discontinued, FDA clearance 1993) for holding endoscopes . Aesop was clamped to the surgical table or to a cart, and either moved the endoscope under voice control or allowed the endoscope to be manually positioned. In 1995, Computer Motion combined two tool-holding robot arms with Aesop to create the Zeus system (discontinued, FDA clearance 2001). The Zeus’s tool arms were teleported, following motions the surgeon made with instrument controls (a.k.a. “master” arms or joysticks) at the surgeon console. Technically, the Zeus is not a robot because it does not follow programmable motions, but rather is a remote computer-assisted telemanipulator with interactive robotic arms. To improve precision in tool motion, the Zeus filters out hand tremor, and can scale large hand motions by the surgeon down to short and precise motions by the tool. As described by Marescaux et al., the Zeus was used in the Lindbergh Operation, the first surgery was (cholecystectomy) performed with the surgeon and patient being separated by a distance of several thousand kilometers .

DA VINCI

Meanwhile, Intuitive Surgical Inc. was developing the da Vinci (initial FDA clearance 1995, Figure. Like the Zeus, the da Vinci is a teleported system, wherein the surgeon manipulates instrument controls at a console and the robot arms follow those motions with motion scaling and tremor reduction. Also like the Zeus, the da Vinci was initially offered with three arms to hold two tools and an endoscope, which are mounted to a single bedside cart.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5.2.1 Position Description

The 'position' of any point, P, on a rigid body in motion with respect to the fixed reference frame can be described by the 3-dimentional Cartesian vector—**p**, as indicated in Fig. 5.12. If the coordinates of point P or the components of vector **p** are, p_x, p_y, p_z, in the fixed frame F, it is denoted as

$$[\mathbf{p}]_F \equiv \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} \tag{5.8}$$

where the subscript F stands for the reference frame where the vector **p**, is represented. The subscripts, x, y and z, represent the projections of the position vector **p**, onto the coordinate axes of the fixed reference frame, namely, along X, Y and Z, respectively. Vector **p** can alternatively be expressed as

$$\mathbf{p} = p_x\mathbf{x} + p_y\mathbf{y} + p_z\mathbf{z} \tag{5.9}$$

where **x**, **y** and **z** denote the unit vectors along the axes, X, Y and Z of the frame F, respectively, as indicated in Fig. 5.12. Their representations in frame F, namely $[\mathbf{x}]_F$, $[\mathbf{y}]_F$ and $[\mathbf{z}]_F$, are as follows:

$$[\mathbf{x}]_F \equiv \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, [\mathbf{y}]_F \equiv \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \text{ and } [\mathbf{z}]_F \equiv \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{5.10}$$

Substituting eq. (5.10) into eq. (5.9), it can be shown that the expression of vector **p** in frame F, i.e. $[\mathbf{p}]_F$, is same as that of given in eq. (5.8). Note that if vector **p** is represented in another fixed frame different from frame F then the vector **p**, will have different components along the new coordinate axes even though the actual position of point P has not changed. Thus, a vector will normally be written without

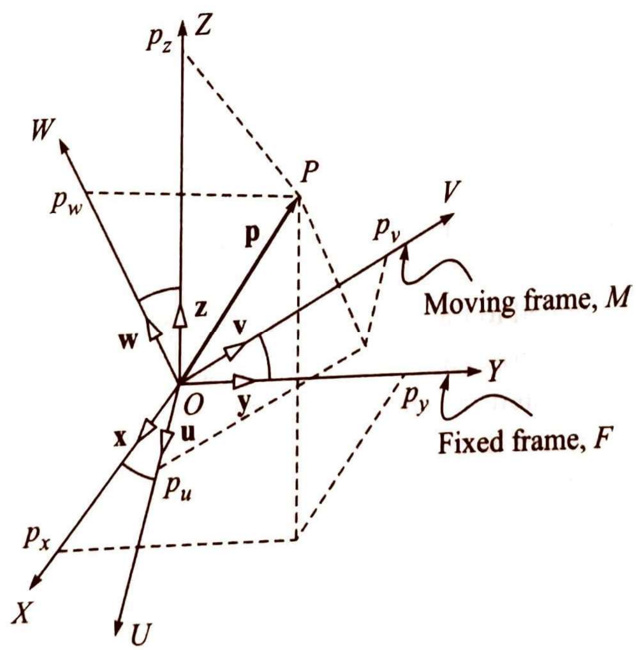


Fig. 5.12 Spatial description

mentioning any frame, e.g. as done in eq. (5.9) which, in contrast to eqs. (5.8) and (5.10), is termed as frame invariant representation, i.e. independent of the choice of any particular reference frame. It is, however, important to note that when a numerical problem is solved one must choose a suitable coordinate frame.

Example 5.5 Position of a Point in the Fixed Frame

If coordinates of a point P in the fixed coordinate frame are $p_x = 3, p_y = 4$, and $p_z = 5$, then the position vector p, from Eq. (5.8) can be given by

$$[\mathbf{p}]_F \equiv \begin{bmatrix} 3 \\ 4 \\ 5 \end{bmatrix}$$

5.2.2 Orientation Description

The 'orientation' of a rigid body with respect to the fixed frame can be described in different ways. For example,

(i) Direction Cosine Representation;

(ii) Euler Angle Representation; and others.

Each one has its own limitations. If necessary, one may switch from one to the other representation during a robot's motion control to avoid the former's limitations. Here, the above two will be presented which are sufficient to understand the underlying concepts and their limitations. Anybody interested in other representations may refer to the books by Tsai (1999) or Angeles (2003).

(i) Direction Cosine Representation To describe the orientation or the rotation of a rigid body, consider the motion of a moving frame M with respect to a fixed frame F, with one point fixed say, the origin of the fixed frame O, as shown in Fig. 5.12. Let **u**, **v** and **w** denote the three unit vectors pointing along the coordinates axes U, V and W of the moving frame M respectively, similar to the unit vectors **x**, **y**, and **z**, along X, Y and Z of the fixed frame F, respectively. Since each of the unit vectors, **u**, **v** or **w**, denotes the position of a point at a unit distance from the origin on the axes of the frame M, they are expressed using their projections on the X, Y, Z axes of the frame F as

$$\mathbf{u} = u_x\mathbf{x} + u_y\mathbf{y} + u_z\mathbf{z} \quad (5.11a)$$

$$\mathbf{v} = v_x\mathbf{x} + v_y\mathbf{y} + v_z\mathbf{z} \quad (5.11b)$$

$$\mathbf{w} = w_x\mathbf{x} + w_y\mathbf{y} + w_z\mathbf{z} \quad (5.11c)$$

where u_x, u_y and u_z are the components of the unit vector **u**, along X, Y and Z axes, respectively. Similarly v_x, v_y, v_z, and w_x, w_y, w_z are defined for the unit vectors **v** and **w**, respectively. Now the point P of the rigid body, as shown in Fig. 5.12 and given by eq. (5.8), is expressed in the moving frame M, as

$$\mathbf{p} = p_u\mathbf{u} + p_v\mathbf{v} + p_w\mathbf{w} \quad (5.12)$$

where p_u, p_v and p_w are the components of the vector **p**, along *U*, *V*, *W* axes of the moving frame *M*. Upon substitution of eqs. (5.11a-c) into eq. (5.12) yields

$$\mathbf{p} = (p_u u_x + p_v v_x + p_w w_x)\mathbf{x} + (p_u u_y + p_v v_y + p_w w_y)\mathbf{y} + (p_u u_z + p_v v_z + p_w w_z)\mathbf{z} \quad (5.13)$$

Comparing the right-hand sides of eqs. (5.8) and (5.13), the following identities are obtained:

$$p_x = u_x p_u + v_x p_v + w_x p_w \quad (5.14a)$$
$$p_y = u_y p_u + v_y p_v + w_y p_w \quad (5.14b)$$
$$p_z = u_z p_u + v_z p_v + w_z p_w \quad (5.14c)$$

Equations (5.14a-c) are written in a matrix form as

$$[\mathbf{p}]_F = \mathbf{Q}[\mathbf{p}]_M \quad (5.15)$$

where $[\mathbf{p}]_F$ and $[\mathbf{p}]_M$ are the representations of the 3-dimensional vector **p**, in frames *F* and *M*, respectively, and **Q** is the 3 × 3 rotation or orientation matrix transforming the representation of vector **p** from frame *M* to *F*. They are given as follows:

$$[\mathbf{p}]_F \equiv \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix}, [\mathbf{p}]_M \equiv \begin{bmatrix} p_u \\ p_v \\ p_w \end{bmatrix}, \text{ and } \mathbf{Q} \equiv \begin{bmatrix} u_x & v_x & w_x \\ u_y & v_y & w_y \\ u_z & v_z & w_z \end{bmatrix}$$

$$= \begin{bmatrix} \mathbf{u}^T\mathbf{x} & \mathbf{v}^T\mathbf{x} & \mathbf{w}^T\mathbf{x} \\ \mathbf{u}^T\mathbf{y} & \mathbf{v}^T\mathbf{y} & \mathbf{w}^T\mathbf{y} \\ \mathbf{u}^T\mathbf{z} & \mathbf{v}^T\mathbf{z} & \mathbf{w}^T\mathbf{z} \end{bmatrix} \quad (5.16)$$

Note the columns of matrix **Q**. They are nothing but the components of the orthogonal (meaning 90° to each other) unit vectors **u**, **v**, and **w** in the fixed frame *F*, which must satisfy the following six orthogonal conditions:

$$\mathbf{u}^T\mathbf{u} = \mathbf{v}^T\mathbf{v} = \mathbf{w}^T\mathbf{w} = 1, \text{ and } \mathbf{u}^T\mathbf{v}(\equiv \mathbf{v}^T\mathbf{u}) = \mathbf{u}^T\mathbf{w}(\equiv \mathbf{w}^T\mathbf{u}) = \mathbf{v}^T\mathbf{w}(\equiv \mathbf{w}^T\mathbf{v}) = 0 \quad (5.17)$$

Moreover, for the three orthogonal vectors **u**, **v** and **w**, the following hold true:

$$\mathbf{u} \times \mathbf{v} = \mathbf{w}, \ \mathbf{v} \times \mathbf{w} = \mathbf{u}, \text{ and } \mathbf{w} \times \mathbf{u} = \mathbf{v} \quad (5.18)$$

Hence, the 3 × 3 rotation matrix **Q**, denoting the orientation of the moving frame *M*, with respect to the fixed frame *F*, is called orthogonal. It satisfies the following properties due to eq. (5.17):

$$\mathbf{Q}^T\mathbf{Q} = \mathbf{Q}\mathbf{Q}^T = \mathbf{1}; \text{ where det } (\mathbf{Q}) = 1, \text{ and } \mathbf{Q}^{-1} = \mathbf{Q}^T \quad (5.19)$$

1 being the 3 × 3 identity matrix. Moreover, if one is interested in finding the rotation description of the frame *F*, with respect to the frame *M* denoted by **Q**′, it can be derived similarly. It can be shown that $\mathbf{Q}' = \mathbf{Q}^T$.

Also note from eq. (5.16), that the (1, 1) element of **Q** is the cosine of the angle between the vectors **u** and **x**, i.e. $\mathbf{u}^T\mathbf{x}$. The same holds true with the other elements of **Q**. Hence, this rotation matrix is known as the 'Direction Cosine Representation' of the rotation matrix. Such representation requires nine parameters, namely, the elements of the 3 × 3 matrix **Q**. However, not all the nine parameters are independent as they must also satisfy the six conditions of eq. (5.17). Thus, only three parameters are independent and should be sufficient to define the three-DOF rotational motion. It is however, difficult to choose the set of three independent parameters. This is the drawback of the Direction Cosine Representation.

Example 5.6 Elementary Rotations

Suppose that a reference frame *M* coincides with the fixed frame *F*. Now, frame *M* is rotated by an angle α about the axis *Z*, as shown in Fig. 5.13(a). The unit vectors of the new frame *M* can be described in terms of their components in the reference frame *F*, as

$$[\mathbf{u}]_F \equiv \begin{bmatrix} C\alpha \\ S\alpha \\ 0 \end{bmatrix}, [\mathbf{v}]_F \equiv \begin{bmatrix} -S\alpha \\ C\alpha \\ 0 \end{bmatrix}, \text{ and } [\mathbf{w}]_F \equiv \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{5.20}$$

where, $S \equiv \sin$; $C \equiv \cos$. Hence, the rotation matrix denoted by $\mathbf{Q}_Z$ is given by

$$\mathbf{Q}_z \equiv \begin{bmatrix} C\alpha & -S\alpha & 0 \\ S\alpha & C\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{5.21}$$

In a similar manner, it can be shown that the rotations of angle β about the axis *Y*, and by an angle γ about the axis *X* are respectively, given by

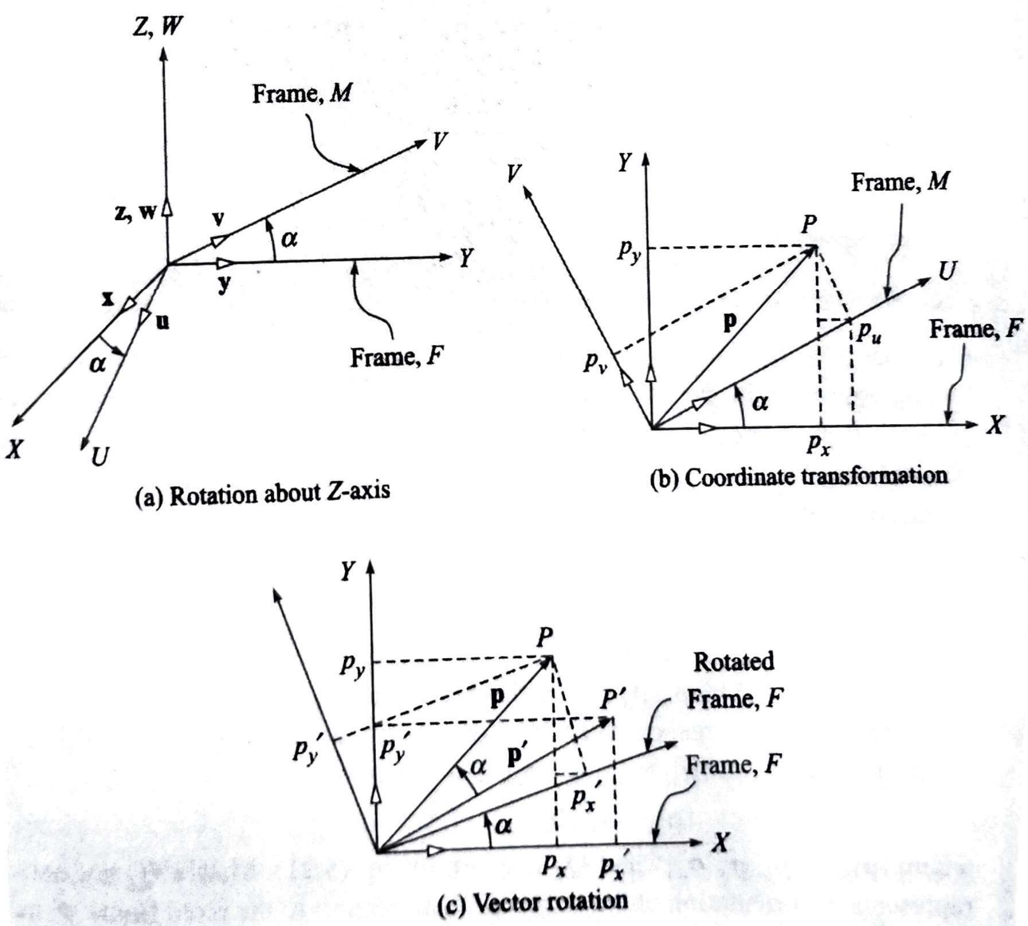


Fig. 5.13 Alternative interpretations of rotation matrix

$$\mathbf{Q}_Y \equiv \begin{bmatrix} C\beta & 0 & S\beta \\ 0 & 1 & 0 \\ -S\beta & 0 & C\beta \end{bmatrix}, \text{ and } \mathbf{Q}_X \equiv \begin{bmatrix} 1 & 0 & 0 \\ 0 & C\gamma & -S\gamma \\ 0 & S\gamma & C\gamma \end{bmatrix} \quad (5.22)$$

The above matrices in eqs. (5.21) and (5.22) are called the 'elementary rotations' and are useful to describe any arbitrary rotation while the angles with respect to the coordinate axes are known.

Example 5.7 Properties of Elementary Rotation Matrices

From eqs. (5.21) and (5.22), matrix multiplication of say, $\mathbf{Q}_z^T$ and $\mathbf{Q}_z$ results the following:

$$\mathbf{Q}_z^T\mathbf{Q}_z = \begin{bmatrix} C\alpha & S\alpha & 0 \\ -S\alpha & C\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C\alpha & -S\alpha & 0 \\ S\alpha & C\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Using the definition of determinant given in Appendix A, it can be easily calculated that $\det(\mathbf{Q}_z) = 1$. Hence, $\mathbf{Q}_z$ satisfies both the properties of a rotation matrix. Similarly, the other two matrices can be shown to have the properties of a rotation matrix as well.

Example 5.8 Coordinate Transformation

Consider two coordinate frames with a common origin. One of them is rotated by an angle α about the axis Z. Let $[\mathbf{p}]_F$ and $[\mathbf{p}]_M$ be the vector representations of point P in frames F and M respectively, as shown in Fig. 5.13(b). On the basis of simple geometry, the relationships between the coordinates of point P in the two coordinate frames are given by

$$p_x = p_u C\alpha - p_v S\alpha \quad (5.23)$$

$$p_y = p_u S\alpha + p_v C\alpha \quad (5.24)$$

$$p_z = p_w \quad (5.25)$$

where p_x, p_y, p_z, and p_u, p_v, p_w are the three coordinates of point P along the axes of frames F and M, respectively. It is easy to recognise from eqs. (5.23) to (5.25) that the vector $[\mathbf{p}]_F \equiv [p_x, p_y, p_z]^T$ is nothing but

$$[\mathbf{p}]_F = \mathbf{Q}_Z[\mathbf{p}]_M \quad (5.26)$$

where $[\mathbf{p}]_M \equiv [p_u, p_v, p_w]^T$ and $\mathbf{Q}_Z$ is given by eq. (5.21). Matrix $\mathbf{Q}_Z$ not only represents the orientation of the frame, M, with respect to the fixed frame, F, as in Fig. 5.13(a), but also transforms the representation of a vector from frame M say, $[\mathbf{p}]_M$, to another frame F, i.e. $[\mathbf{p}]_F$.

Example 5.9 Vector Rotation

Consider the vector **p**, which is obtained by rotating a vector **p**′ in the *X*-*Y*-plane by an angle α about the axis Z, of the reference frame F of Fig. 5.13(c). Let p'_x, p'_y, p'_z be the coordinates of vector **p**′ in frame *F*, i.e. $[\mathbf{p}']_F \equiv [p'_x, p'_y, p'_z]^T$. Then, vector **p** in frame *F* $[\mathbf{p}]_F$, has the following components:

$$p_x = p'_x C\alpha - p'_y S\alpha \quad (5.27)$$

$$p_y = p'_x S\alpha + p'_y C\alpha \quad (5.28)$$

$$p_z = p'_z \quad (5.29)$$

which can be obtained by rotating the fixed frame *F*, with which vector **p**′ is attached by an angle α counter-clockwise about the *Z*-axis so that vector **p**′ reaches **p**, as indicated in Fig. 5.13(c). Equations (5.27)–(5.29) can be rewritten in a more compact form as

$$[\mathbf{p}]_F = \mathbf{Q}_Z[\mathbf{p}']_F \quad (5.30)$$

where $\mathbf{Q}_Z$ is given by eq. (5.21).

(ii) Euler Angles Representation The Euler angles constitute a 'minimal' representation of the orientation as obtained by composing the three elementary rotations with respect to the axes of the current frames. There is a possibility of twelve distinct sets of Euler angles with regard to the sequence of possible elementary rotations, namely, *XYZ*, *XZY*, *XZX*, *XYX*, *YXZ*, *YZX*, *YXY*, *YZY*, *ZXY*, *ZYZ*, *ZXZ*, and *ZYX*. Amongst all, the *ZYZ* set is commonly used in the Euler angle representation. This implies that the fixed frame *F*, first rotates about its *Z*-axis to reach an intermediate frame *A*, then about the *Y*-axis of the rotated frame, i.e. *Y*′ of frame *A*, to reach another intermediate frame *B* and finally, about the *Z*-axis of the twice rotated frame, i.e. *Z*″ of frame *B*, to reach the desired frame *M*, as shown in Fig. 5.14. Let ϕ, θ, and φ be the angles about *Z*, *Y*′, and *Z*″, respectively. The overall rotation described by these angles is then obtained as the composition of the elementary rotations, as explained below: Referring to Fig. 5.14,

- Rotate the fixed frame *F*, by the angle ϕ, about the axis Z, as indicated in Fig. 5.14(a). This rotation is described by the rotation matrix $\mathbf{Q}_Z$, as derived in eq. (5.21) i.e.,

$$\mathbf{Q}_z \equiv \begin{bmatrix} C\phi & -S\phi & 0 \\ S\phi & C\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (5.31a)$$

- Rotate the current frame *A* by an angle θ about its *Y*′ axis, Fig. 5.14(b). This rotation is denoted by $Q_{Y'}$ and is described by the rotation matrix $\mathbf{Q}_Y$ of eq. (5.22), i.e.,

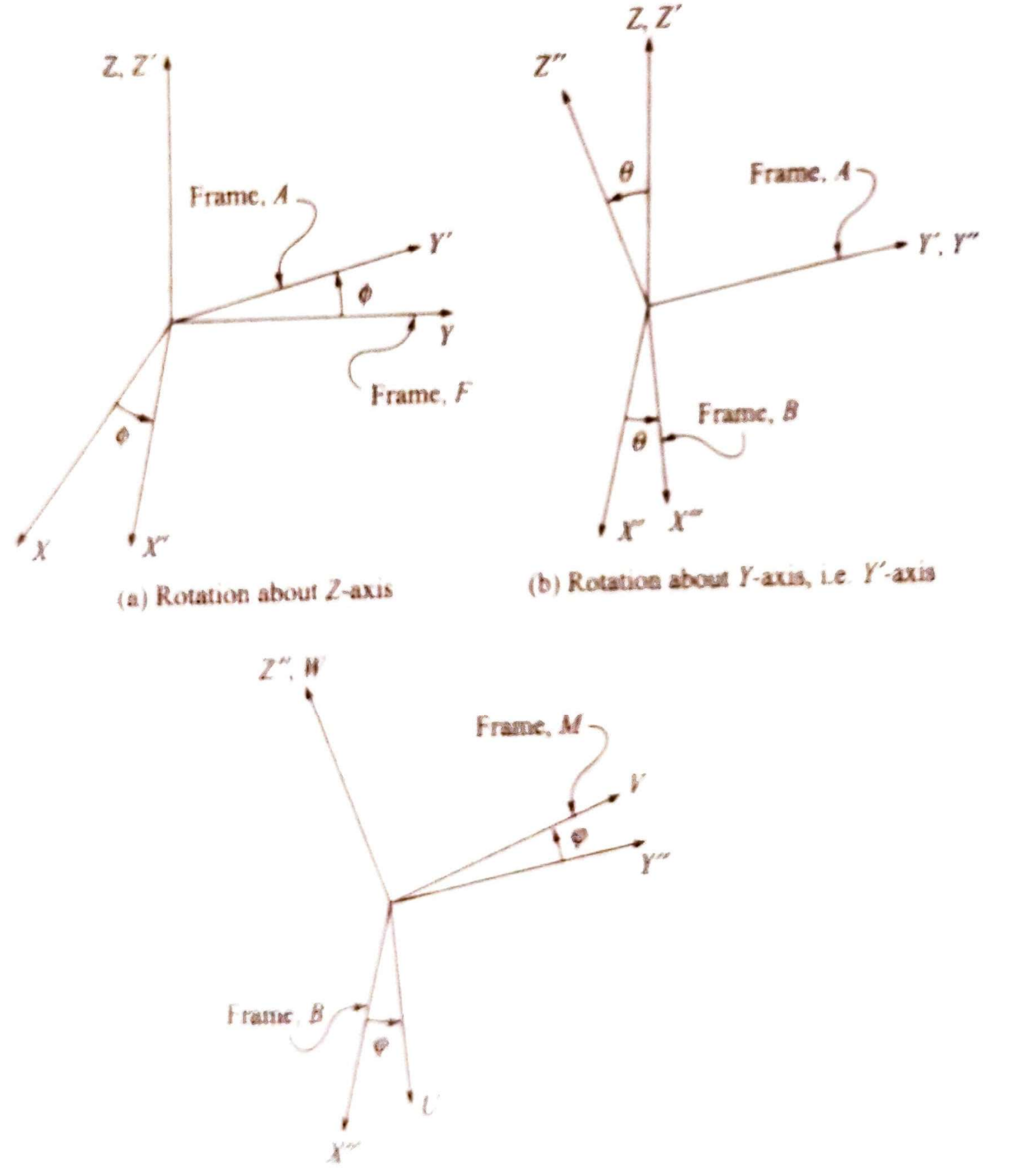
$$\mathbf{Q}_{Y'} \equiv \begin{bmatrix} C\theta & 0 & S\theta \\ 0 & 1 & 0 \\ -S\theta & 0 & C\theta \end{bmatrix} \quad (5.31b)$$

- Rotate the current frame B by an angle φ about its Z'' axis, Fig. 5.14(c). This rotation is denoted by $\mathbf{Q}_{Z''}$ and is described by the rotation matrix, $\mathbf{Q}_Z$ of eq. (5.21), i.e.,

$$\mathbf{Q}_{Z''} = \begin{bmatrix} C\varphi & -S\varphi & 0 \\ S\varphi & C\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (5.31c)$$

The resulting orientation of the frame M as denoted by $\mathbf{Q}$, is obtained from the composition of the three elementary rotations $\mathbf{Q}_Z$, $\mathbf{Q}_{Y'}$ and $\mathbf{Q}_{Z''}$, with respect to their current frames. It is obtained via post-multiplications of the successive rotation matrices, i.e.

$$\mathbf{Q} = \mathbf{Q}_Z \mathbf{Q}_{Y'} \mathbf{Q}_{Z''} \quad (5.31d)$$



(a) Rotation about Z-axis

(b) Rotation about Y-axis, i.e. Y'-axis

(c) Rotation about Z-axis, i.e. Z''-axis

Fig. 5.14 The ZYZ Euler angles

whose elements are computed below:

$$\mathbf{Q} \equiv \begin{bmatrix} C\phi C\theta C\varphi - S\phi S\varphi & -C\phi C\theta S\varphi - S\phi C\varphi & C\phi S\theta \\ S\phi C\theta C\varphi + C\phi S\varphi & -S\phi C\theta S\varphi + C\phi C\varphi & S\phi S\theta \\ -S\theta C\varphi & S\theta S\phi & C\theta \end{bmatrix} \quad (5.31e)$$

The drawback of the minimal Euler angles representation, eq. (5.31e), is that it sometimes fails in finding the solution of an inverse problem, i.e. for a given rotation matrix to find the equivalent Euler rotation angles. For example, if **Q** is given as follows:

$$\mathbf{Q} \equiv \begin{bmatrix} q_{11} & q_{12} & q_{13} \\ q_{21} & q_{22} & q_{23} \\ q_{31} & q_{32} & q_{33} \end{bmatrix} \quad (5.32a)$$

then the angle ϕ, can be obtained from the comparison of (1, 3) and (2, 3) elements of **Q** given by eqs. (5.31e) and (5.32a), i.e.

$$\phi = atan2\left(\frac{q_{23}}{S\theta}, \frac{q_{13}}{S\theta}\right) \quad (5.32b)$$

where "$atan2(y, x)$" is the two-argument function that yields one unique solution for the angle. The solution of eq. (5.32b) exists provided $S\theta \neq 0$, i.e., when $\theta \neq 0$ or $n\pi$, for $n = 1, 2, \ldots$ An important aspect of the rotation representation, either direction cosine or Euler angle or any other, is that unlike vectors it is non-commutative, i.e. the order of rotations are important in deriving the correct rotation matrix. As illustrated in Fig. 5.15(a–c), the rotations of a box about Z and current Y axes are different from the rotation about Y and Z axes, as shown in Fig. 5.16(a-c). In order to show it mathematically, the resultant matrix for the rotations about Z and Y-axes, denoted by $\mathbf{Q}_{ZY}$, can be given by

$$\mathbf{Q}_{ZY} = \mathbf{Q}_Y \mathbf{Q}_Z = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \quad (5.33a)$$

where $\mathbf{Q}_Y$, and $\mathbf{Q}_Z$ are as follows:

$$\mathbf{Q}_Y \equiv \begin{bmatrix} C90^\circ & 0 & S90^\circ \\ 0 & 1 & 0 \\ -S90^\circ & 0 & C90^\circ \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix};$$

$$\mathbf{Q}_Z \equiv \begin{bmatrix} C90^\circ & -S90^\circ & 0 \\ S90^\circ & C90^\circ & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (5.33b)$$

Note the order of multiplication in eq. (5.33a) is reverse to that of eq. (5.31d). This is due to the fact that the rotations in eq. (5.31d) are with respect to the current frames, whereas in eq. (5.33a) they are with respect to the fixed frame. The result of eq.

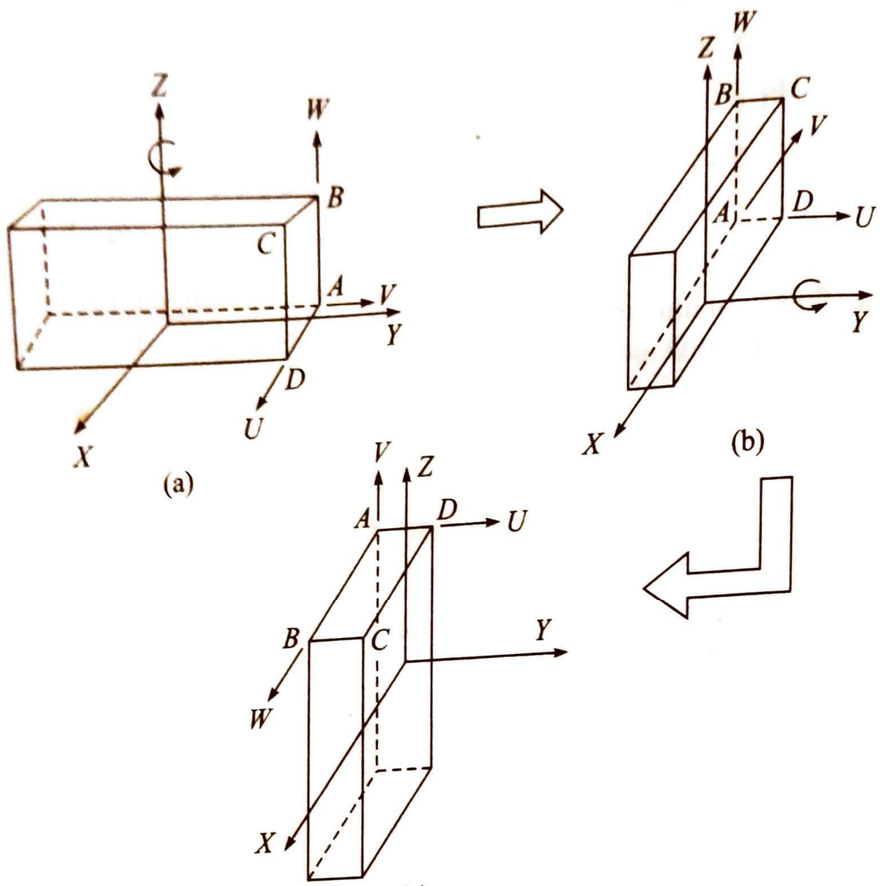


Fig. 5.15 Successive rotation of a box about *Z* and *Y*-axes

(5.33a) can be verified from Fig. 5.15(c) using the concept of direction cosine representation of a rotation matrix as explained earlier. Similarly, the resultant rotation matrix for the rotations about *Y* and *Z*-axes, as denoted by $\mathbf{Q}_{YZ}$, can be obtained as

$$\mathbf{Q}_{YZ} = \mathbf{Q}_Z\mathbf{Q}_Y = \begin{bmatrix} 0 & -1 & 0 \\ 0 & 0 & 1 \\ -1 & 0 & 0 \end{bmatrix} \quad (5.33c)$$

Comparing eqs. (5.33a) and (5.33c), it is obvious that the two sequences of rotations are different. However, the same is not true for the vector representation of a point *P* with respect to *O*, one can either add vector **b** to **a** or **a** to **b**, as in Fig. 5.17. Both additions will result in the same vector **p**.

5.3 COORDINATE TRANSFORMATION

As illustrated in Sub-section 5.2.1, the position of a rigid body in space is expressed in terms of the position of a suitable point on the body say, O_M in Fig. 5.18, with respect to the origin *O*, of the fixed frame *F*, while its orientation or rotation is expressed in terms of the unit vector components of the moving frame *M*, attached to

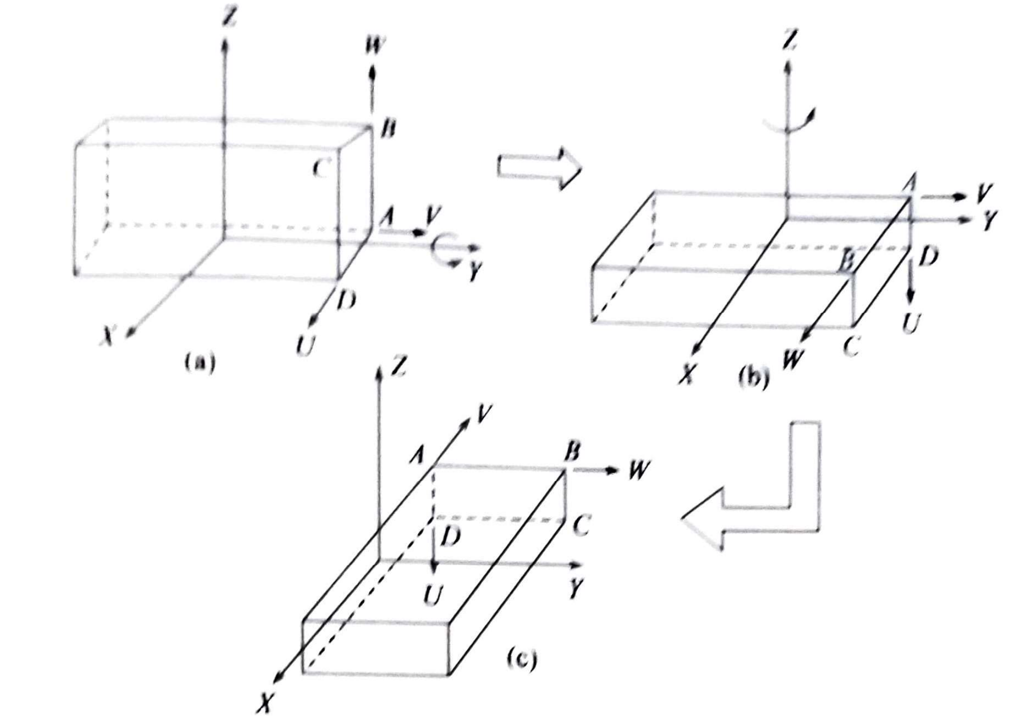


Fig. 5.16 Successive rotation of a box about Y and Z-axes

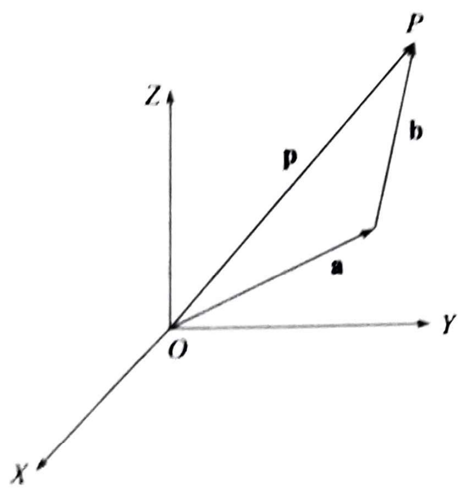


Fig. 5.17 Addition of two vectors

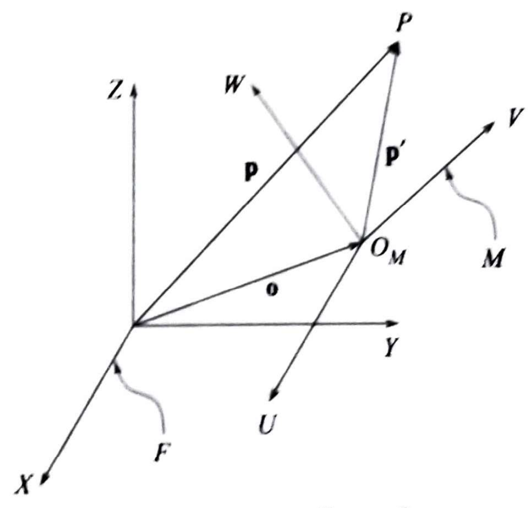


Fig. 5.18 Two coordinate frames

the body, as explained in Sub-section 5.2.2. Referring to Fig. 5.18, the relation between the two coordinate frames namely, F and M, are derived as follows: Consider an arbitrary point P on the rigid body with which the frame M is attached at O_M. Let $\mathbf{p}$ and $\mathbf{p}'$ be the vectors denoting the point P, from the origin of the frames, F and M, respectively. In addition, let $\mathbf{o}$ be the position vector denoting the translation of the origin of frame M, O_M, from that of frame F, i.e. O. Thus,

$$\mathbf{p} = \mathbf{o} + \mathbf{p}' \tag{5.34}$$

Note that if $\mathbf{p}'$ is known in the moving frame M, then it is nothing but the coordinates of point P in frame M, i.e. $[\mathbf{p}']_M$. Moreover, if $\mathbf{Q}$ is the orientation of frame M with respect to frame F then vector $\mathbf{p}'$ in frame F is $[\mathbf{p}']_F = \mathbf{Q}[\mathbf{p}']_M$. Hence, the vector, $\mathbf{p}$, in the fixed frame F, i.e. $[\mathbf{p}]_F$, can be obtained as

$$[\mathbf{p}]_F = [\mathbf{o}]_F + \mathbf{Q}[\mathbf{p}']_M \tag{5.35}$$

Equation (5.35) represents the 'coordinate transformation,' of point P of the rigid body from the moving frame M to the fixed frame F, while both, translation and rotation are involved.

5.3.1 Homogeneous Transformation

The coordinate transformation given by eq. (5.35), can be rearranged as

$$\begin{bmatrix} [\mathbf{p}]_F \\ 1 \end{bmatrix} = \begin{bmatrix} \mathbf{Q} & [\mathbf{o}]_F \\ \mathbf{0}^T & 1 \end{bmatrix} \begin{bmatrix} [\mathbf{p}']_M \\ 1 \end{bmatrix} \quad (5.36)$$

where $\mathbf{0} \equiv [0,\ 0,\ 0]^T$ is the three-dimensional vector of zeros. Equation (5.36) is written in a compact form as

$$\overline{[\mathbf{p}]}_F = \mathbf{T}\overline{[\mathbf{p}']}_M \quad (5.37)$$

where $\overline{[\mathbf{p}]}_F$ and $\overline{[\mathbf{p}']}_M$ are the four-dimensional vectors obtained by putting one at the bottom of the original three-dimensional vectors $[\mathbf{p}]_F$ and $[\mathbf{p}']_M$, respectively, as the fourth element, whereas the 4×4 matrix $\mathbf{T}$, is called the 'homogeneous transformation matrix'. Equation (5.36) or (5.37) is simple in the sense that the transformation of a vector, which includes both translation and rotation from frame M to F, is done by just multiplying one 4×4 matrix, instead of a matrix multiplication and vector addition, as in eq. (5.35). However, from the view of computational complexity i.e., the numbers of multiplications/divisions and additions/subtractions required in a computer program, eq. (5.35) is more economical as compared to eq. (5.36) or (5.37), as some unnecessary multiplications and additions with 1s and 0s will have to be performed. It is pointed out here that, for the homogeneous transformation matrix $\mathbf{T}$, the orthogonality property does not hold good, i.e.

> **Why homogeneous?**
>
> Matrix T of eq. (5.36) takes care of both the translation and rotation of the frame attached to the body with respect to the fixed frame.

$$\mathbf{T}^T\mathbf{T} \neq \mathbf{1} \quad \text{or} \quad \mathbf{T}^{-1} \neq \mathbf{T}^T \quad (5.38)$$

However, the inverse of the homogeneous transformations matrix $\mathbf{T}$, can be obtained easily from eq. (5.36) as

$$\mathbf{T}^{-1} = \begin{bmatrix} \mathbf{Q}^T & -\mathbf{Q}^T[\mathbf{o}]_F \\ \mathbf{0}^T & 1 \end{bmatrix} \quad (5.39)$$

Example 5.10 Pure Translation

Referring to Fig. 5.19(a), consider the frame M, which is obtained from the frame F by the translation of it by two units along Y, and one unit along Z. Their relation is represented by a homogeneous transformation matrix namely,