SREENIVASA INSTITUTE OF TECHNOLOGY AND MANAGEMENT STUDIES

(Autonomous)

(AUTOMATION AND ROBOTICS)

18MEC325

LECTURE NOTES

III - B.TECH / II – SEMESTER REGULATION: R18

PREPARED BY

FACULTY INCHARGE : Ms.K. SANTHOSH PRIYA

DESIGNATION : ASSISTANT PROFESSOR

DEPARTMENT : MECHANICAL

SREENIVASA INSTITUTE OF TECHNOLOGY AND MANAGEMENT STUDIES

(Autonomous)

DEPARTMENT of MECHANICAL ENGINEERING

AUTOMATION AND ROBOTICS

(18MEC325)

III B.Tech II Semester

L	T	P	C
3	1	0	3

18MEC325 AUTOMATION AND ROBOTICS

Course Educational Objectives:

- To study the various fundamental concepts of automation.
- To understand the basic concepts associated with the design and functioning and applications of robots.
- To study about the drives and sensors used in robots.
- To learn about analysing robot kinematics, dynamics and robot programming.

UNIT – 1: BASICS OF AUTOMATION

Basic elements of an automated system – Need – Types – Advanced automation function – Levels of automation – Hardware components for automation and process control – Automated storage and retrieval system – Material transport system and equipments – Over view of automated identification technique – Bar code technology.

UNIT – 2: AUTOMATED FLOW LINES AND LINE BALANCING

Automated flow lines: Part transfer methods and mechanisms – Types of flow lines – Flow line with/without buffer storage – Qualitative analysis. **Assembly line balancing:** Assembly process and systems assembly line – Line balancing methods – Ways of improving line balance and flexible assembly lines.

UNIT – 3: INDUSTRIAL ROBOTICS AND DRIVE SYSTEM

Definition – Robot anatomy – Co-ordinate systems, Work envelope, types and classification – Specifications – Pitch, yaw, roll, joint notations, speed of motion, pay load – Robot parts and functions – Need for robots – Different applications. **Robot Drive System:** Pneumatic drives – Hydraulic drives – Mechanical drives – Electrical drives – Servo motors and stepper motor – Grippers – Mechanical grippers, pneumatic and hydraulic grippers, magnetic grippers, vacuum Grippers; two fingered and three fingered grippers; internal grippers and external grippers.

UNIT – 4: KINEMATICS AND DYNAMICS OF ROBOTS

Robot Kinematics: Homogeneous transformations as applicable to rotation and translation – D-H notation – Forward and inverse kinematics. **Robot Dynamics:** Differential transformation – Jacobians, Lagrange-Euler and Newton-Euler formations.

Trajectory Planning: Trajectory planning and avoidance of obstacles – Path planning – Skew motion – Joint integrated motion – Straight line motion.

UNIT – 5: ROBOT PROGRAMMING AND APPLICATION

Robot Sensors: Range sensor – Proximity sensor – Touch sensor – Force and torque sensor. **Robot Programming:** Teach pendant programming, lead through programming, robot programming languages – VAL programming – Motion commands, sensor commands, end effecter commands and simple programs. **Robot Applications:** Robot application in manufacturing industry – Applications in assembly and inspection.

Course Outcomes:

Upon completion of this course, the students will be able to:

- ✓ Understand the concept of automation in manufacturing industries.
- ✓ Have knowledge on the fundamentals of Robotics, Robot Kinematics and Programming which help them to build and work with Robots.

Text Books:

1. Robotics Control, Sensing, Vision and Intelligence, Fu.K.S. Gonzalz.R.C., and Lee C.S.G., 1987, McGraw-Hill Book Co.,
2. Automation, Production Systems and CIM, M.P.Groover, 3/e, 2008, Prentice- Hall of India, Pvt. Ltd., New Delhi.

Reference Books

1. Fundamentals of Robotics Analysis and Control, C Robert J Schilling, 2009, Pearson Education.
2. Introduction to Robotics Mechanics and Education, Craig J.J., 2008.
3. Robotics Technology and Flexible Automation, Deb S.R. and Deb S., 2010, McGraw Hill Education.
4. Industrial Robotics-Technology, Programming and Applications, M.P.Groover, 2001, McGrawHill.
5. Foundation of Robotics: Analysis and Control, Yoshikawa, 2004, Prentice Hall of India.

On successful completion of the course, students will be able to:

Course Outcomes		POs related to Cos
CO1	**Summarize the various fundamental and advanced concepts of automation in industry**	**PO1**
CO2	**Understand the line balancing and flow line of robotics in automated**	**PO1, PO2**
CO3	**Demonstrate the basic concepts associated with industrial robots and driving system used in robots**	**PO1**
CO4	**Compare the kinematics and Dynamics of robots**	**PO1, PO2**
CO5	**Explain about sensors used in robots, Robot programming and applications**	**PO1**

UNIT – 1: BASICS OF AUTOMATION

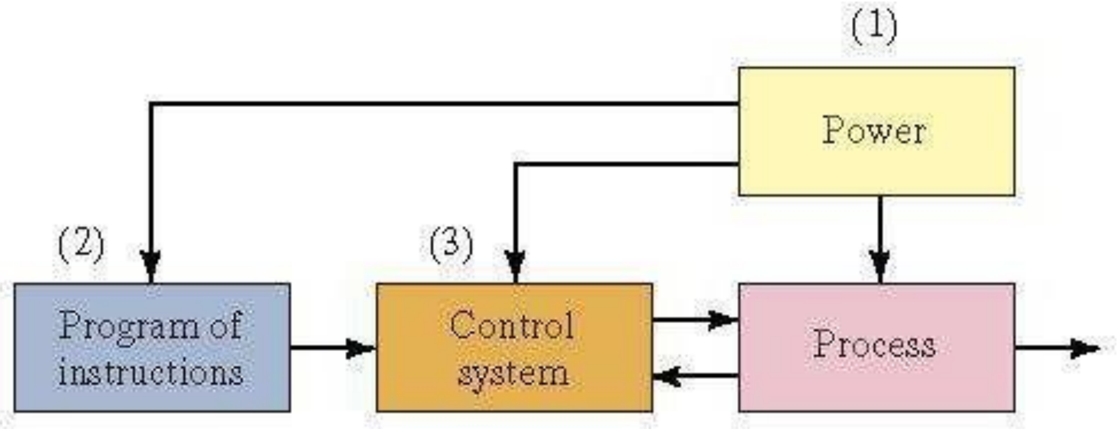
Automation

Automation and robotics are 2 closely related technologies.
Automation as a technology that is concerned with use of mechanical, electronic and computer-based systems in the operation and control of production
Example: NC machine tools and industrial robots

Automation is the use of control systems and information technologies to reduce the need for human work in the production of goods and services.

Automation is defined as **"The creation & application of technology to monitor & control the production and delivery of products and services."**

Basic elements of an automated system



An automated system consists of three elements

1.Power: To accomplish process and operate the system

2.Program of instructions: To direct the process

3.Control system: To control and accurate the instructions

1.Power:

power is required to drive the process as well as the controls. The principal source of power in automated systems is electricity. Electric power has many advantages in automated as well as nonautomated processes

- Electrical power can be readily converted to alternative energy forms: mechanical, thermal, light, acoustic, hydraulic, and pneumatic.
- Electrical power at low levels can be used to accomplish functions such as signal transmission, information processing, and data storage and communication.
- Electrical energy can be stored in long-life batteries for use in locations where an external source of electrical power is not conveniently available.

Power for the Process:

In production, the term *process* refers to the manufacturing operation that is performed on a work unit.

2.Program of instructions:

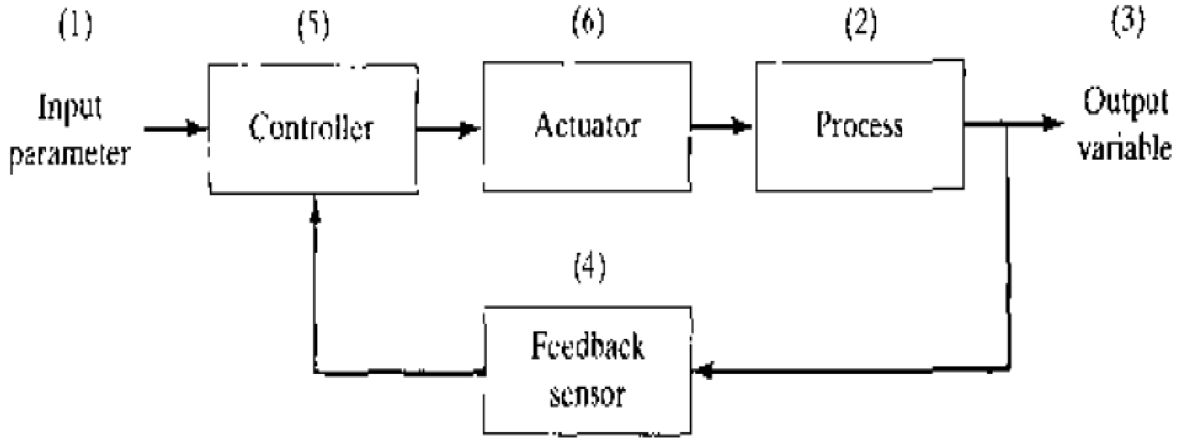
The actions performed by an automated process are defined by a program of instructions. The manufacturing operation involves low, medium, or high production. Each part or product requires one or more processing steps are performed during a work cycle. The particular processing steps for the work cycle are specified in a *work cycle program.* Work cycle programs are called *part programs* in numerical control.

3.Control system

The controls in an automated system can be either closed loop or open loop. A *closed loop control system,* also known as a *feedback control system.* is one in which the output variable is compared with an input parameter, and any difference between the two is used to drive the output into agreement with the input.

closed loop system

A closed loop control system consists of six basic elements:
(I) Input parameter,
(2) Process,
(3) Output variable,
(4) Feedback sensor,
(5) Controller,
(6) Actuator.



(I) Input parameter: The input parameter, often referred to as the *set point,* represents the desired value of the output.

(2) Process: The process is operation or function being controlled

(3) Output variable: The output variable is desired result of product

(4) Feedback sensor: A sensor is used to measure the output variable and closed loop between input and output

(5) Controller: The controller compares the output with the input and makes the required adjustment in the process

(6) Actuator: These are the hardware devices which perform the required job.

Open loop system

The open loop control system operates without feedback loop. In this system the controller operates without measuring the output variable, so no comparison is made between the actual value of the output and desired value of input.

Need of automation

1. To increase labour productivity

Automating a manufacturing operation usually increase production rate and labour productivity this means greater output per hour of labour input.

2. To reduce labour cost

For Increasing production increasing labour and labour cost has been a continuous trend in old industrialization societies. consequently, higher investment in automation has become economical justified to replace manual operations. Machines are increasingly being substituted for human labour to reduce unit product cost.

3. To improve worker safety

Automating a given operation and transferring the worker from active participation in the process to a monitoring role makes the worker safer.

4. To reduce manufacturing lead time

Automation helps to reduce the elapsed time between customer order and product delivery providing a competitive advantage to the manufacturer for future orders.

5. To reduce or eliminate routine manual and clerical tasks

An argument can be put that there is a social value in automating operations that are routine, fatiguing and possible risk some tasks. Automating such tasks improves the general level of working conditions.

6. To improve product quality

By automation the production rate is increased due to uniformity and conformity of specifications. The product quality has improved.to mitigate (making less severe or serious) the effect of labour shortages. There is general shortage of labour in many advanced nations and this has stimulated the development of automated operations as a substitute to labour.

7. To accomplish process that can't be done manually

Certain operations can't be accomplished without the aid of a machine. These processes require precision, complexity of geometry that can't be achieved manually. These processes can only be realized by the computer-controlled systems.

Types of automation

There are 3 broad classes of industrial automation.

1. Fixed automation
2. Programmable automation
3. Flexible automation

1. Fixed automation:

Fixed automation is used when the volume production is very high and it is therefore appropriate to design specialized equipment to process the product or a component very efficiently under high production rates. Example; Automobile industry where highly integrated transfer lines consisting of several dozen workstations are used to perform machining operations on engine and transmission components.

Dis-advantages:

i. Risk encountered with fixed automation is this, since the initial investment cost is high, if volume of production is turns out to be lower than anticipated (expected or predicted). Then unit cost becomes greater than anticipated

ii. The equipment is specially designed to produce one product and after that products life cycle is finished. The equipment is likely to become obsolete.

Characteristics of fixed automation

- Sequence of operations integrate to equipment
- It is difficult to automate changes in the design of product
- It is used where high volume of production required
- In these production rates is high
- In this automation no new products are processed for a given sequence of operation

2. Programmable automation

It is used when the volume production is relatively low and there are variety of products to be made

In this case the production equipment is designed to be adaptable to variations in product configuration

The adaptability feature is accomplished by operating equipment under control of a programme of instructions which has been prepared for given product.

The programme is read in to a production equipment and the equipment perform the particular sequence of processing operations to make the product. Because of programming feature and the resulting adaptability many different and unique products can be economically in small batches.

Characteristics of programmable automation

- In this equipment is to be designed
- Different types of programmes loaded in equipment in order to change sequence of operations and produce products with new configurations
- It is used for small batches of production

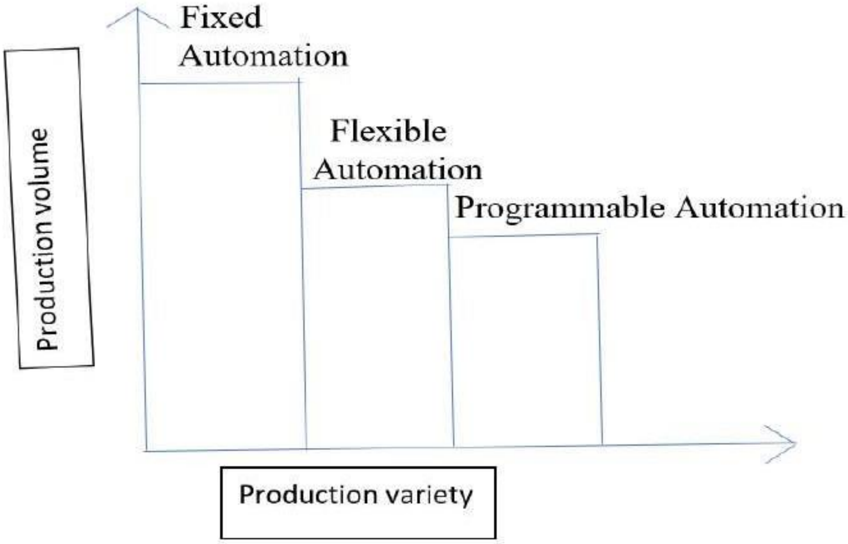
3. **Flexible automation**

   It includes FMS (Flexible Manufacturing System) and CIMS (Computer Integrated Manufacturing System).

   Flexible automated system typically consists of a series of work stations that are interconnected by a material handling and storage system. A central computer is used to control the various activities that occur in the system, routing the various parts to the appropriate stations and controlling the programmed operations at different stations

   Characteristics of flexible automation

   - It is used for mid volume production
   - It includes FMS and CIM
   - It consists of series of fluctuations which are connected by material handling and storage system.
   - Central computer is used to control the various activities programme at the different stations
   - In FMS the different products is made at same time on same manufacturing system.



SREENIVASA INSTITUTE OF TECHNOLOGY AND MANAGEMENT STUDIES

(Autonomous)

DEPARTMENT of MECHANICAL ENGINEERING

AUTOMATION AND ROBOTICS

(16MEC325A)

Advanced Automation Functions

In addition to the general automation functions there are some advanced automation functions which are used for different processes. Generally, they are used for maintaining and safety and performance of the system. Some of the advanced automation functions are

1. Safety monitoring
2. Maintenance and repair diagnostics
3. Error detection and recovery

1. Safety monitoring:

One of the main reasons of using Automation is to remove the workers form doing hazardous operations which can lead to the loss of the life. However, the workers are needed to operate the machines instead of doing that hazardous work. The automated machines are designed safely in order they should not be self-destructive. Thus, there are reasons to monitor the system safely. They are:

1. To protect the workers
2. To protect the system which is associated with it.

Safety monitoring of a system involves safety tracking of the system using the sensors. If there is a hazard then the safety monitoring system responds in either of the ways:

1. By giving an alarm sound (or)
2. By reducing the speed of the system (or)
3. By turning off the automated system.

2. Maintenance and repair diagnostics:

Modern automation systems are becoming more complex by using the maintenance and repair components. Actually, they are the components which are used for the maintaining and reducing the failures. There are three modes of operation which are used for performing this task.

a) ***Status Monitoring:*** Initially in this mode the status of the present system is estimated. It monitors over it by using the sensors or by using the parameters of the system. By using them the current status of the system is being monitored.

b) ***Failure notification:*** This mode comes under procedure when the failure occurs. It compares the present values and the previous values before and after failures.

c) ***Recommending for the repair:*** here after noting the repair, this mode takes the decision how to repair and what are the parts which are to be repaired

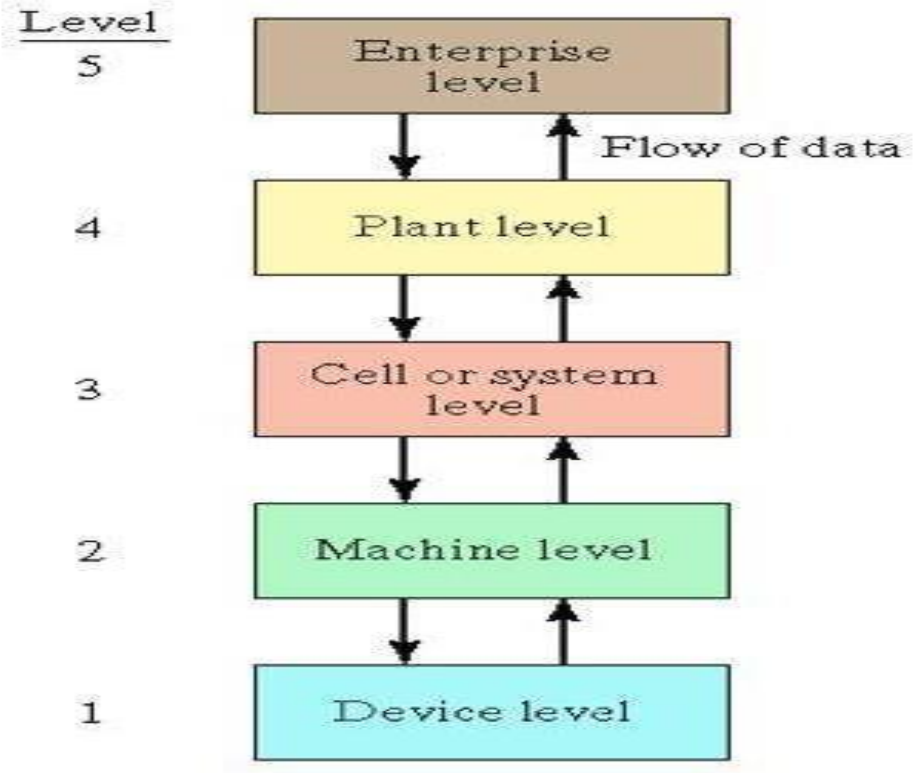
3. Error detection and recovery

The error detection can be done using the sensors. The different types of errors can be formed in the production system they are: random errors and systematic errors etc. These can be detected by using the detecting systems and the recovering system is used for recovering the errors. Thus these are the advanced functions which are necessary for making a system automate.

1. *Error detection* – functions:
    - Use the system's available sensors to determine when a deviation or malfunction has occurred
    - Correctly interpret the sensor signal
    - Classify the error
2. *Error recovery* – possible strategies:
    - Make adjustments at end of work cycle
    - Make adjustments during current work cycle
    - Stop the process to invoke corrective action
    - Stop the process and call for help

Levels of automation

The automated system can be applied to various levels of operations, normally automation with the individual machines. In production the machines itself is made up of subsystems that may be themselves automated. The various levels of automation is as follows



1.Device level:

It is the lowest level in our automation. It includes the actuators sensors and other hardware components that comprise the machine level. The devices are combined into a individual control loops to form next level of machine.

Eg: The feed back control loop for one axis of CNC machine,
Single joint of an industrial robot.

2.Machine level:

The hardware at the device level is assembled into individual machines like CNC machine tools and similar production equipment, industrial robots, material handling equipment.

3. Cell or system level:

It is the manufacturing cell or system level which operates under instruction from the plant level. It is a group of machines are workstations connected by material handling system, computer and other equipments.

4. Plant level:
   This is the factory production or system level. It receives instructions from the corporate information system and translates them into operational plants for production.
   It consists of order processing, process planning, inventory control, purchasing, material requirement planning, shop floor control and quality control.
5. Enterprise level:
   This is the highest level consisting of the corporate information system. This includes marketing and sales, accounting, design, research, aggregate planning and master production schedule

Hardware components for automation and process control

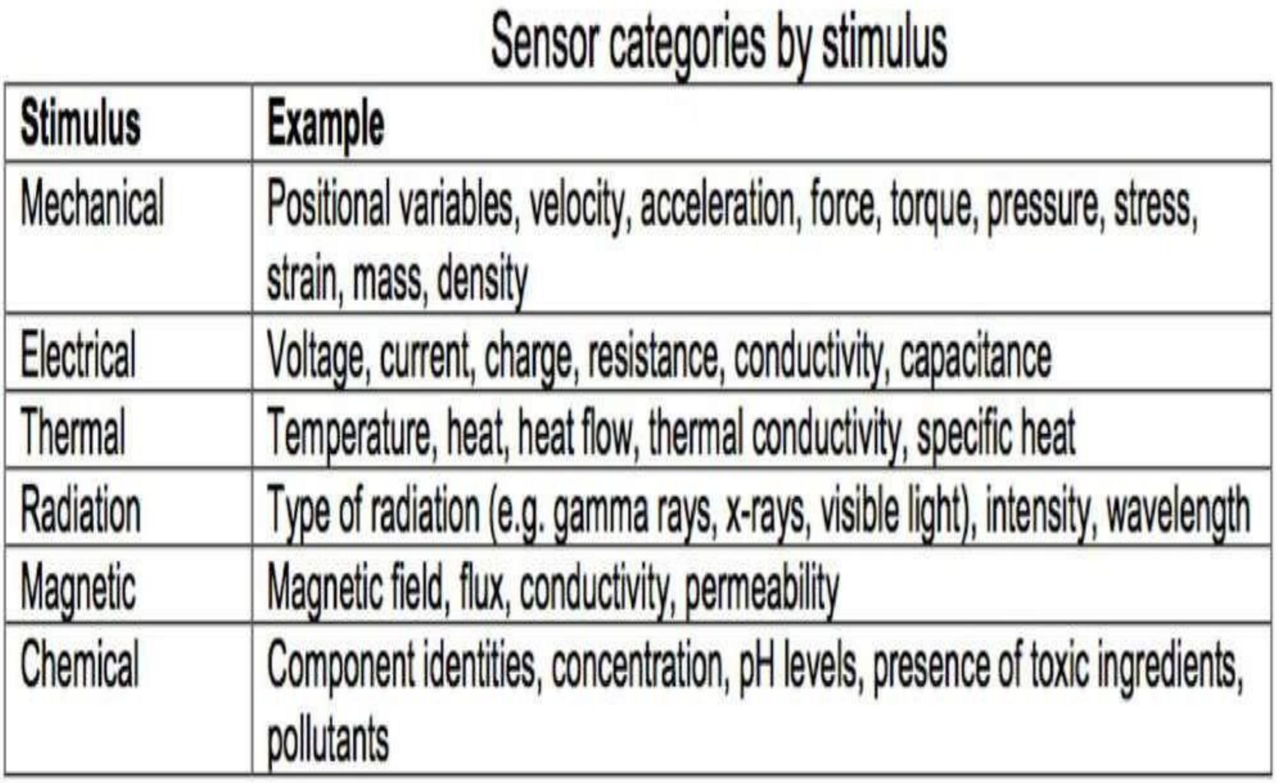
The main hard ware components for automation and control are

1. Sensors
2. Actuators
3. Analog-to-Digital Conversion
4. Digital-to-Analog Conversion

1. Sensors:

A sensor is a transducer that converts a physical stimulus from one form into a more useful form to measure the stimulus
Sensors can be classified into two basic categories:

1. *Analog (continuous)*
   Examples: thermocouple, strain gauges, potentiometers.
2. *Discrete Binary (on/off)*
   Examples: Limit switch, photoelectric switches.
   Digital (e.g., pulse counter)
   Examples: photoelectric array, optical encoder.



Sensor categories by stimulus

Stimulus	Example
Mechanical	Positional variables, velocity, acceleration, force, torque, pressure, stress, strain, mass, density
Electrical	Voltage, current, charge, resistance, conductivity, capacitance
Thermal	Temperature, heat, heat flow, thermal conductivity, specific heat
Radiation	Type of radiation (e.g. gamma rays, x-rays, visible light), intensity, wavelength
Magnetic	Magnetic field, flux, conductivity, permeability
Chemical	Component identities, concentration, pH levels, presence of toxic ingredients, pollutants

2. Actuators:

Actuators are hardware devices that convert a controller command signal into a change in a physical parameter.

The change is usually mechanical (e.g., position or velocity).

An actuator is also a transducer because it changes one type of physical quantity into some alternative form (e.g. electric current to rotational speed of electric motor).

Types of Actuators

1. *Electrical actuators*

Electric motors (linear or rotational)

- **DC servomotors**

  DC motors are widely used:

  ♦ Convenience of using direct current.

E.g. motors in automobiles.

- Linear Torque-Speed relationship.
- One special type of DC motors is Servomotors.
- A feedback back loop is used to control speed.

- **AC motors**

Mostly used in industry.

Advantages: Higher power supply
Ease of maintenance

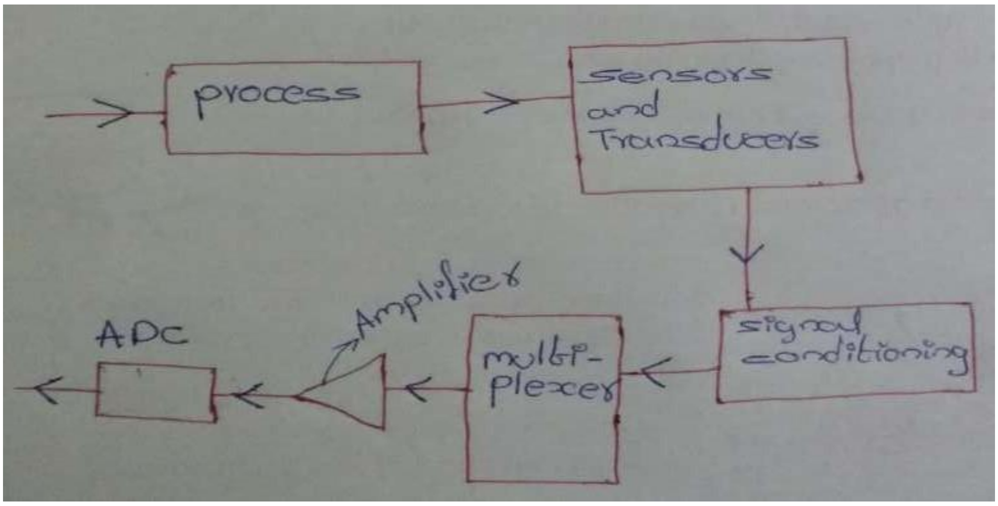
Two types: Induction motor
Synchronous motor

- **Stepper motors**

Provides rotation in the form of discrete angular displacement (step angles).
Each step angle is actuated by a discrete electrical pulse.
These Are used in open loop control systems.

2. *Hydraulic actuators:* Use hydraulic fluid as the driving force
3. *Pneumatic actuators:* Use compressed air as the driving force

3. Analog-to-Digital Conversion



The continuous analog signals from the process must be converted into digital values. The procedure for converting an analog signal from the process into digital form consist of following steps

- **Sensor and transducer**

This is measuring device that generates the analog signal

- **Signal conditioning**

The continuous analog signal from the transducer may require conditioning to render (provide or give) it into more suitable form

Common signal conditioning includes

- Filtering to remove random noise
- Conversion from one signal to another

- **Multiplexer**

The multiplexer is a switching device connected in series with each input channel from the process. It is used to share the analog to digital converter among the input channels.

- **Amplifier**

Amplifier are used to scale the incoming signal up or down to be compatible with the range of the analog to digital converted.

- **ADC (Analog to Digital Converter)**

As the name indicates the function of ADC is to convert the incoming analog signal into its digital counterpart.

4. Digital-to-Analog Conversion

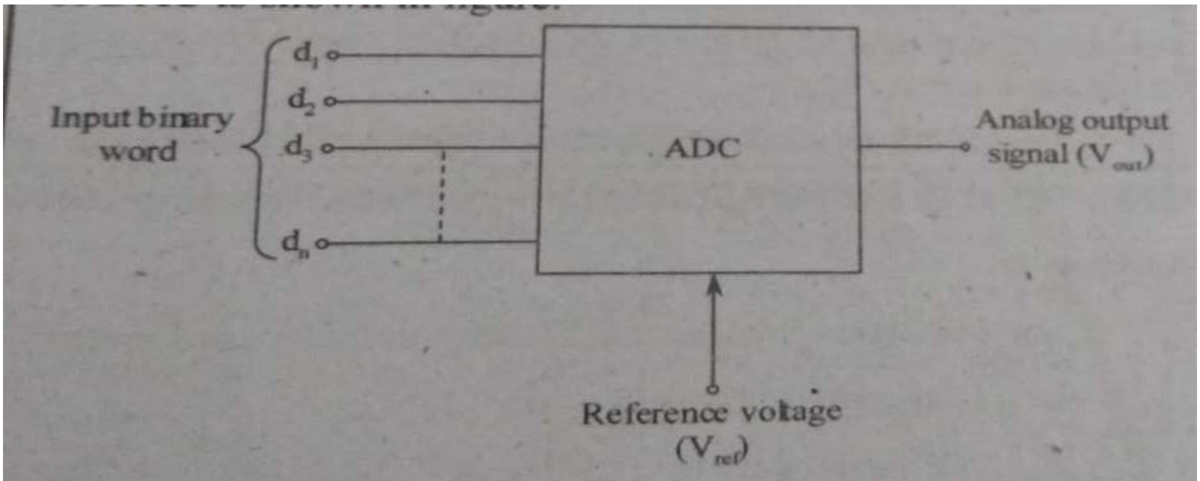


Figure: Functional Block Diagram of Digital to Analog Converter

A simple form of DAC (Digital-to-Analog Conversion) using a summing amplifier to form the weighted sum of all the non-zero bits in the input word. The reference voltage is connected to the resistor by means of electronic switches which respond to binary one

The values of input resistances depend on which bit in the word a switch is responding to the value of resistor for successive bits from the LSB (Limit Switch Box) being halved. Hence the sum of voltage is a weighted sum of the digits in the work, such a system is referred as a weighted resistor network. The limitations of the weighted resistor network is that accurate resistance have to be used for each of the resistors and it is difficult to obtain wide range of such resistors. This form of DAC tends to be limited to 4-bit conversions.

Automated storage and retrieval system

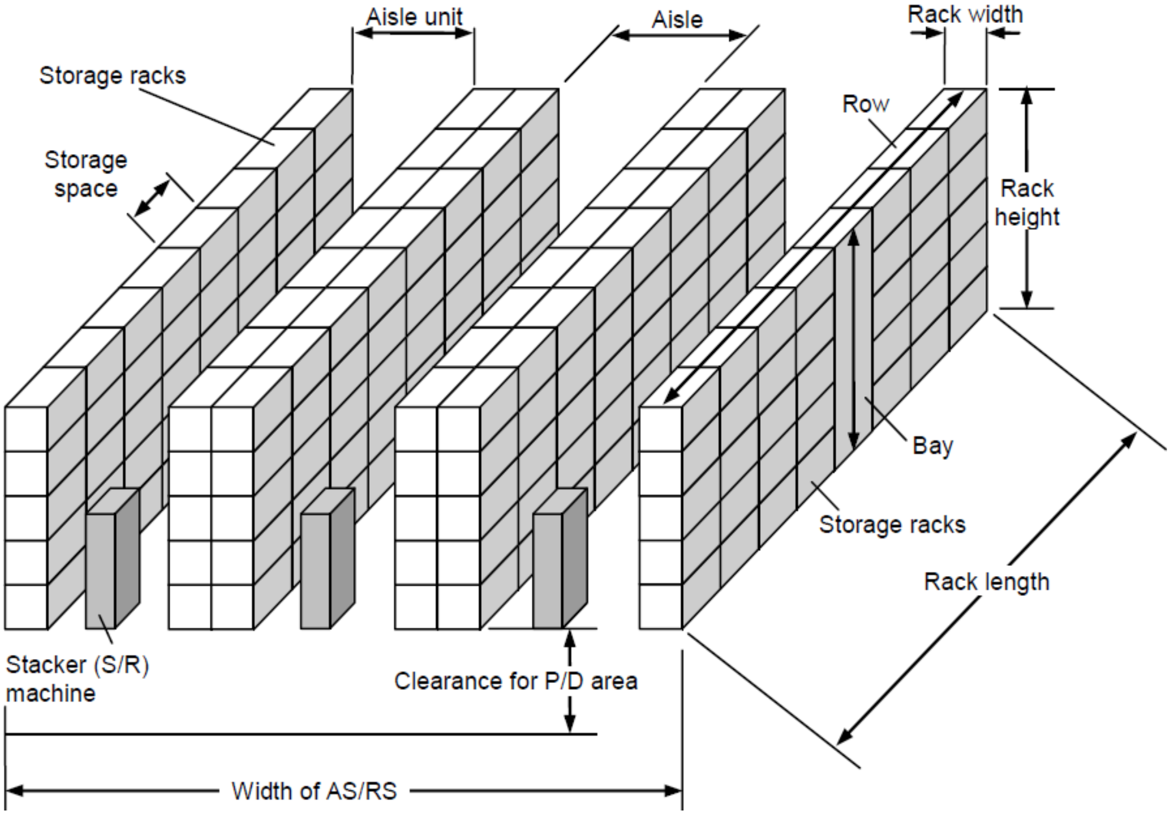
An automated storage/retrieval system (AS/RS) can be defined as a storage system under which a defined degree of automation is to be implemented to ensure precision accuracy and speed in performing storage and retrieval operations. These automated storage and mechanized systems eliminate human intervention in performing basic sets of operations.

Objectives for Installing AS/RS

1. Increasing the storage capacity

2. Increasing the stock rotation
3. Utilization of maximum floor space
4. Recovering the space for manufacturing facilities
5. Customer service to be improved

AS (Automated Storage) and RS (Retrieval System) COMPONENTS AND TERMINOLOGY



Storage Space

It is the three-dimensional space in the storage racks used to store a single load unit of material.

Storage Racks

The automated storage and retrieval system contain several rows of storage racks for storing the material items. The storage structure of automated storage and retrieval system is much taller (can be as tall as 30 meters) than that of the convention al storage and retrieval systems.

Bay

It is the height of the storage rack from floor to the ceiling.

Row

It is a series of bays placed side by side.

Aisle

It is the spacing between two rows for the machine operations of AS/RS.

Aisle Unit

It encompasses aisle space and racks adjacent to an aisle.

Storage Structure

It is the rack framework, made of fabricated steel that supports the loads contained in the AS/RS and is used to store inventory items.

Storage/Retrieval Machine

It is used to move items in and out of inventory. An S/R machine is capable of both horizontal and vertical movement. A rail system along the floor guides the machine and a parallel rail at the top of the storage structure is used to maintain its alignment.

- The pallet is moved from P and D station to the storage rack by storage and retrieval cranes.
- Whenever there is a request for the item to the central computer, the computer searches its memory for the storage location and directs the stacker crane to retrieve the pallet.
- An S/R machine is capable of both horizontal and vertical movement. A rail system along the floor guides the machine and a parallel rail at the top (up to 30m) of the storage structure is used to maintain its alignment.

Material transport system and equipments

Material-Handling System

- A material-handling system can be simply defined as an integrated system involving such activities as handling, storing, and controlling of materials.

- The primary objective of using a material handling system is to ensure that the material in the right amount is safely delivered to the desired destination at the right time and at minimum cost.
- The material handling system is properly designed not only to ensure the minimum cost and compatibility with other manufacturing equipment but also to meet safety concerns.

Principles of Material Handling

The 10 principles of material handling are listed and explained as follows:

Planning Principle: All material handling should be the result of a deliberate plan where the needs, performance objectives, and functional specification of the proposed methods are completely defined at the outset.

Standardization Principle: Material handling methods, equipment, controls, and software should be standardized within the limits of achieving overall performance objectives and without sacrificing needed flexibility, modularity, and throughput.

Work Principle: Material handling work should be minimized without sacrificing productivity or the level of service required of the operation.

Ergonomic Principle: Human capabilities and limitations must be recognized and respected in the design of material handling tasks and equipment to ensure safe and effective operations.

Unit Load Principle: Unit loads shall be appropriately sized and configured in a way which achieves the material flow and inventory objectives at each stage in the supply chain.

Space Utilization Principle: Effective and efficient use must be made of all available space.

System Principle: Material movement and storage activities should be fully integrated to form a coordinated, operational system that spans receiving, inspection, storage, production, assembly, packaging, unitizing, order selection, shipping, transportation, and the handling of returns.

Automation Principle: Material handling operations should be mechanized and/or automated where feasible to improve operational efficiency, increase responsiveness, improve consistency and predictability. decrease operating costs, and eliminate repetitive or potentially unsafe manual labour.

Environmental Principle: Environmental impact and energy consumption should be considered as criteria when designing or selecting alternative equipment and material handling systems.

Life Cycle Cost Principle: A thorough economic analysis should account for the entire life cycle of all material handling equipment and resulting systems.

Types of Material handling equipment

A great variety of material handling equipment is available commercially. Material handling equipment includes:

- Material Transport Equipment
- Storage systems
- Unitizing equipment, and
- Identification and tracking systems

Material Transport Equipment

Material transport includes equipment that is used to move materials inside a factory, warehouse. or other facility. This equipment can be divided into the following five categories:

Industrial Trucks: Industrial trucks divide into two types: non-powered and powered. Non-powered trucks are platforms or containers with wheels that are pushed or pulled by human workers to move materials. Powered industrial trucks are steered by human workers. They provide mechanized movement of materials.

Fort lift truck

Forklift truck is a powered industrial truck used to lift and transport materials. A forklift hydraulics are controlled with either levers directly manipulating the hydraulic valves or by electrically controlled actuators, using small “finger” levers for control. It is available in many variations and load capacities.

Advantages:

1. It is useful for lifting heavy materials like heavy component of a machine or a finished product which is heavily weighted.
2. It has mobility or movement

Pallet truck

Advantages:

1. Quick lift pumps design.
2. Ultra-urethane wheels and sealed dual-precision ball bearings require less than 75 lbs pulling force at full capacity.
3. Hydraulic pump includes overload and upper limit relief valve.
4. Include two steering wheels and two front load rollers.
5. Steering wheels include bearing dust covers, providing longer life.

Automated Guided Vehicles (AGVs): AGVs are battery-powered, automatically steered vehicles that follow defined pathways in the floor. The pathways are unobtrusive. AGVs are used to move unit loads between load and unload stations in the facility. Routing variations are possible, meaning that different loads move between different stations. They are usually interfaced with other systems to achieve the full benefits of integrated automation.

- An automated guided vehicle system is a battery-powered driver-less vehicle with programming capabilities for destination, path selection, and positioning.
- The AGVS belongs to a class of highly flexible, intelligent, and versatile material handling systems used to transport materials from various loading locations to various unloading locations throughout the facility.

The type of AGVSs

1. AGVS towing vehicles: usually, towing applications involve the bulk movement of product into and out of warehouse areas. Towing vehicles are better used for large volumes with long moving distances of 1000 ft or more.

2. AGVS unit load transporters: are equipped with decks that permit transportation of an individual unit load on board the vehicle. The deck can be powered or non-powered roller, chain or belt deck, lift-and-lower type, or custom deck with multiple compartments. Unit load transporters are often equipped with automatic load transfer and normally used in warehousing and distribution systems where the guide path lengths are relatively short but the volumes are high.

3. AGVS pallet trucks: are designed to lift, makeover, and transport palletized loads. The vehicle is used for picking up and dropping off loads from and to floor level, thus eliminating the need for fixed load stands. It can be loaded and unloaded in automatically or manually. For load transportation, the vehicle normally proceeds along the path to a specific storage area destination, pulls off onto a spur, lowers the pallet forks to the floor, pulls from the pallet, and then automatically returns empty to the loading area.

4. AGVS forklift trucks: has the ability to pick up and drop off palletized loads both at floor level and on stands, and pickup height can be different from the drop-off height. The vehicles can position its forks at any height so that conveyors or load stands with different height in the material handling system can all be served. It is one of the most expensive AGVS types, so they are applied only in systems where full automation is required. A system with these vehicles requires a more intricate path layout and a method for accurately positioning the loads on the floor or on stands. It also requires greater discipline than other systems.

5. AGVS light-load transporters: They are used to handle small, light parts over a moderate distance and to distribute the parts between storage and number of workstations. They are designed to operate in areas with limited space.

6. AGVS assembly-line vehicles: are adaptation of the light-load transporter for applications involving serial assembly processes. The guided vehicle carries major subassemblies such motors, transmissions, or even automobiles. As the vehicle moves from one station to the next, succeeding assembly operations are performed. The major advantage of the AGVS assembly line is lower expense and ease of installation compared with hard assembly lines.

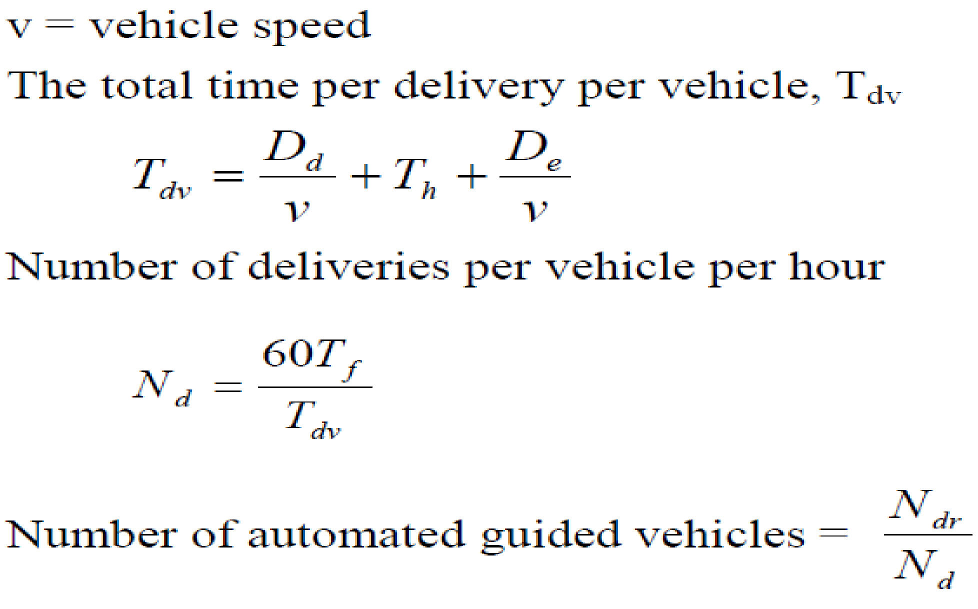
The line can easily be changed by adjusting the guide path if necessary and by reprogramming.

2. *Automatic loading and unloading* can be accomplished in many different ways:

- Automatic couple and uncouple
- Powered roller, belt, and chain
- Powered lift and lower device

- Powered push or pull device
- Number of AGV Required

A simple analysis to determine the number of vehicles:
Dd = total average loaded travel distance
De = total average empty travel distance
Ndr = number of deliveries required per hour
Th = loading and unloading time
Tf = traffic factor that accounts for blocking of vehicles and waiting of vehicles in line and at intersections. If there is no congestion, the traffic factor is 1. Whoever, when more vehicles are involved, the traffic factor value will certainly be less than 1. Normally, Tf lies between 0.85 to 1.
v = vehicle speed
The total time per delivery per vehicle, Tdv



v = vehicle speed

The total time per delivery per vehicle, T_{dv}

$$T_{dv} = \frac{D_d}{v} + T_h + \frac{D_e}{v}$$

Number of deliveries per vehicle per hour

$$N_d = \frac{60T_f}{T_{dv}}$$

$$\text{Number of automated guided vehicles} = \frac{N_{dr}}{N_d}$$

Monorails & Other Rail-Guided Vehicles: These are self-propelled vehicles that ride on a fixed rail system that is either on the floor or suspended from the ceiling. The vehicles operate independently and are usually driven by electric motors that pick up power from an electrified rail. Like AGVs, routing variations are possible in rail-guided vehicle systems.

Conveyors: Conveyors constitute a large family of material transport equipment that are designed to move materials over fixed paths, generally in large quantities or volumes. Examples include-roller, belt, and tow-line conveyors. Conveyors can be either powered or non-powered. Powered conveyors are distinguished from other types of powered material transport equipment in that the mechanical drive system is built into the fixed path. Non-powered conveyors are activated either by human workers or by gravity.

Cranes & Hoists: These are handling devices for lifting, lowering, and transporting materials, often as very heavy loads. Hoists accomplish vertical lifting; both manually operated and powered types are available. Cranes provide horizontal travel and generally include one or more hoists.

Cranes

➢ Storage systems

Storage methods and equipment can be classified as follows:
Bulk storage: This consists of simply storing materials in an open floor area, generally in pallet loads or other containers. It requires little or no storage equipment.

Rack systems: Rack systems are structural frames designed to stack unit loads vertically, thus increasing the vertical storage efficiency compared to bulk storage.

Shelving and bins: Steel shelving comes in standard widths, depths, and heights to serve a variety of storage requirements, Shelves can include bins, which are containers for loose items.

Drawer storage: This storage medium is more costly than shelves, but it is more convenient. Finding items stored in shelves can be difficult if the shelf level is too high or too low or too deep. Drawers compensate for this by pulling out to reveal their entire contents. Drawer storage is generally used for tools, hardware, and other small items.

Automated storage systems: Automated and semi-automated systems are available to deposit and withdraw items into and from the storage compartments. There are two basic types: (1) automated storage/retrieval systems, consisting of rack and shelf systems that are accessed by an automated or mechanized crane, and (2) carousel systems that rotate storage bins past a stationary load/unload station.

➢ Unitizing equipment

The term unitizing equipment refers to (1) containers used to keep individual items during handling and (2) equipment used to load and package the containers.
Containers for holding individual items: Containers include ***pallets, boxes, baskets, drums, buckets, and barrels*.** Although seemingly mundane, this type of equipment is very important for moving materials efficiently as a unit load,

rather than as individual items. A given facility must often standardize on a specific type and size of the container if it utilizes automatic transport and/or storage equipment to handle the loads.

Loading and packing equipment: The second category of unitizing equipment, loading and packaging equipment, includes ***Palletizer***, designed to automatically load cartons onto pallets and shrink-wrap plastic film around them for shipping. Other wrapping and packaging machines are also included in this equipment category, as are ***Depalletizers***, designed to unload cartons from pallets.

➢ Identification and tracking systems

- Material handling must include a means of keeping track of the materials being moved or stored. This is normally done by appending some kind of label to the item, carton, or unit load that uniquely distinguishes it.
- The most common label used today consists of ***bar codes*** that can be read quickly and automatically by bar code readers. This is the same basic technology employed by grocery stores and retail merchandisers.
- Other types of labels include ***magnetic stripes*** and ***radio frequency tags*** that are broadly capable of encoding more data than bar codes.

Automatic Identification Technology

INTRODUCTION:

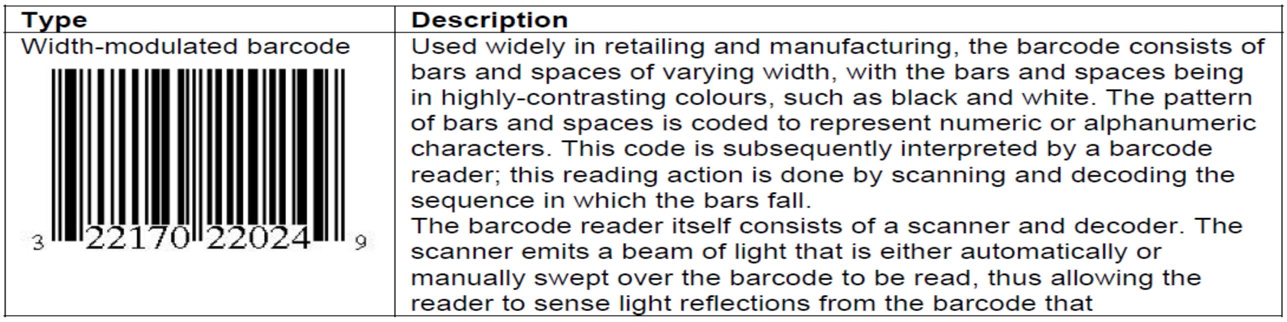
Automatic Identification Technology (Auto ID) that stores real time data. It is a series of vertical bars or a graphical bar pattern which can, (depending on the width and pattern) encode numbers and letters in a format which can easily be retrieved and interpreted by a bar code reader.
Barcoding is a computer aided process of generating codified information, which is subsequently printed on a predefined stationary, invariably on a self-adhesive label for several later applications.

WHAT IS BARCODE

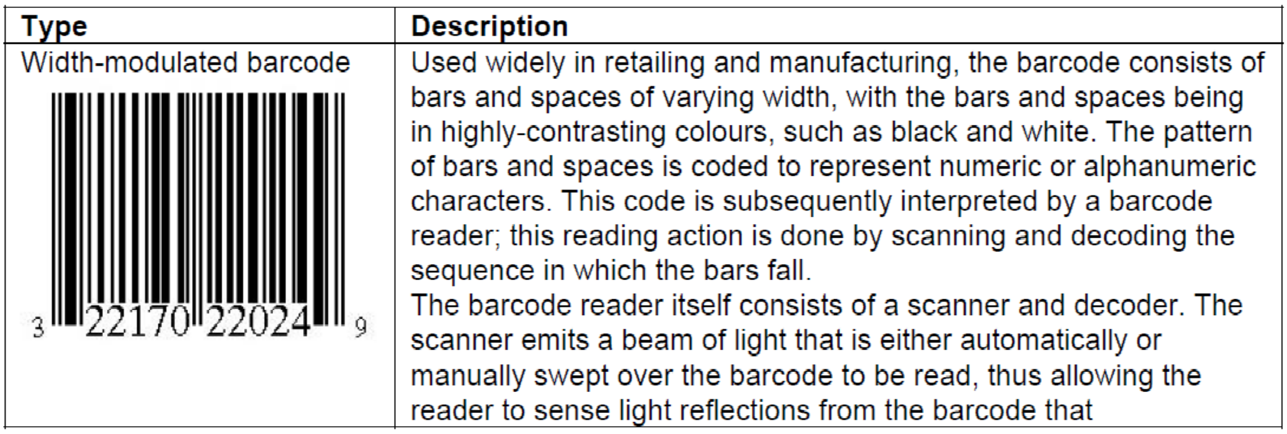
Barcode are a pattern of bars and spaces of varying width that represent digits, letters or other punctuation symbols to identify an item or object.

Barcode Technology

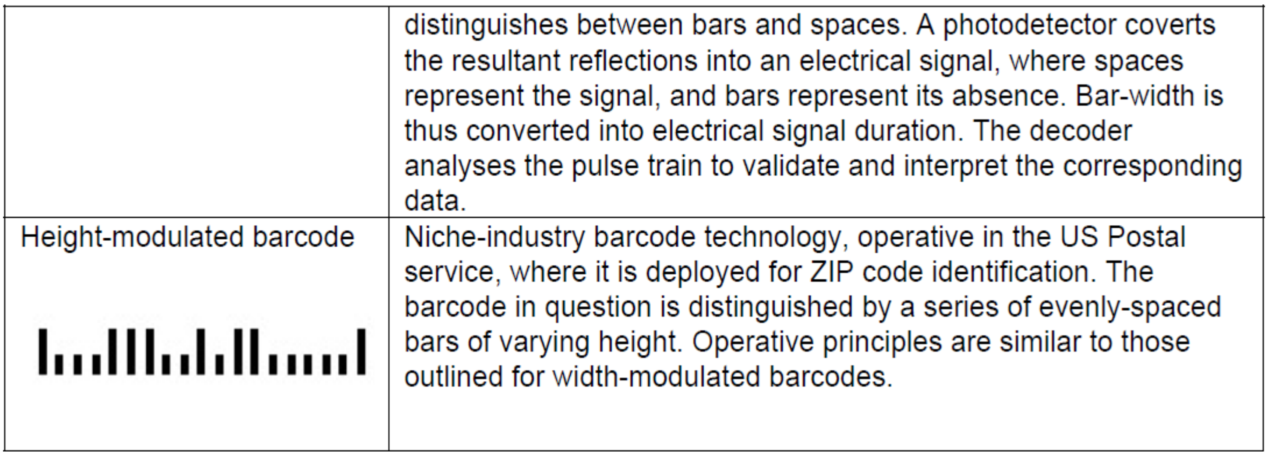
There are two basic types of barcode technology, linear and two-dimensional Linear or one-dimensional bar code technology is the most widely used AIDC technique. There are two forms of linear barcode: width-modulated barcodes, and height-modulated barcodes. These are outlined in some detail in Table



Type	Description
Width-modulated barcode 3 22170 22024 9	Used widely in retailing and manufacturing, the barcode consists of bars and spaces of varying width, with the bars and spaces being in highly-contrasting colours, such as black and white. The pattern of bars and spaces is coded to represent numeric or alphanumeric characters. This code is subsequently interpreted by a barcode reader; this reading action is done by scanning and decoding the sequence in which the bars fall. The barcode reader itself consists of a scanner and decoder. The scanner emits a beam of light that is either automatically or manually swept over the barcode to be read, thus allowing the reader to sense light reflections from the barcode that



Type	Description
Width-modulated barcode 3 22170 22024 9	Used widely in retailing and manufacturing, the barcode consists of bars and spaces of varying width, with the bars and spaces being in highly-contrasting colours, such as black and white. The pattern of bars and spaces is coded to represent numeric or alphanumeric characters. This code is subsequently interpreted by a barcode reader; this reading action is done by scanning and decoding the sequence in which the bars fall. The barcode reader itself consists of a scanner and decoder. The scanner emits a beam of light that is either automatically or manually swept over the barcode to be read, thus allowing the reader to sense light reflections from the barcode that



	distinguishes between bars and spaces. A photodetector coverts the resultant reflections into an electrical signal, where spaces represent the signal, and bars represent its absence. Bar-width is thus converted into electrical signal duration. The decoder analyses the pulse train to validate and interpret the corresponding data.
Height-modulated barcode	Niche-industry barcode technology, operative in the US Postal service, where it is deployed for ZIP code identification. The barcode in question is distinguished by a series of evenly-spaced bars of varying height. Operative principles are similar to those outlined for width-modulated barcodes.

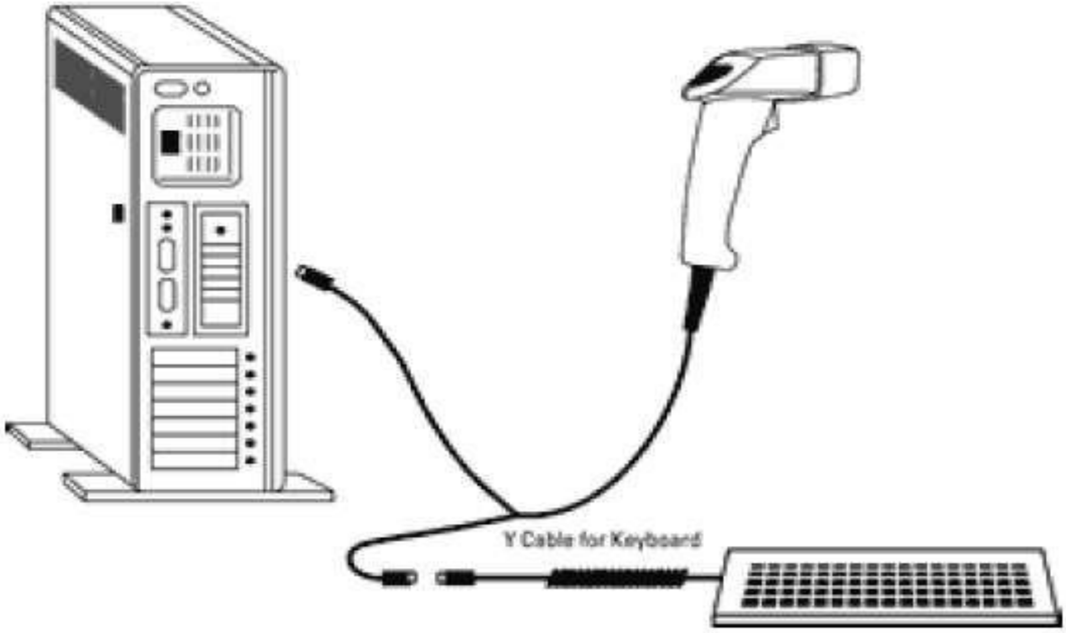
USE OF BARCODE SCANNERS

Barcode scanner is a device used to extract information optically from the barcode. Barcode scanners are of various types. These may be hand –held or fixed type. Barcode symbols consist of series of vertical dark bars separated by light spaces. When illuminated reflected light is detected by electro optical sensor. The intensity of reflected light from the dark bars is less than that of spaces (white lines). Reflected light is converted into electronical voltage signals.

The decoder converts this data into the character data representation of the symbol’s code.

Connecting the Scanner –Keyboard Wedge

1.Turn off power before connecting the scanner
2.Remove the keyboard connector from the PC.
3.Connect the cable’s modular connector to the scanner.
4.Connect the male connector to the keyboard port in the PC and the female connector to the keyboard cable. You may need to use the Din/Mini Din adapter (included) to match your keyboard connectors.



Connecting the Scanner

WORKING OF BARCODE SYSTEM

Barcode technology works in the same way as a keyboard. As pressing a key sends a signal containing a character code to the computer, reading a barcode results in the same kind of signals being sent to the processor. The barcode, in effect, acts as a unique control number, which is associated with a record giving appropriate details of individual items. While scanning, the light is reflected from the barcode and the pickup optical device receives less light from the dark bars than from the spaces between them. The signals received through this process are then converted into a form, which can be recognized by the computer

ADVANTAGES OF USING BARODE TECHNOLOGY

a. It Increased accuracy of data input (error free)
b. It Improves efficiency of the staff and quality of services;
c. Rapid access to total production costs
d. It Increased user satisfaction and hence improves the image of the library;
e. Reliable statistics for Management Information System (MIS) and management
f. Real time data collection

Computerised circulation system and application of barcode

Before discussing of barcode-based circulation system, it is necessary to study the difficulties experienced in the manual system so that the usefulness of barcode technology can be appreciated:

Some of the difficulties in the manual system area:

1. It is difficult to know the status of a particular book.
2. Providing reservation for books is a tedious job.
3. It is cumbersome to ascertain that to whom a particular book has been issued.
4.To provide a clearance certificate to a particular reader is quite difficult since the counter assistant will have to verify borrower’s record and other documents to ascertain whether a particular book is pending against the borrower or not.

Use of barcode system for Security Check

The barcoded identity card will also perform the security check at the gate and allow only authorized persons to enter in libraries. This is the checking system when a user leaves the library with the issued document. For this purpose, barcode technology can be effectively used and a terminal can be installed on the gate. Since charging/discharging is done online, the whole database is automatically updated. When borrower leaves the library, accession number of the document carried by the user will again be scanned at the gate. In case of issued document, the computer will approve the exit. But, in case, someone is carrying a document that has not been issued, the computer will give an alarm and a message to the immediate effect.

Identification of membership at the gate

We know very well that in libraries entry is restricted to their members only. Thus, a person is deputed on the gate as gateman or security guard to check identity cards of each person entering the library. If the members are provided barcoded identity cards, then this checking becomes very easy. A barcode scanner is installed at the gate of the library and every person entering the library has to place his/her identity card on the scanner. If the person is not a member of the library, the computer will give the alarm and thus restrict the entry and the identification of unauthorized entry will be made.

Use of barcode system for monitoring Attendance

The barcode technology could be used for monitoring the attendance of the users. Under this process, the identity cards of the user have to be barcoded with their library codes and a barcode scanner is installed at the gate of the organization. Every user has to get his/her identity card scanned at the gate while entering. The system will maintain the statistics of users of the library. Under the manual system most of the libraries maintain gate register wherein members are requested to enter his/her details and mark their signature as a proof of their visit to the library. It is time consuming and users show indifference towards entering their particulars. When users are provided with barcoded identity cards, it is possible to overcome all these difficulties. Thus, user statistics are useful for various purposes, particularly for improvement in library services and control

Issue of No Dues Certificate

No dues certificate is issued when any member leaves the organisation/institution and his/her membership is cancelled and the library issues no dues certificate. This process is time consuming and error prone in a manual system. In an automated system using barcode technology the member surrenders his/her identity card and the counter staff scan it. The automation package will search the database for any document issued in his/her name. If nothing is due, no dues certificate will be printed

SREENIVASA INSTITUTE OF TECHNOLOGY AND MANAGEMENT STUDIES

(Autonomous)

DEPARTMENT of MECHANICAL ENGINEERING

AUTOMATION AND ROBOTICS

(16MEC325A)

UNIT – 2: AUTOMATED FLOW LINES AND LINE BALANCING

Automated flow line:

It consists of several machines or workstations which are linked together by work handling devices that transfer parts between the stations is called automated flow.

The objective of use of flow line automation are: -

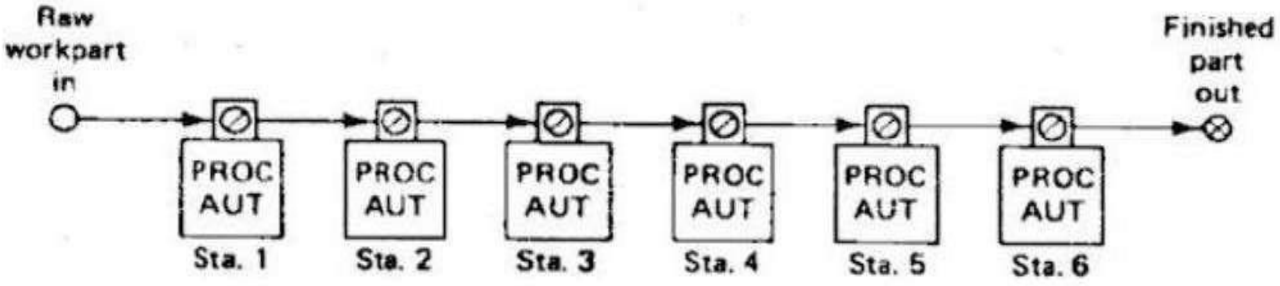
1) To reduce Labour cost
2) To increase the production rate
3) To reduce work in progress
4) To minimise distance moved between operations
5) To achieve specialization of operations.
6) To achieve integration of operations.

Types of automated flow line:-

It is basically divided into two types depending upon the forms in which the work flow can take place as.

1) In – Line type:-

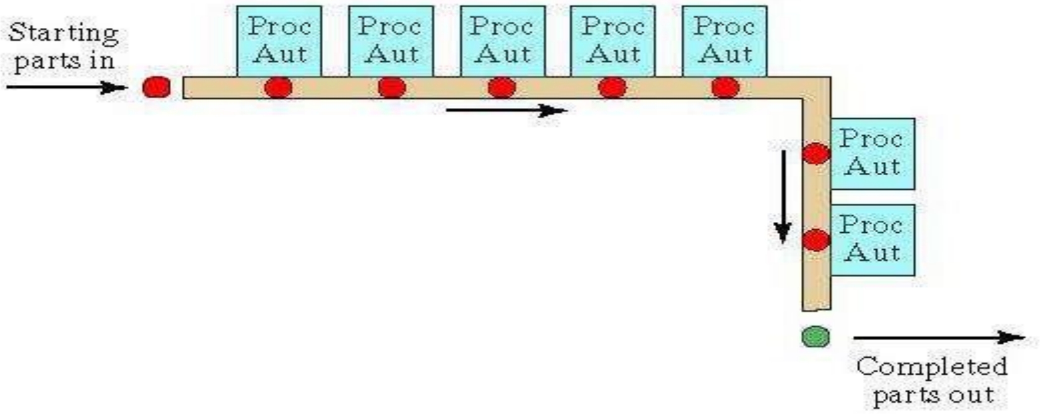
- It consists of sequence workstations in a more –or- less straight-line arrangement as shown in figure.
- The transfer of work parts occurs automatically and the workstations carry out their specialized functions automatically.
- A raw work part enters one end of the line and the processing steps are performed sequentially as the part moves from one station to the next. It is possible to incorporate buffer storage zones into the flow line, either al a single location or between every workstation. It is also possible to include inspection stations in the line to automatically perform intermediate checks on the quality of the work parts.



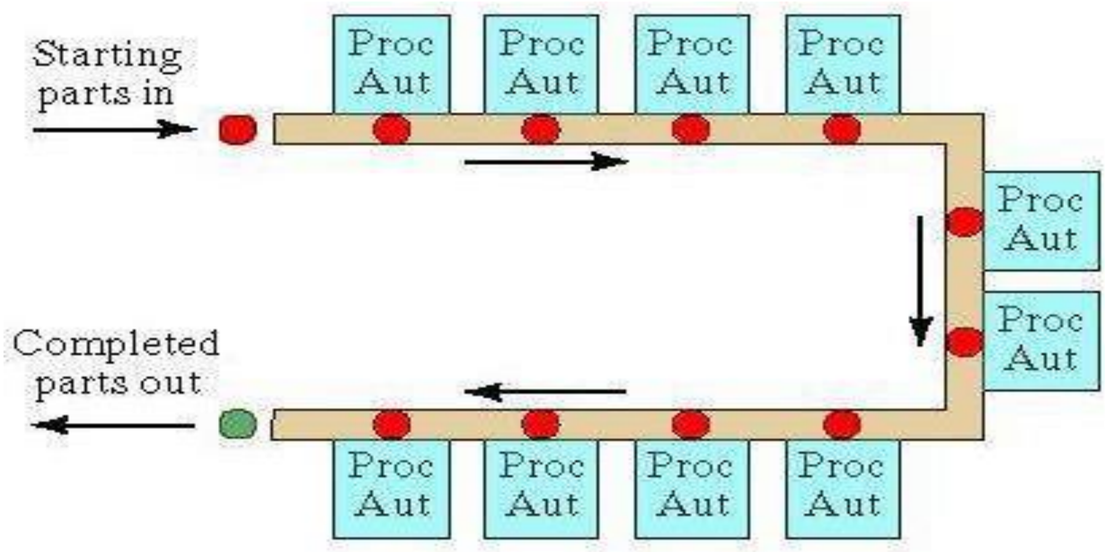
Example: Metal cutting operation (machining of engine heads, engine blocks at different work stations to obtain final shape) with in-line transfer mechanism.

2) Segmented In-Line Type

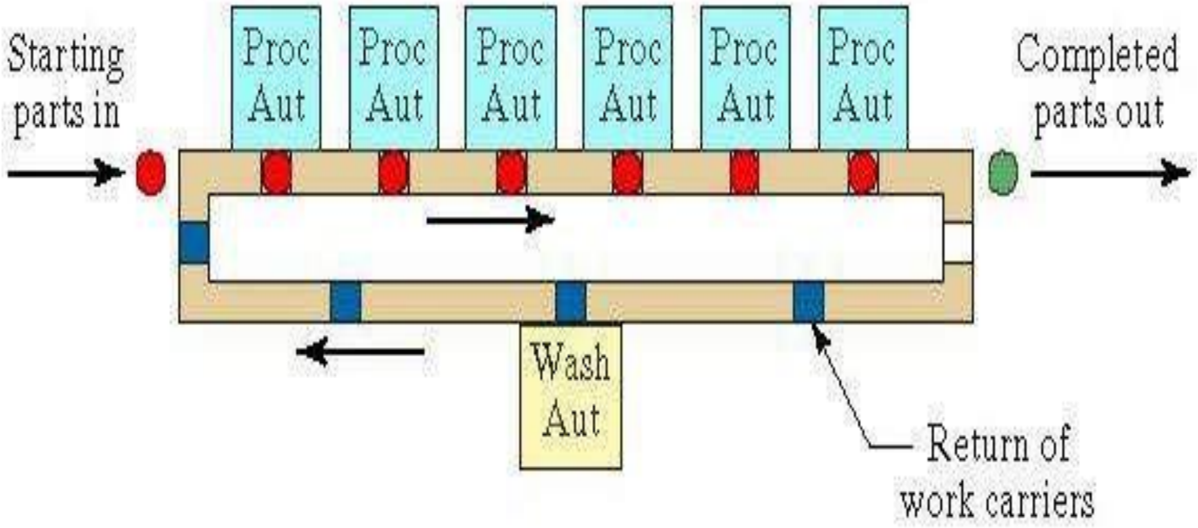
- The segmented *in-line* configuration consists of two or more workstations arranged in a straight-line, perpendicular to each other with L-Shaped or U-shaped or Rectangular shaped as shown in figure.
- The flow of work can take a few 90° turns, either for workpieces reorientation, factory layout limitations, or other reasons, and still qualify as a straight-line configuration.



L-shaped configuration



U-shaped configuration

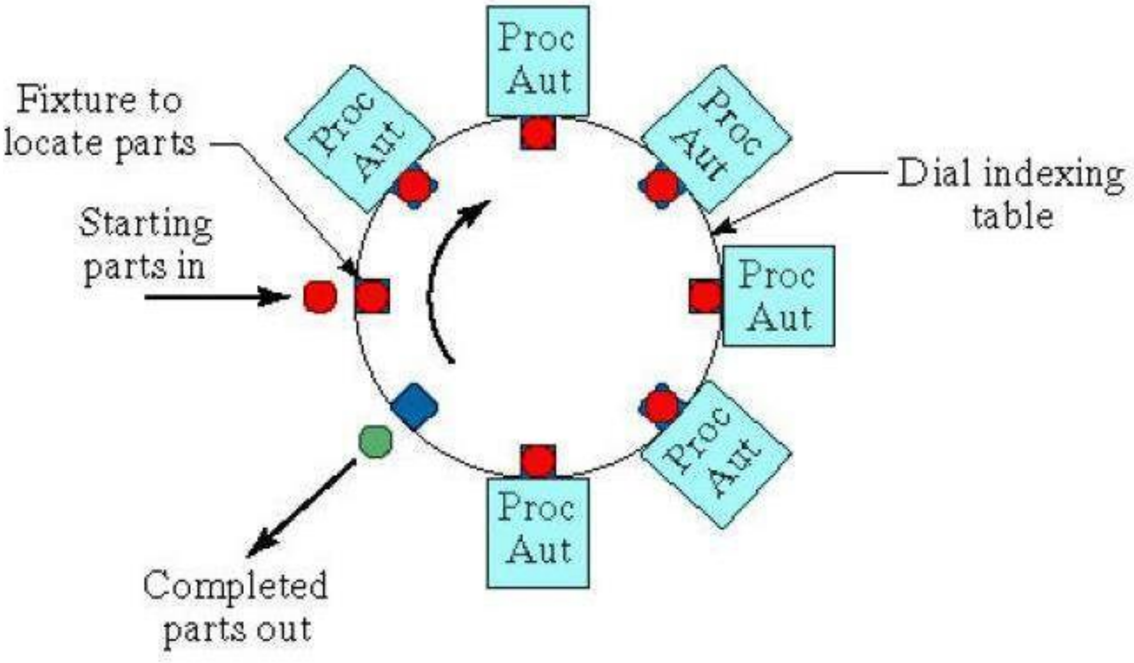


Rectangular-shaped configuration

3) Rotary type

In the *rotary* configuration, the work parts are indexed around a circular table or dial. The workstations are stationary and usually located around the outside periphery of the dial.

This type of equipment is often referred to as an *indexing machine* or *dial index machine* and the configuration is shown in Figure



Rotary configuration

Part Transfer Methods or Methods of Work part Transport

The transfer mechanism of the automated flow line must not only move the partially completed workparts or assemblies between adjacent stations, it must also orient and locate the parts in the correct position for processing at each station. The general methods of transporting workpieces on flow lines can be classified into the following three categories:

1. Continuous transfer
2. Intermittent or synchronous transfer
3. Asynchronous or power-and-free transfer

1) Continuous transfer

With the continuous method of transfer, the workparts are moved continuously at Constant speed. This requires the workheads to move during processing in order to maintain continuous registration with the workpart.

2) Intermittent transfer

As the name suggests, in this method the workpieces are transported with an intermittent or discontinuous motion. The workstations are fixed in position and the parts are moved between stations and then registered at the proper locations for processing. All workparts are transported at the same time and, for this reason, the term "synchronous transfer system" is also used to describe this method of workpart transport.

3) Asynchronous transfer

This system of transfer, also referred to as a "power-and-free system," allows each workpart to move to the next station when processing at the current station has been completed. Each part moves independently of other parts. Hence, some parts are being processed on the line at the same time that others are being transported between stations. Asynchronous transfer systems offer the opportunity for greater flexibility than do the other two systems, and this flexibility can be a great advantage in certain circumstances.

Workpart Transfer Mechanisms

The function of transfer mechanism is not only to move the workstations or assemblies to adjacent workstations, but also to orient and locate the parts in correct location for processing, at corresponding workstations.

These mechanisms can be grouped into two types:

1. Linear Transfer Mechanism
2. Rotary Transfer Mechanism

1. Linear Transfer Mechanism:

This mechanism is used to impart a linear motion to the workpart in automated production systems.

Following linear mechanisms are mostly employed for linear transfer of workpart.

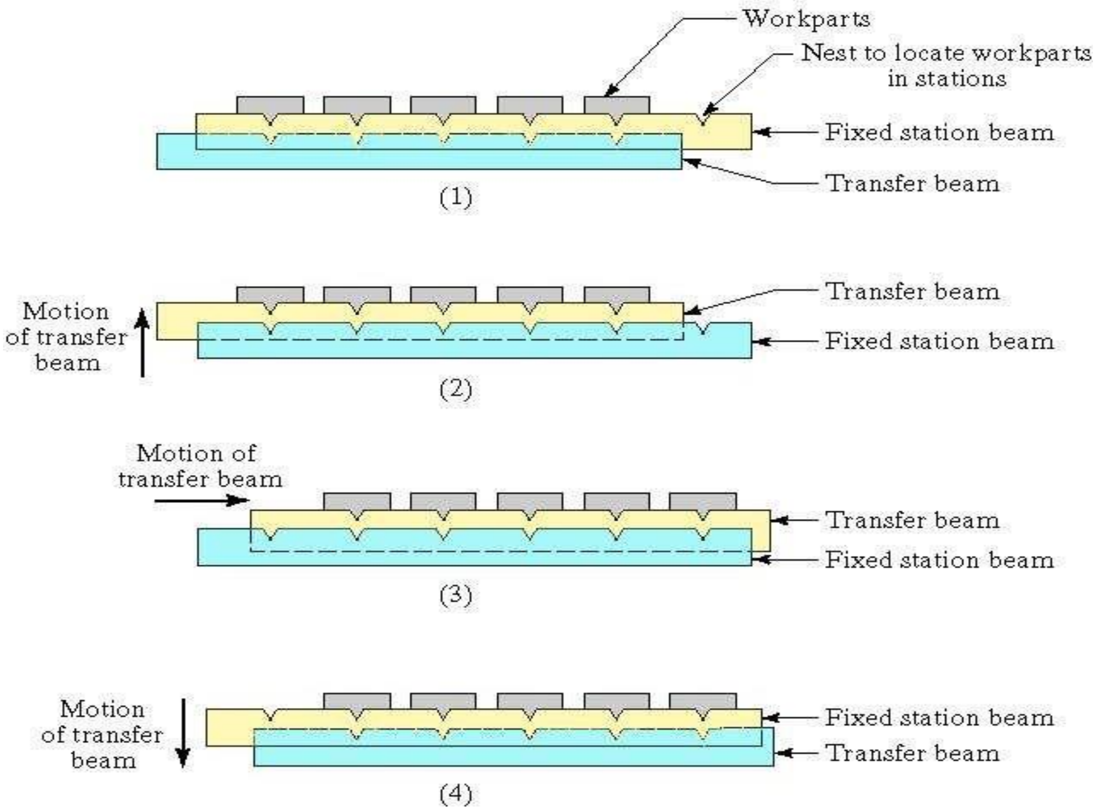
a) Walking Beam Transfer Mechanism
b) Chain Drive Conveyor System
c) Powered Roller Conveyor System

a) Walking Beam Transfer Mechanism

The walking beam transfer system is a linear transfer mechanism employed to transfer the work parts between work stations, to perform specific operations at their respective workstations. This mechanism has a transfer bar and fixed beam

The workparts are held on the fixed station beam, the transfer bar lifts the workparts from their respective workstations, moves linearly and locate the parts into the nests of the next working stations for accurate processing

The bar is then pulled back to get ready for the next transfer cycle and the cycle continues in the sequence to perform the operations. The walking beam transfer mechanism is shown in figure



b) Chain Drive Conveyor System

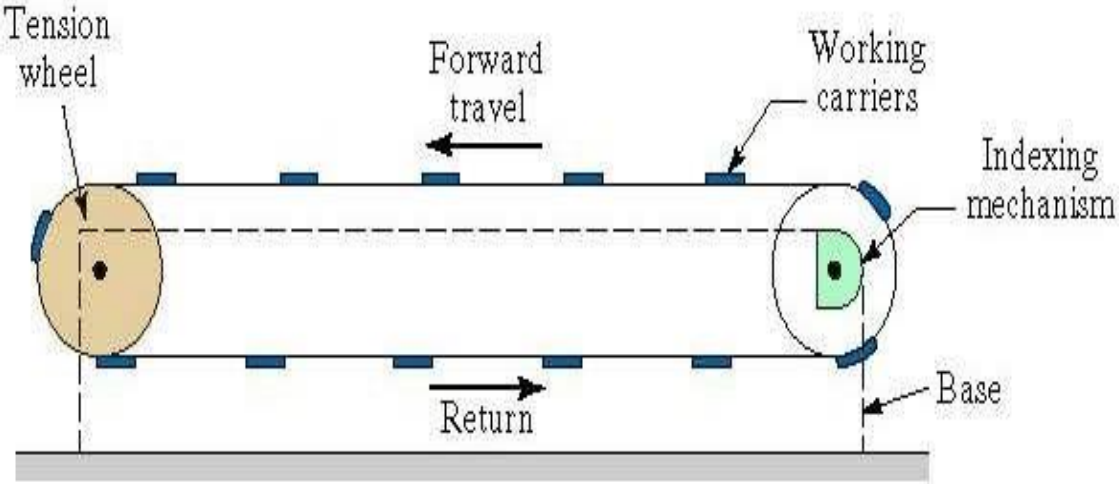
The chain drive conveyor system is a workpart transfer mechanism which enables work transfer either in horizontal or vertical direction.

This mechanism is employed with a chain drive or flexible steel belt, which is driven by pulleys. When the pulleys rotate about the horizontal axis it called over and under configuration and when pulleys rotate about the vertical axis then it is called around the corner configuration.

In this chain conveyor system, the pulley turns about the horizontal axis. The pulleys provide the rotation for chain drive by the friction between them. The work carriers are held on the chain drive. Thus, as the chain moves, the work carriers are also moved to perform the specific operation at corresponding work stations.

The arrangement of system is shown in figure. The indexing mechanism is connected to driving pulley and is designed as per the sequence of operations to be performed.

The tension wheel is arranged at a certain distance and is used to support the indexing mechanism pulley. The number of work carriers and their location depends upon the distance between the pulleys. They can move in forward and return travel with respect to the driving pulley.



c) Powered Roller Conveyor System

The powered roller conveyor system is a linear transfer mechanism used to transfer workparts from one workstation to other. This system can be driven by two transfer mechanisms i.e., chain drive or belt drive.

In chain drive the work carriers are held on either chains or rollers. When workparts are placed on the chain, it slides along the workstations. And when workparts are placed on the rollers, chain drives the rollers

In belt drive the work carriers are held on the belt, which is driven by the rollers. Belt beneath (below) the rollers, moves due to friction between them.

Powered roller conveyor system is employed in stock handling systems and automated flow lines. This system is used to drive pallets into workstation for processing flat riding surfaces.

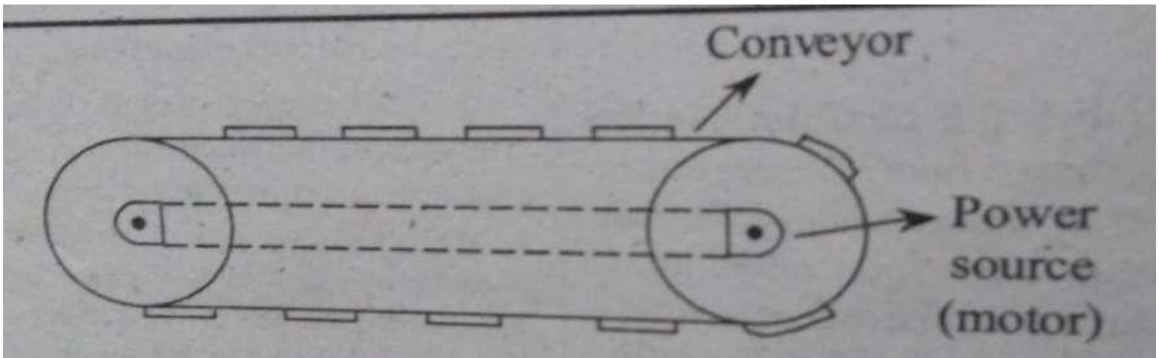


Figure: Power Rolled Conveyor System

2. Rotary Transfer Mechanism:

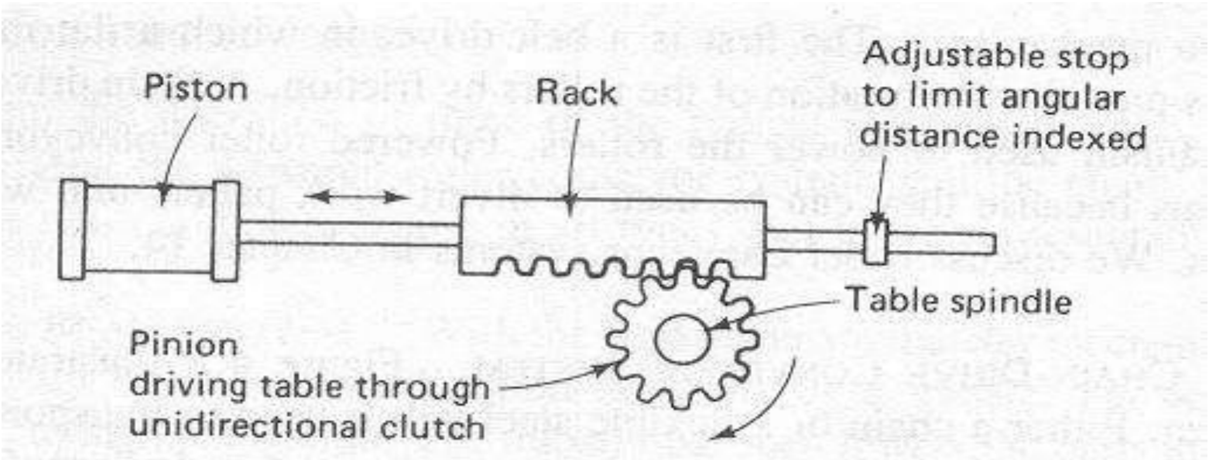
The rotary transfer mechanisms are used for indexing a circular table or dial at different equi-angular positions to perform the specific operations at corresponding workstations. Following four types of rotary transfer mechanisms are mostly used

a) Rack and Pinion Mechanism
b) Ratchet and Pawl Mechanism
c) Cam Mechanism
d) Geneva Mechanism

a) Rack and Pinion Mechanism

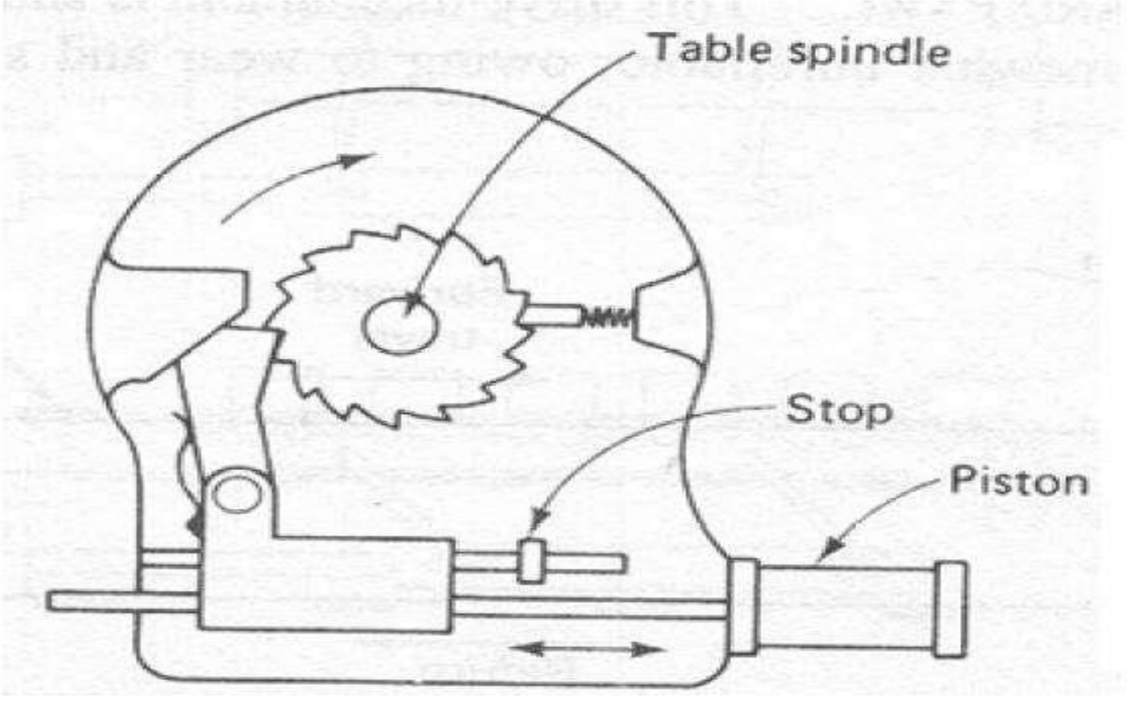
The rack and pinion mechanism convert the linear (i.e., back and forth) motion of rack into oscillatory motion of the indexing table. This mechanism is simple in construction. The mechanism comprises of a rack and pinion are, which are in mesh with each other. The pinion gear is incorporated with the indexing table shaft and the rack is connected to a piston drive. The drive mechanism is either hydraulic or pneumatic.

When drive is applied, the rack moves back and forth, thus the indexing table move in oscillatory motion through pinion gear. The drive is applied as per the requirement and respective operation to be performed at the desired workstation. This mechanism is employed for low speed operations associated with indexing table. The indexing table is expensive than the rotary table.



b) Ratchet and Pawl Mechanism

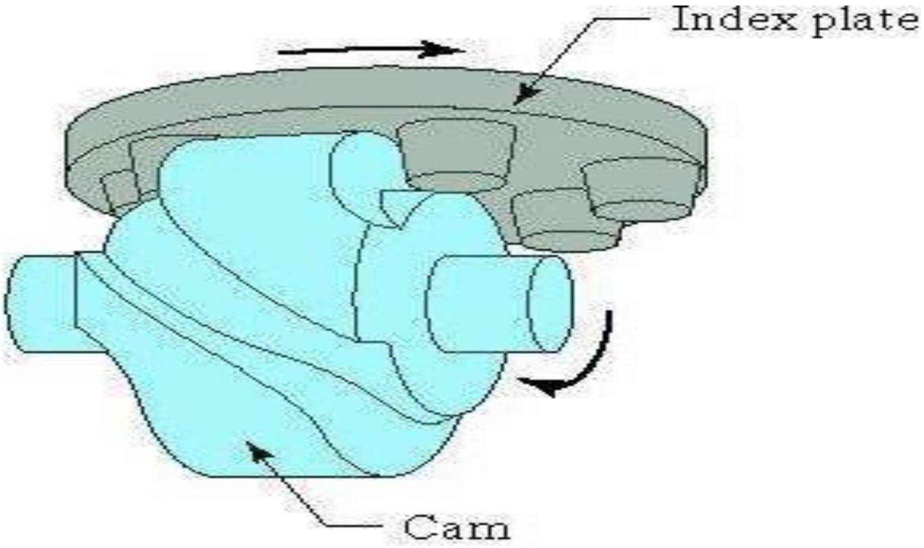
The ratchet and pawl mechanism is a method of indexing a circular or dial table at different equi-angular positions to perform respective operations at corresponding workstations. This mechanism converts the linear motion into rotary motion. The mechanism comprises of a ratchet and pawl, assembly where the ratchet is attached to the indexing table shaft and the pawl is connected to a piston drive. The ratchet and pawl are in mesh with each other to perform operations. The mechanism is controlled either pneumatically or hydraulically. This mechanism is shown in figure. Due to more number of components, this mechanism is unreliable.



c) Cam Mechanism:

Cam mechanism is a method of rotary transfer mechanism used to index the circular table for specific operations at corresponding workstations. This mechanism converts the rotary movement of cam into rotary motion of the indexing table. The mechanism comprises of a cam which is designed to give varying of velocities and dwell (specified or particular) characteristics

and to perform a wide range of operations. The table is connected to cam through indexing plate, thus the motion of cam, results in desired rotation of dial or circular table.
This mechanism is widely used in industries, although it is expensive, due to high accuracy and more reliable for indexing the table. The cam mechanism is shown in figure



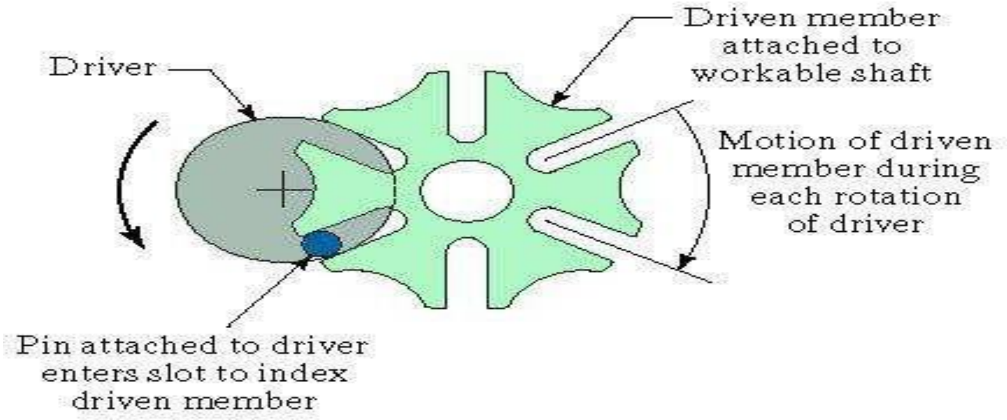
d) Geneva Mechanism:

Geneva mechanism is a rotary transfer mechanism and uses a circular rotating driver, which rotates continuously. The driver has a pin which enters into the slot of a driven member, for indexing the dial. This mechanism is specified according to the number of slots in the driven member connected to the dial shaft. The Geneva is available as four, six and eight slots. The number of slots equal to number of workstations.
If the Geneva or driven member has four slots, then each turn of the driver will cause the table to advance one fourth of a turn. Thus, 90^{O} of complete rotation of drive is used for rotation of drive is used for indexing the table and other 270^{O} is dwell.

The angle of rotation of work station during indexing the dial is given as

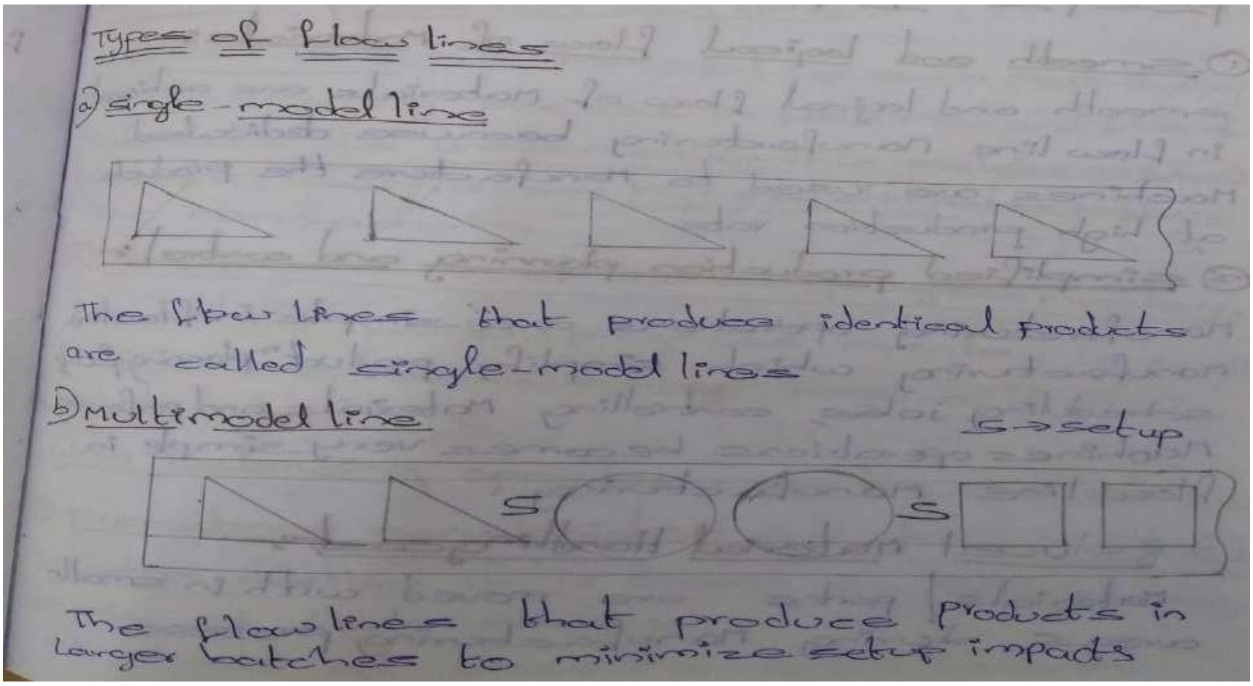
$$\theta = \frac{360}{Ns}$$

Where Ns is number of slots in Geneva



Flow line

- A route followed through successive stages of manufacturing a product.
- It is a combination of machine tools sequentially arranged and integrated with a transfer line



Types of flow lines

a) single-model line

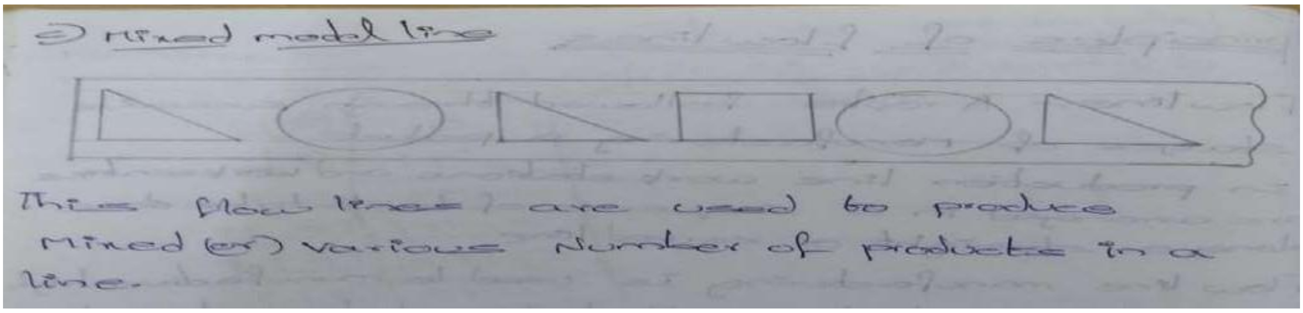
The flow lines that produce identical products are called single-model lines

b) Multimodel line

S → setup

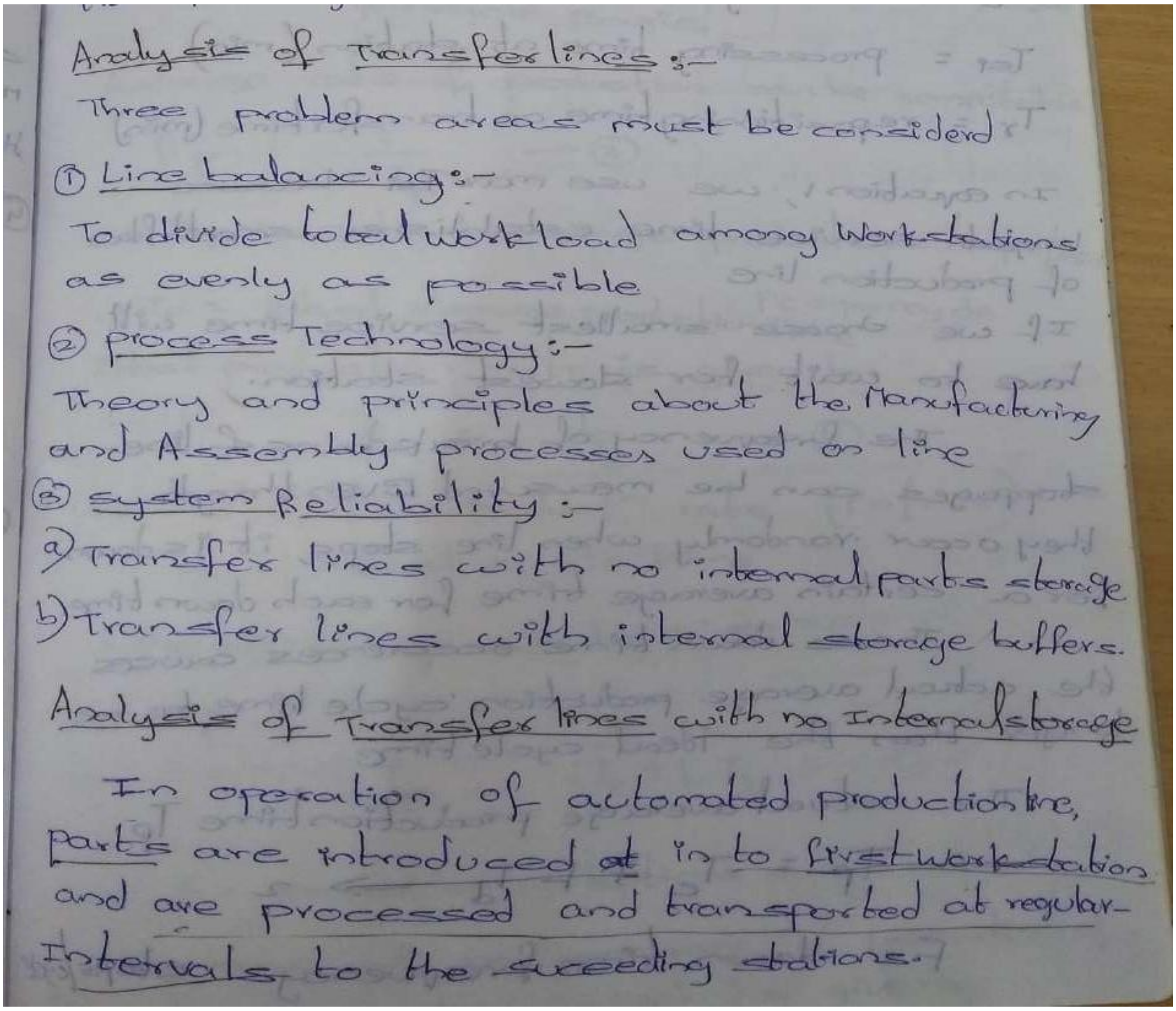
S S

The flow lines that produce products in larger batches to minimize setup impacts



⇒ Mixed model line

This flow lines are used to produce Mixed (or) various Number of products in a line.



Analysis of Transfer lines :-

Three problem areas must be considerd

① Line balancing :-

To divide total workload among Workstations as evenly as possible

② process Technology :-

Theory and principles about the Manufacturing and Assembly processes used on line

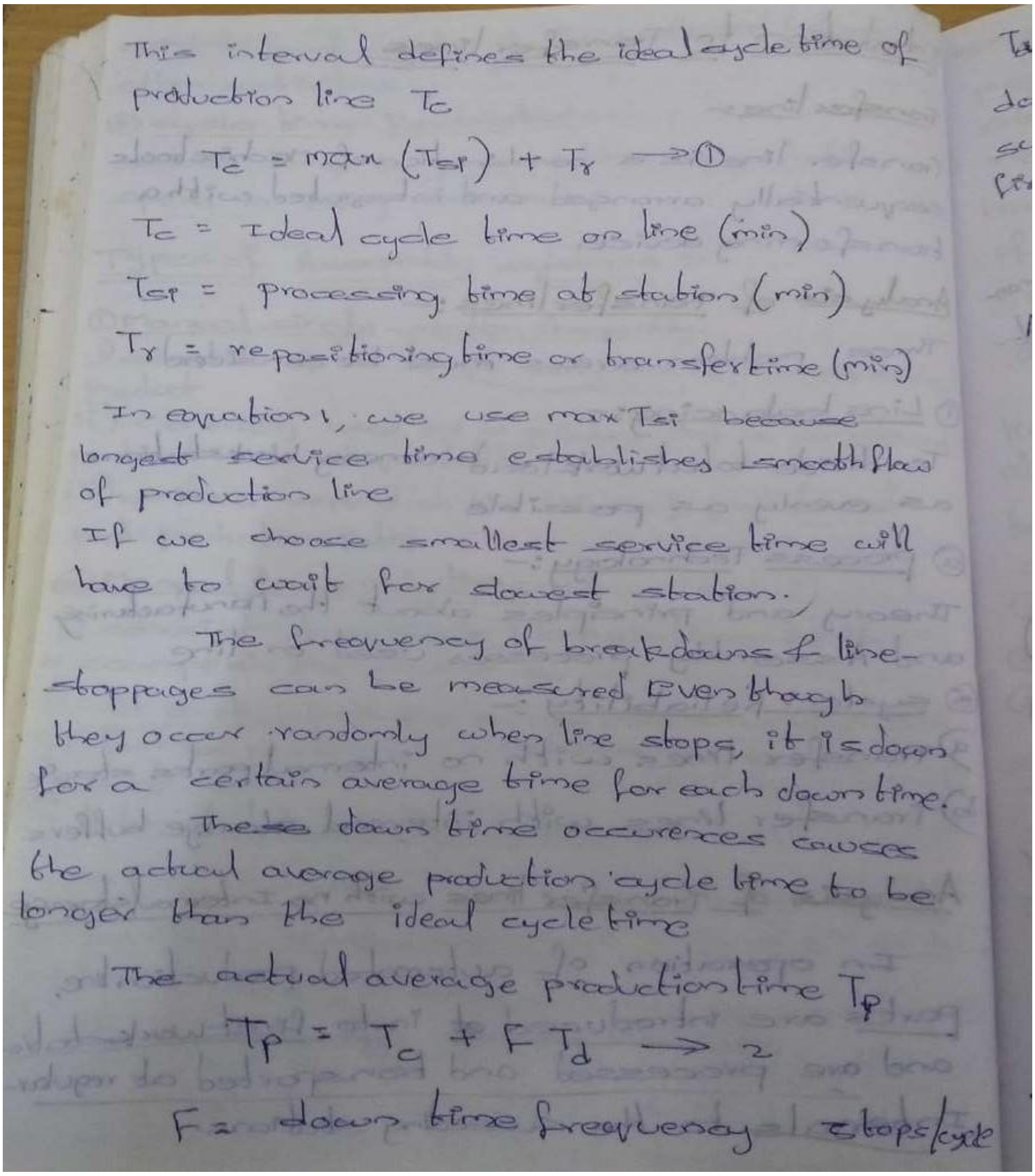
③ system Reliability :-

a) Transfer lines with no internal parts storage

b) Transfer lines with internal storage buffers.

Analysis of Transfer lines with no Internal storage

In operation of automated production line, parts are introduced at in to first workstation and are processed and transported at regular-Intervals to the succeeding stations.



This interval defines the ideal cycle time of production line T_c

$$T_c = \max(T_{si}) + T_r \rightarrow ①$$

T_c = Ideal cycle time on line (min)

T_{si} = processing time at station (min)

T_r = repositioning time or transfer time (min)

In equation 1, we use max T_{si} because longest service time establishes smooth flow of production line

If we choose smallest service time will have to wait for slowest station.

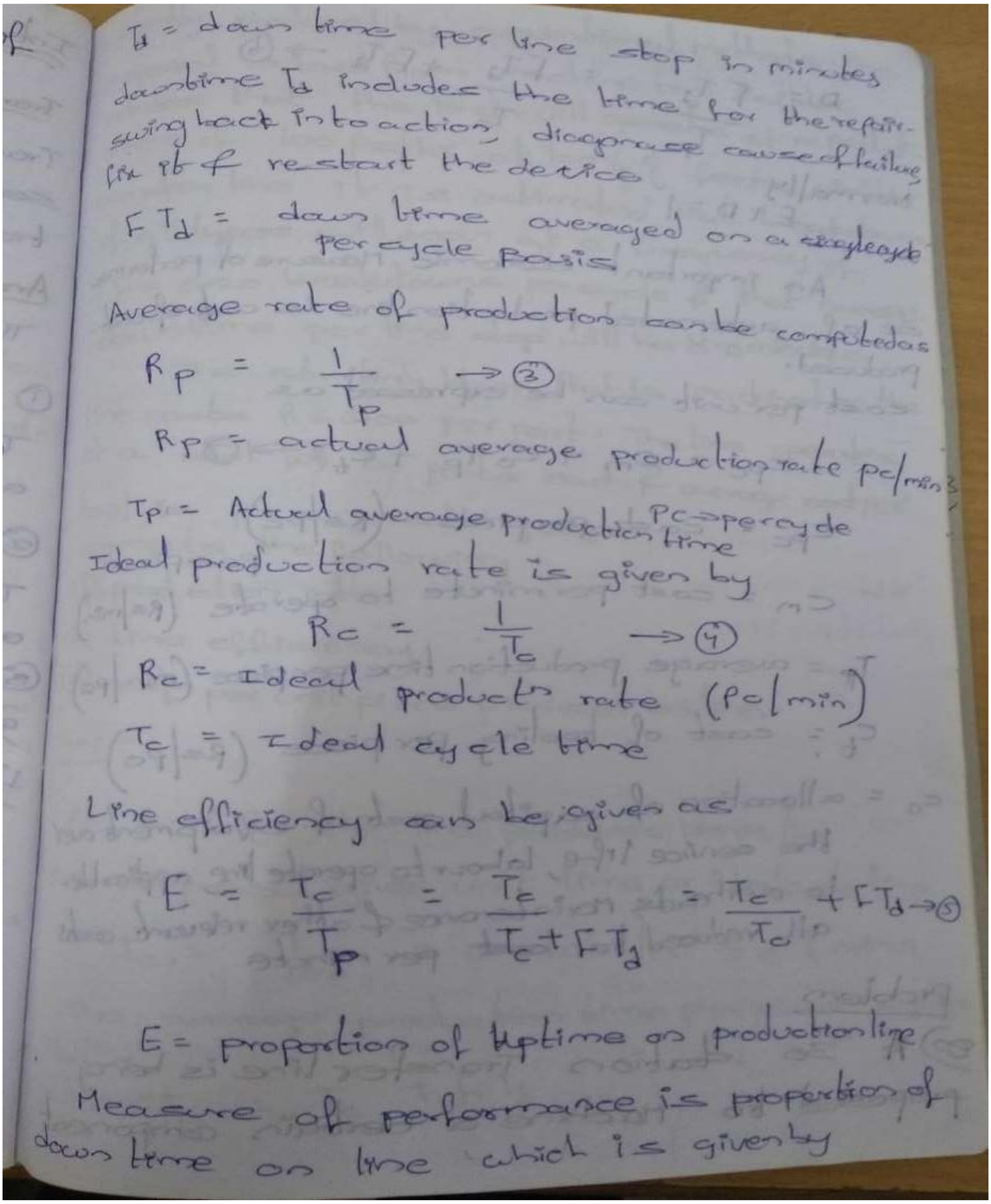
The frequency of breakdowns & line-stoppages can be measured Even though they occur randomly when line stops, it is down for a certain average time for each down time.

These down time occurences causes the actual average production cycle time to be longer than the ideal cycle time

The actual average production time T_p

$$T_p = T_c + F T_d \rightarrow 2$$

F = down time frequency stops/cycle



T_d = down time per line stop in minutes

downtime T_d includes the time for the repair swing back into action, diagnose cause of failure fix it & restart the device

FT_d = down time averaged on a ~~cycle~~ cycle per cycle basis

Average rate of production can be computed as

$$R_p = \frac{1}{T_p} \rightarrow ③$$

R_p = actual average production rate pc/min

T_p = Actual average production time (pc → per cycle)

Ideal production rate is given by

$$R_c = \frac{1}{T_c} \rightarrow ④$$

R_c = Ideal producti rate (pc/min)

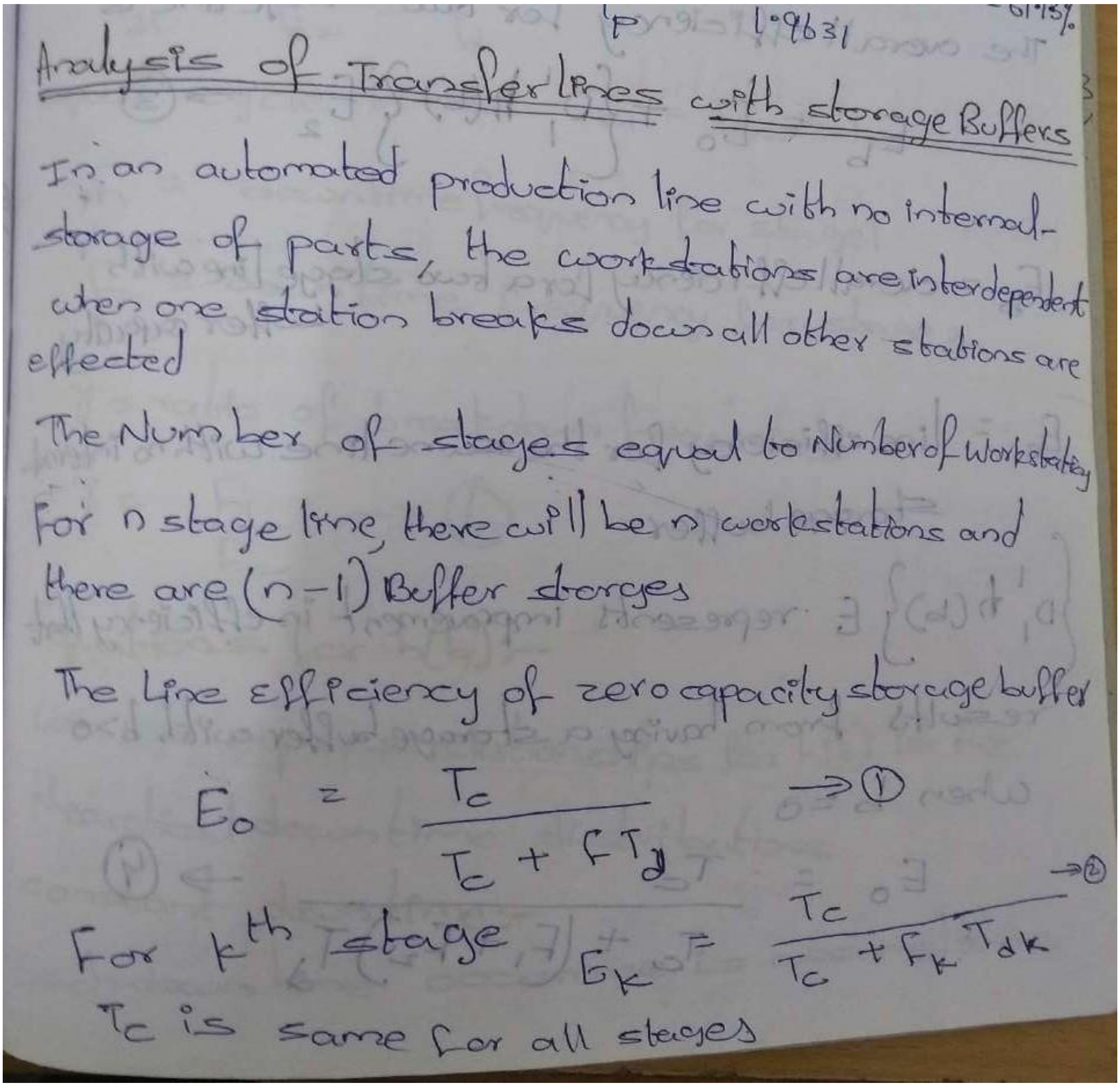
T_c = Ideal cycle time

Line efficiency can be given as

$$E = \frac{T_c}{T_p} = \frac{T_c}{T_c + FT_d} = \frac{T_c}{T_c} + FT_d \rightarrow ⑤$$

E = proportion of uptime on production line

Measure of performance is proportion of down time on line which is given by



P 1·9631 61·15%

Analysis of Transfer lines with storage Buffers

In an automated production line with no internal storage of parts, the workstations are interdependent when one station breaks down all other stations are effected

The Number of stages equal to Number of Workstations

For n stage line, there will be n workstations and there are (n-1) Buffer storages

The Line efficiency of zero capacity storage buffer

$$E_0 = \frac{T_c}{T_c + F T_d} \rightarrow ①$$

For k^{th} stage $E_k = \frac{T_c}{T_c + F_k T_{dk}}$ → ②

T_c is same for all stages

Concept of Assembly Process

The following are 3 major processes used to accomplish the assembly of components.

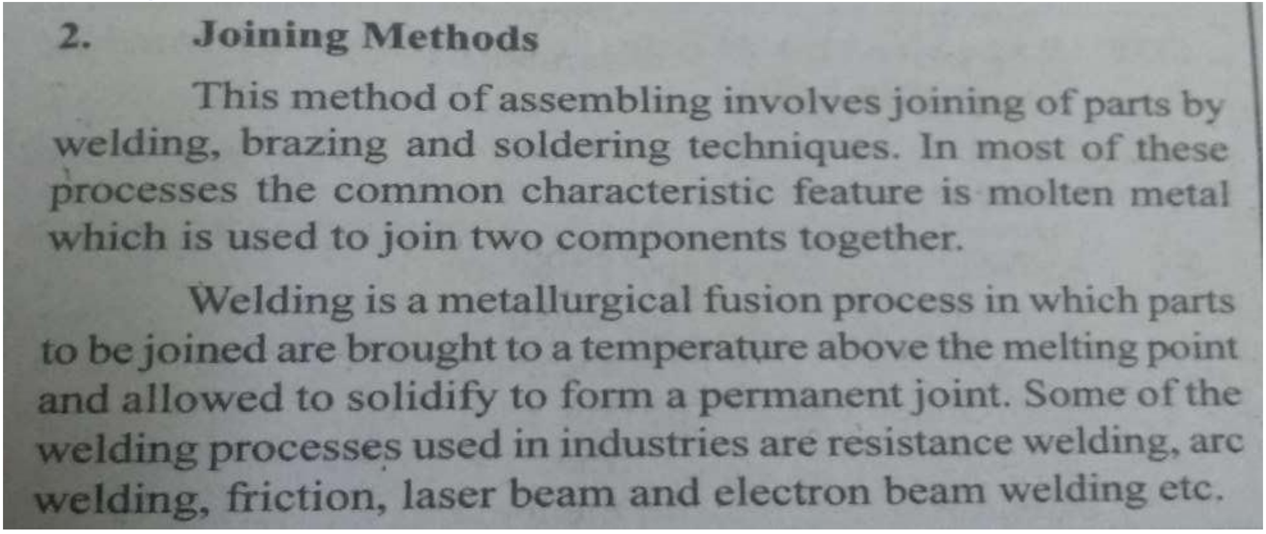
1. Mechanical fastening
2. Joining methods
3. Adhesive bonding

1. Mechanical fastening

Mechanical fastening involves various methods to join two or more parts together by some mechanical action. These mechanical fastening includes

a) Thread fastening
b) Riveting
c) Press fits and Shrink fits
d) Snap fits
e) Sewing and Stitching

2. Joining methods



2. Joining Methods

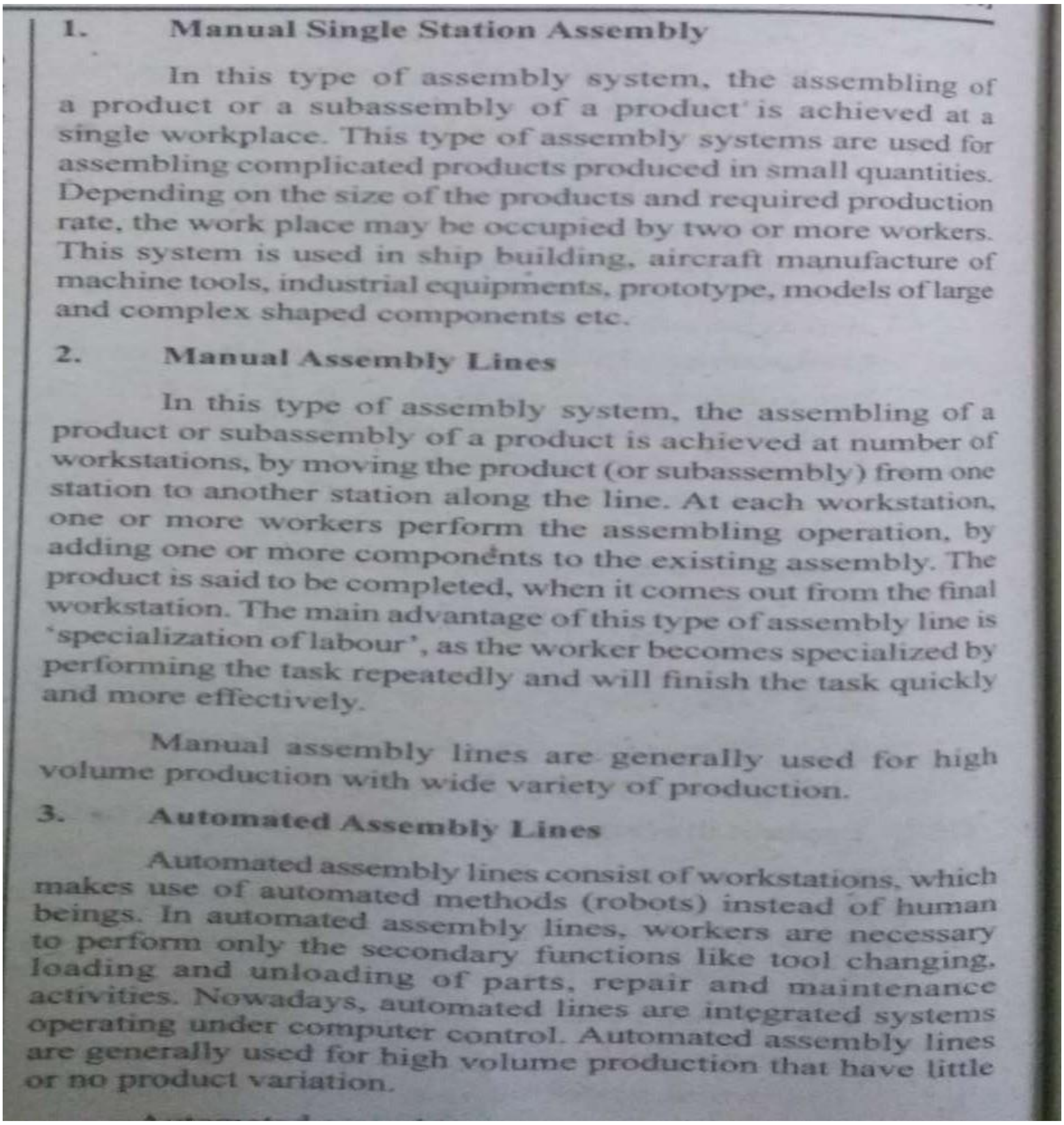
This method of assembling involves joining of parts by welding, brazing and soldering techniques. In most of these processes the common characteristic feature is molten metal which is used to join two components together.

Welding is a metallurgical fusion process in which parts to be joined are brought to a temperature above the melting point and allowed to solidify to form a permanent joint. Some of the welding processes used in industries are resistance welding, arc welding, friction, laser beam and electron beam welding etc.

Assembly systems

The various assembly systems employed in industries to perform various assembly process are classified as below

1. Manual single station assembly
2. Manual assembly line
3. Automated assembly line



1. Manual Single Station Assembly

In this type of assembly system, the assembling of a product or a subassembly of a product is achieved at a single workplace. This type of assembly systems are used for assembling complicated products produced in small quantities. Depending on the size of the products and required production rate, the work place may be occupied by two or more workers. This system is used in ship building, aircraft manufacture of machine tools, industrial equipments, prototype, models of large and complex shaped components etc.

2. Manual Assembly Lines

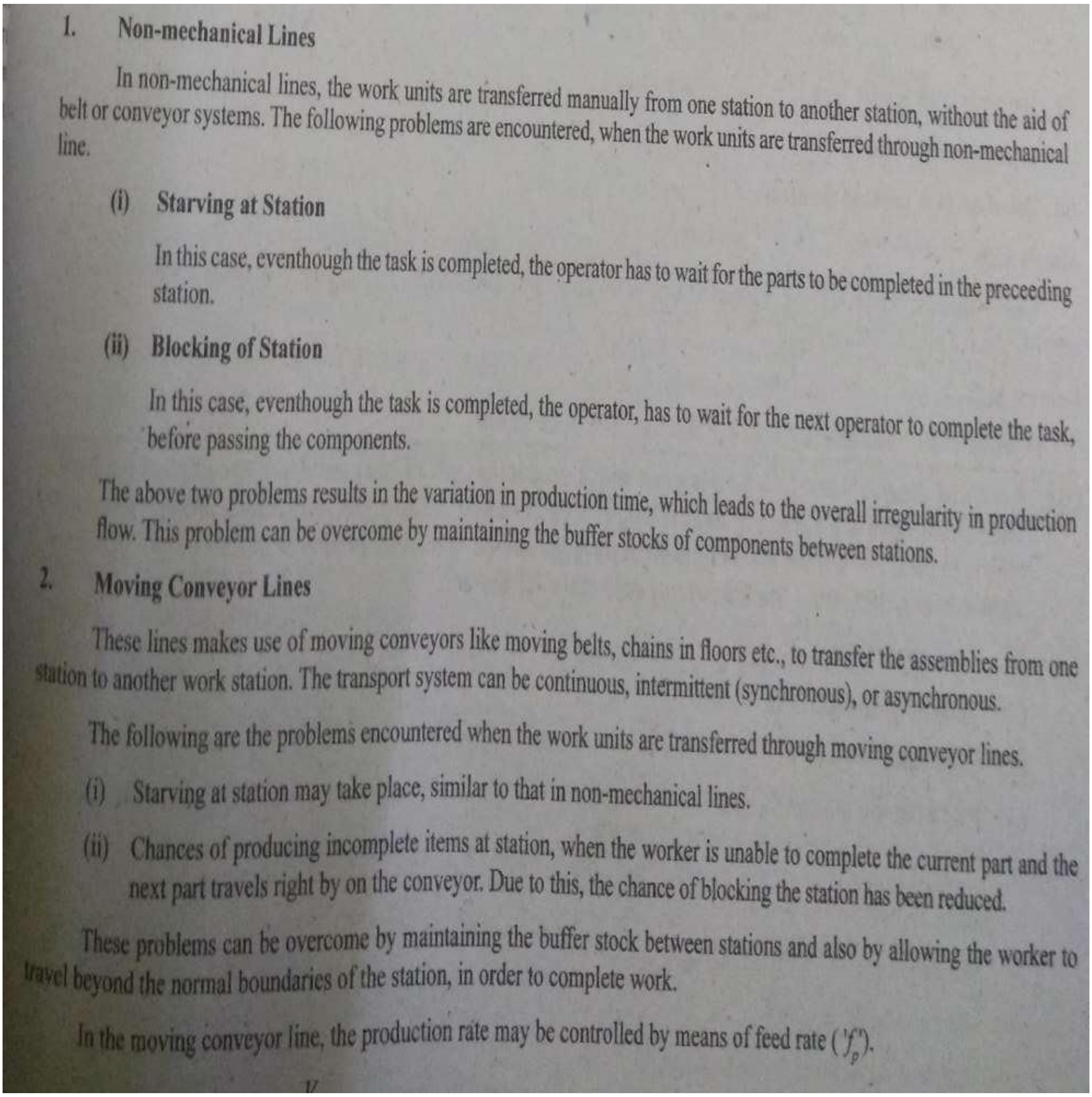
In this type of assembly system, the assembling of a product or subassembly of a product is achieved at number of workstations, by moving the product (or subassembly) from one station to another station along the line. At each workstation, one or more workers perform the assembling operation, by adding one or more components to the existing assembly. The product is said to be completed, when it comes out from the final workstation. The main advantage of this type of assembly line is 'specialization of labour', as the worker becomes specialized by performing the task repeatedly and will finish the task quickly and more effectively.

Manual assembly lines are generally used for high volume production with wide variety of production.

3. Automated Assembly Lines

Automated assembly lines consist of workstations, which makes use of automated methods (robots) instead of human beings. In automated assembly lines, workers are necessary to perform only the secondary functions like tool changing, loading and unloading of parts, repair and maintenance activities. Nowadays, automated lines are integrated systems operating under computer control. Automated assembly lines are generally used for high volume production that have little or no product variation.

Non-mechanical and conveyor lines in manual assembly line



1. Non-mechanical Lines

In non-mechanical lines, the work units are transferred manually from one station to another station, without the aid of belt or conveyor systems. The following problems are encountered, when the work units are transferred through non-mechanical line.

(i) Starving at Station

In this case, eventhough the task is completed, the operator has to wait for the parts to be completed in the preceeding station.

(ii) Blocking of Station

In this case, eventhough the task is completed, the operator, has to wait for the next operator to complete the task, before passing the components.

The above two problems results in the variation in production time, which leads to the overall irregularity in production flow. This problem can be overcome by maintaining the buffer stocks of components between stations.

2. Moving Conveyor Lines

These lines makes use of moving conveyors like moving belts, chains in floors etc., to transfer the assemblies from one station to another work station. The transport system can be continuous, intermittent (synchronous), or asynchronous.

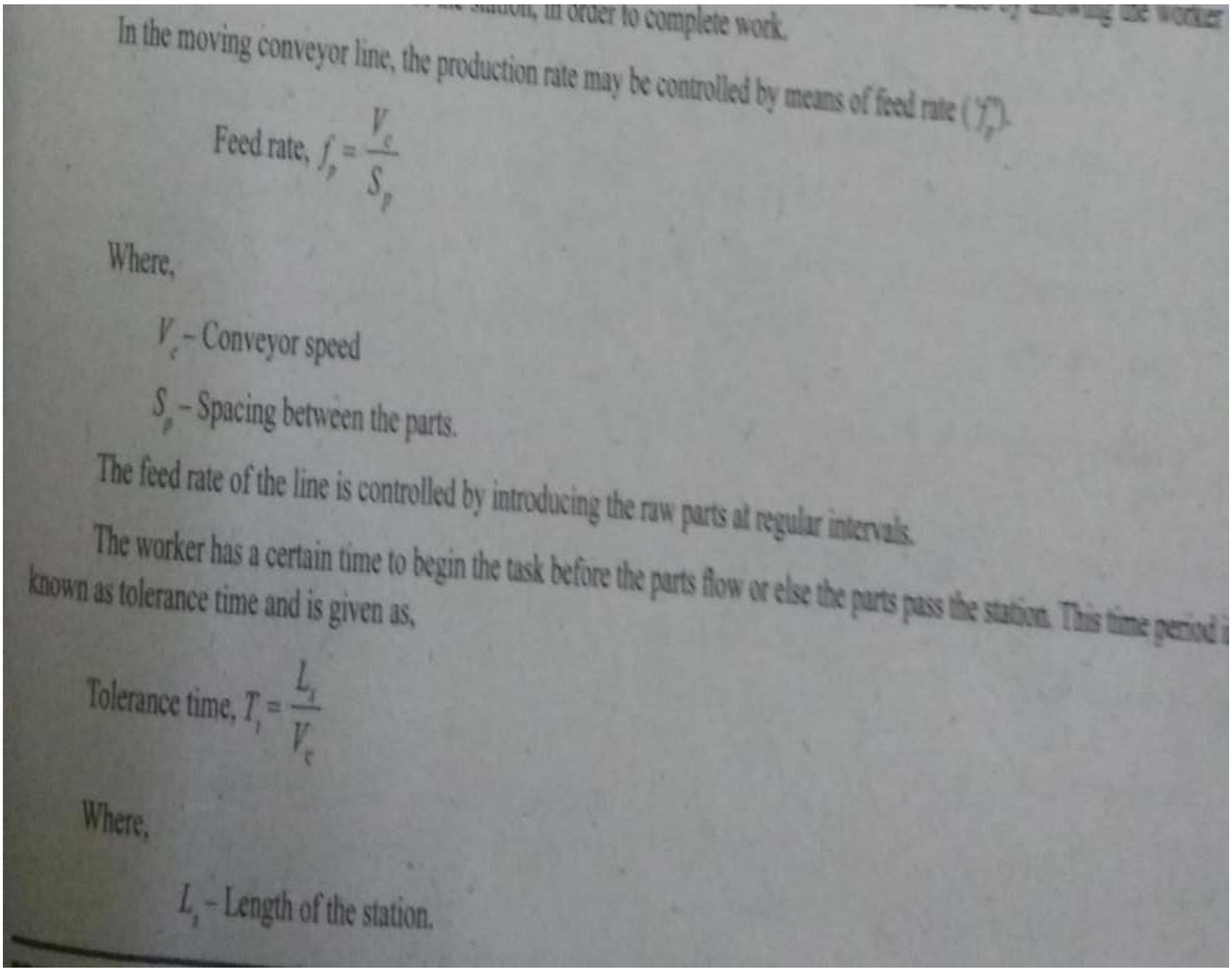
The following are the problems encountered when the work units are transferred through moving conveyor lines.

(i) Starving at station may take place, similar to that in non-mechanical lines.

(ii) Chances of producing incomplete items at station, when the worker is unable to complete the current part and the next part travels right by on the conveyor. Due to this, the chance of blocking the station has been reduced.

These problems can be overcome by maintaining the buffer stock between stations and also by allowing the worker to travel beyond the normal boundaries of the station, in order to complete work.

In the moving conveyor line, the production rate may be controlled by means of feed rate ('f_p').



in order to complete work.

In the moving conveyor line, the production rate may be controlled by means of feed rate (f_p).

$$\text{Feed rate, } f_p = \frac{V_c}{S_p}$$

Where,

V_c - Conveyor speed

S_p - Spacing between the parts.

The feed rate of the line is controlled by introducing the raw parts at regular intervals.

The worker has a certain time to begin the task before the parts flow or else the parts pass the station. This time period i known as tolerance time and is given as,

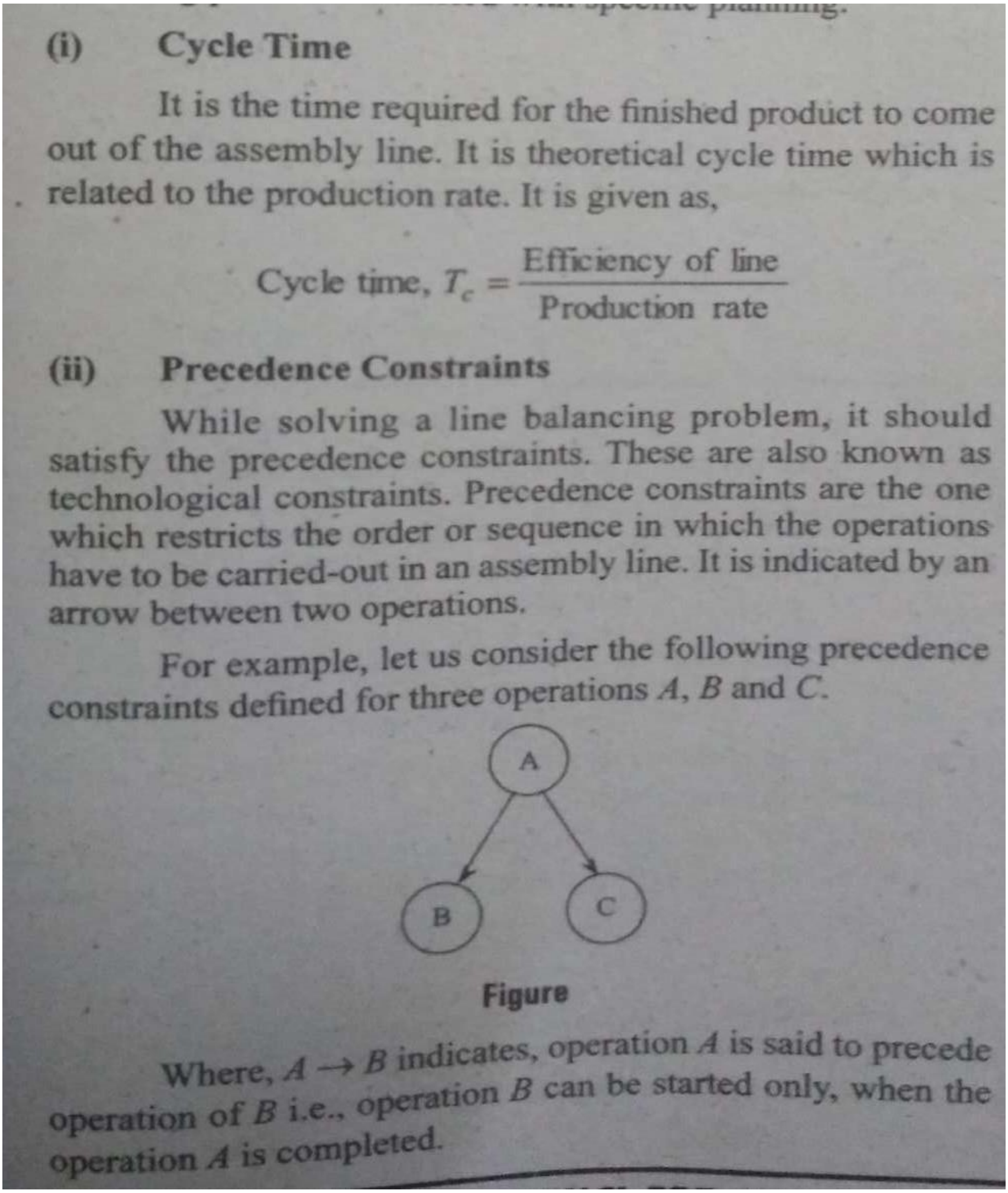
$$\text{Tolerance time, } T_t = \frac{L_s}{V_c}$$

Where,

L_s - Length of the station.

Terminology used in line balancing problem

Line balancing problem is concerned to the assignment of equal amount of work to the individual workers at specific workstations. For high production on assembly lines the line balancing problem is carried with specific planning.



(i) Cycle Time

It is the time required for the finished product to come out of the assembly line. It is theoretical cycle time which is related to the production rate. It is given as,

$$\text{Cycle time, } T_c = \frac{\text{Efficiency of line}}{\text{Production rate}}$$

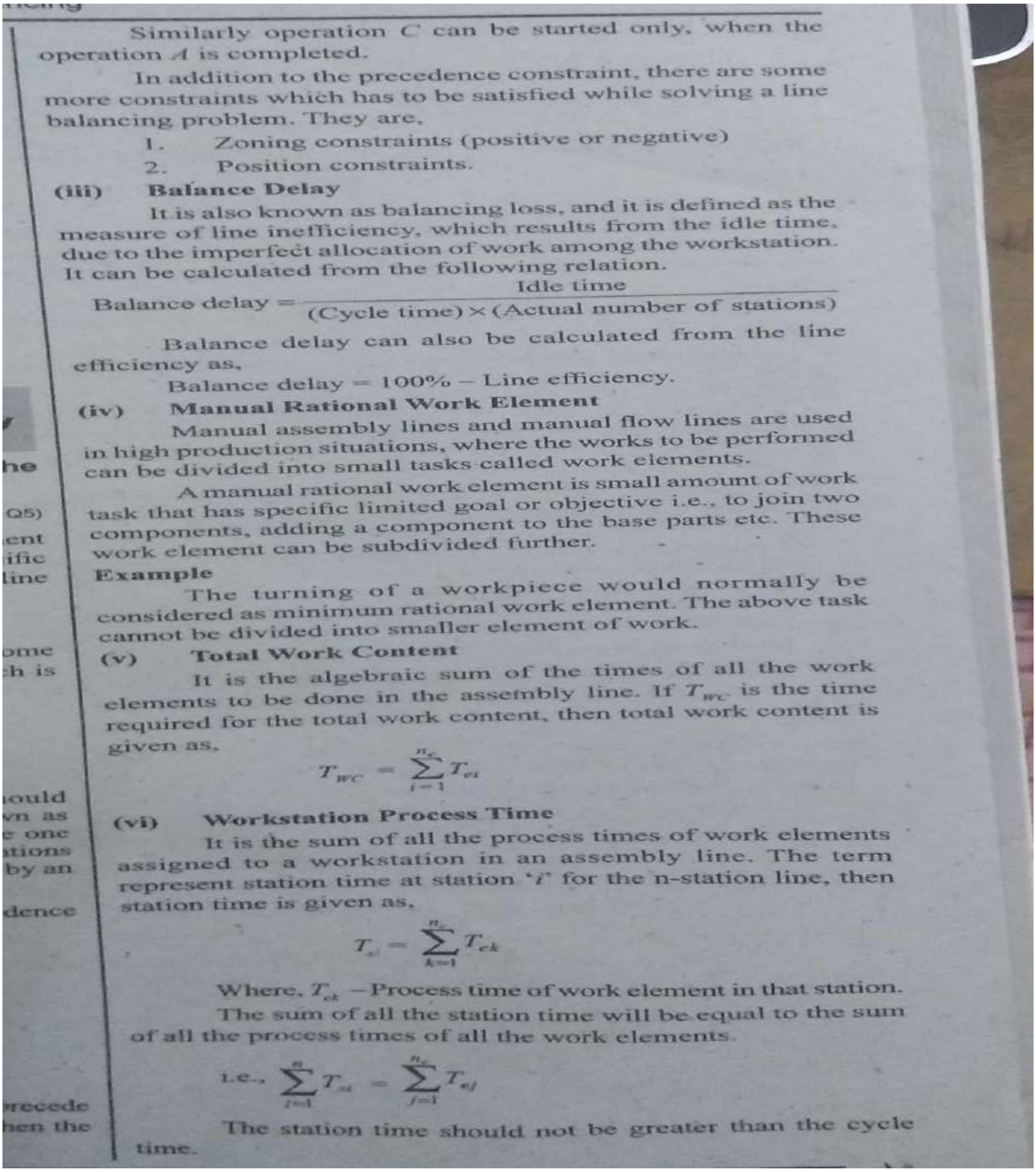
(ii) Precedence Constraints

While solving a line balancing problem, it should satisfy the precedence constraints. These are also known as technological constraints. Precedence constraints are the one which restricts the order or sequence in which the operations have to be carried-out in an assembly line. It is indicated by an arrow between two operations.

For example, let us consider the following precedence constraints defined for three operations A, B and C.

Figure

Where, $A \rightarrow B$ indicates, operation A is said to precede operation of B i.e., operation B can be started only, when the operation A is completed.



Similarly operation C can be started only, when the operation A is completed.

In addition to the precedence constraint, there are some more constraints which has to be satisfied while solving a line balancing problem. They are,

1. Zoning constraints (positive or negative)
2. Position constraints.

(iii) Balance Delay

It is also known as balancing loss, and it is defined as the measure of line inefficiency, which results from the idle time, due to the imperfect allocation of work among the workstation. It can be calculated from the following relation.

$$\text{Balance delay} = \frac{\text{Idle time}}{(\text{Cycle time}) \times (\text{Actual number of stations})}$$

Balance delay can also be calculated from the line efficiency as,

Balance delay = 100% − Line efficiency.

(iv) Manual Rational Work Element

Manual assembly lines and manual flow lines are used in high production situations, where the works to be performed can be divided into small tasks called work elements.

A manual rational work element is small amount of work task that has specific limited goal or objective i.e., to join two components, adding a component to the base parts etc. These work element can be subdivided further.

Example

The turning of a workpiece would normally be considered as minimum rational work element. The above task cannot be divided into smaller element of work.

(v) Total Work Content

It is the algebraic sum of the times of all the work elements to be done in the assembly line. If T_{wc} is the time required for the total work content, then total work content is given as,

$$T_{WC} = \sum_{i=1}^{n_e} T_{ei}$$

(vi) Workstation Process Time

It is the sum of all the process times of work elements assigned to a workstation in an assembly line. The term represent station time at station 'i' for the n-station line, then station time is given as,

$$T_{si} = \sum_{k=1}^{n_e} T_{ek}$$

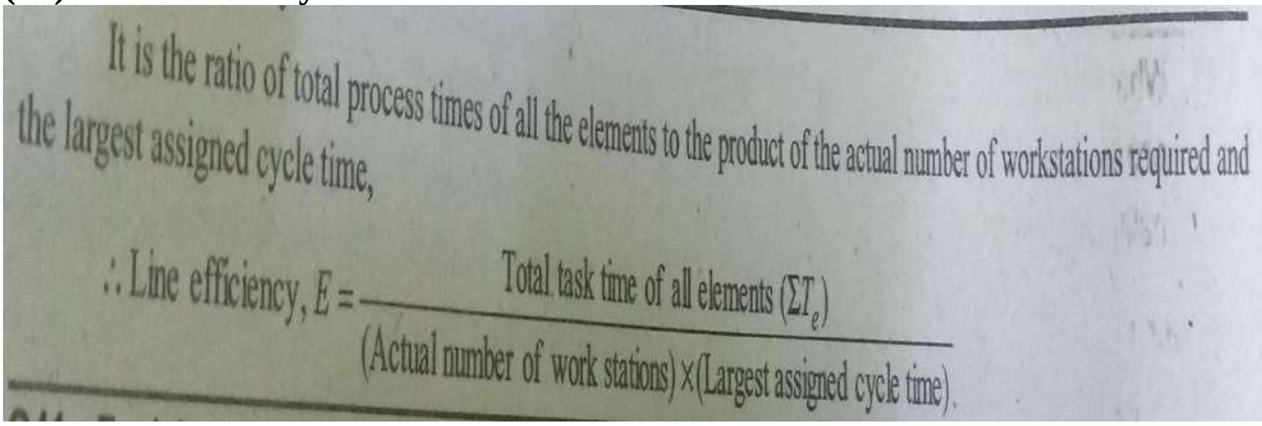
Where, T_{ek} – Process time of work element in that station.

The sum of all the station time will be equal to the sum of all the process times of all the work elements.

$$\text{i.e., } \sum_{i=1}^{n} T_{si} = \sum_{j=1}^{n_e} T_{ej}$$

The station time should not be greater than the cycle time.

(vii) Line Efficiency



It is the ratio of total process times of all the elements to the product of the actual number of workstations required and the largest assigned cycle time,

$$\therefore \text{Line efficiency, } E = \frac{\text{Total task time of all elements } (\Sigma T_e)}{(\text{Actual number of work stations}) \times (\text{Largest assigned cycle time})}.$$

Methods of Line Balancing :-

I) Largest Candidate rule :-

In this method, work elements are arranged in descending orders of Te.

II) Kill bridge and wester's Method:-

It implied work element are selected according to their position in precedence of diagram.

III) Ranked positioned eights methods :-

It implies calculating RPW (ranked positioned weight value) for each element.

SREENIVASA INSTITUTE OF TECHNOLOGY AND MANAGEMENT STUDIES

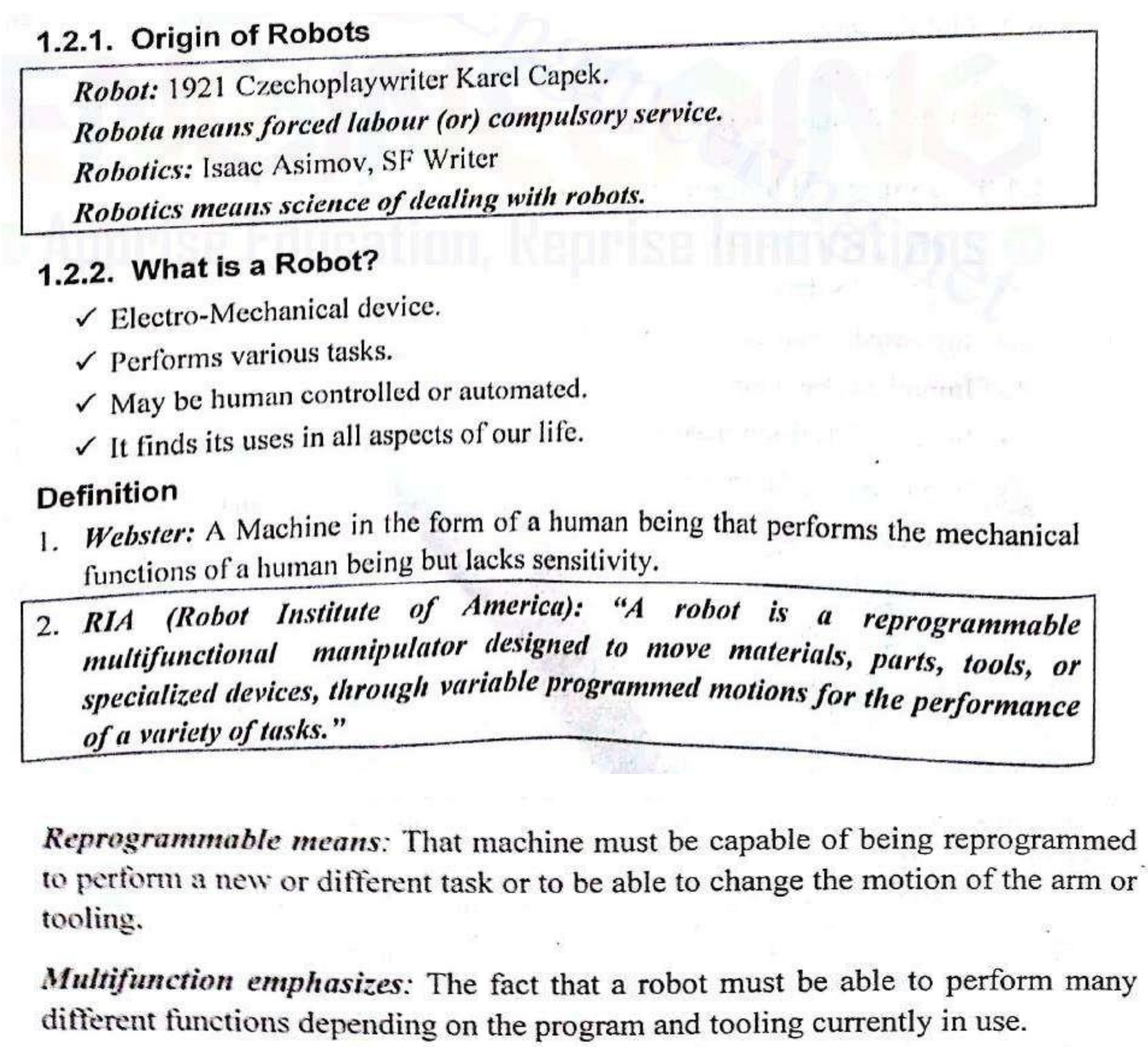
(Autonomous)

DEPARTMENT of MECHANICAL ENGINEERING

AUTOMATION AND ROBOTICS

(16MEC325A)

UNIT – 3: INDUSTRIAL ROBOTICS AND DRIVE SYSTEM



1.2.1. Origin of Robots

Robot: 1921 Czechoplaywriter Karel Capek.

Robota means forced labour (or) compulsory service.

Robotics: Isaac Asimov, SF Writer

Robotics means science of dealing with robots.

1.2.2. What is a Robot?

- ✓ Electro-Mechanical device.
- ✓ Performs various tasks.
- ✓ May be human controlled or automated.
- ✓ It finds its uses in all aspects of our life.

Definition

1. ***Webster:*** A Machine in the form of a human being that performs the mechanical functions of a human being but lacks sensitivity.
2. ***RIA (Robot Institute of America): "A robot is a reprogrammable multifunctional manipulator designed to move materials, parts, tools, or specialized devices, through variable programmed motions for the performance of a variety of tasks."***

Reprogrammable means: That machine must be capable of being reprogrammed to perform a new or different task or to be able to change the motion of the arm or tooling.

Multifunction emphasizes: The fact that a robot must be able to perform many different functions depending on the program and tooling currently in use.

Robot anatomy means: "Study of skeleton of robot (or) physical part"

✓ The mechanical structure of a robot is like the skeleton in the human body.

✓ The robot anatomy is, therefore, the study of structure of robot, that is physical construction of the manipulator structure.

✓ The mechanical structure of manipulator that consists of rigid bodies (links) connected by means of joints, is segmented into an arm that ensures mobility and reachability, a wrist that confers orientation, and an end effector that performs the required task.

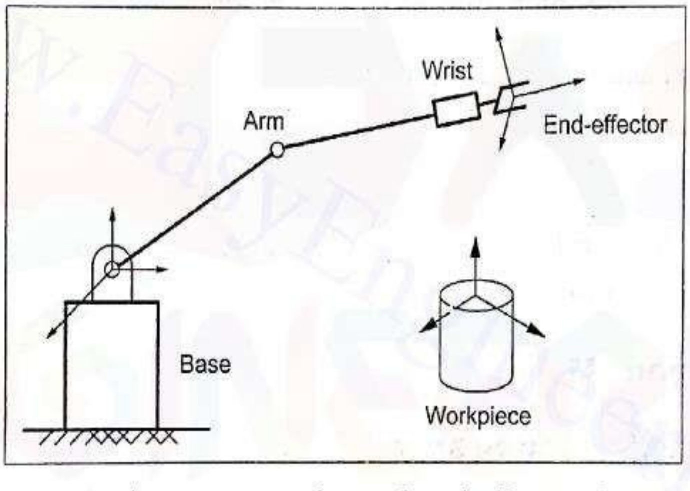
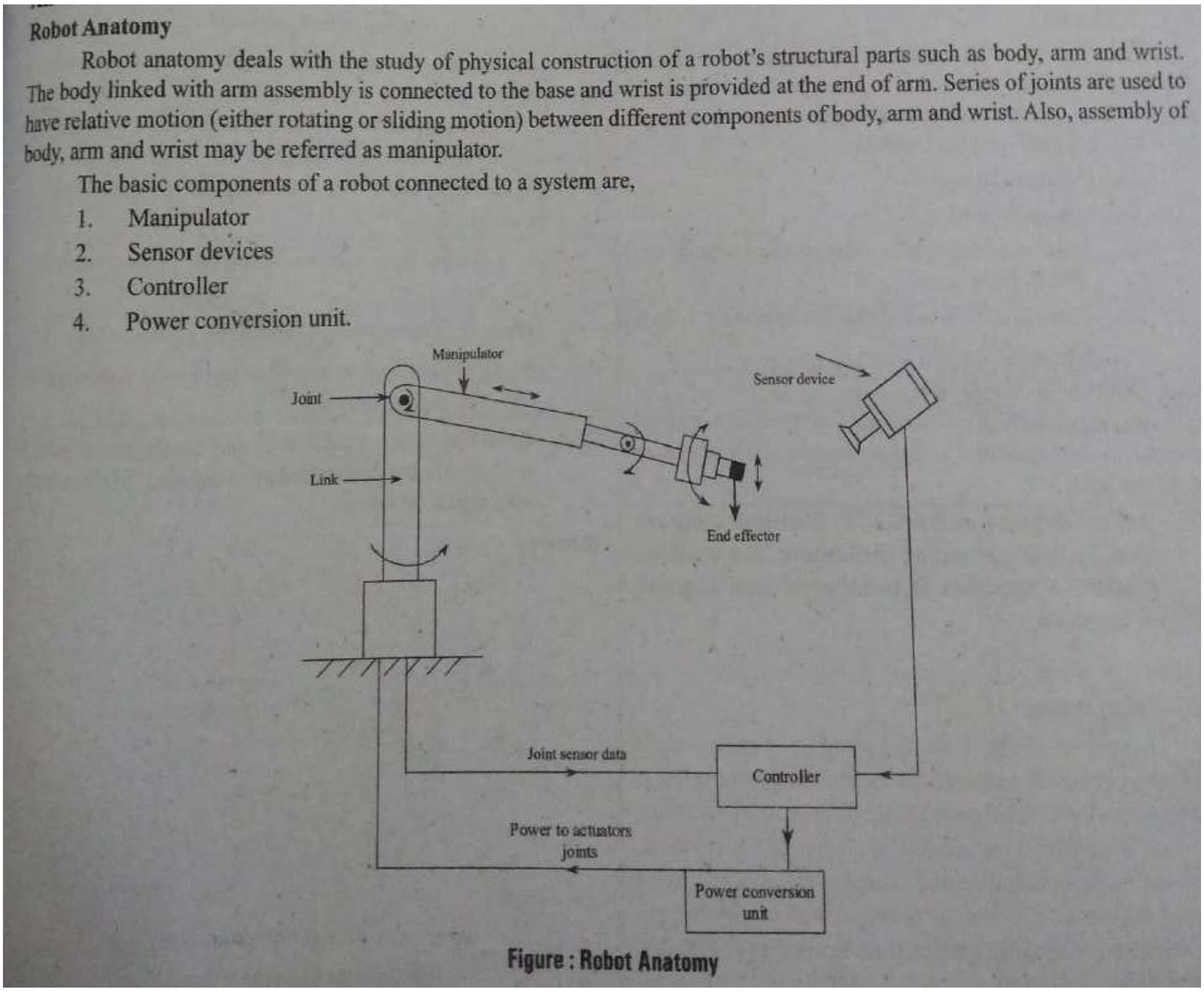


Fig. 1.1. The base, arm, wrist and end effector forming the



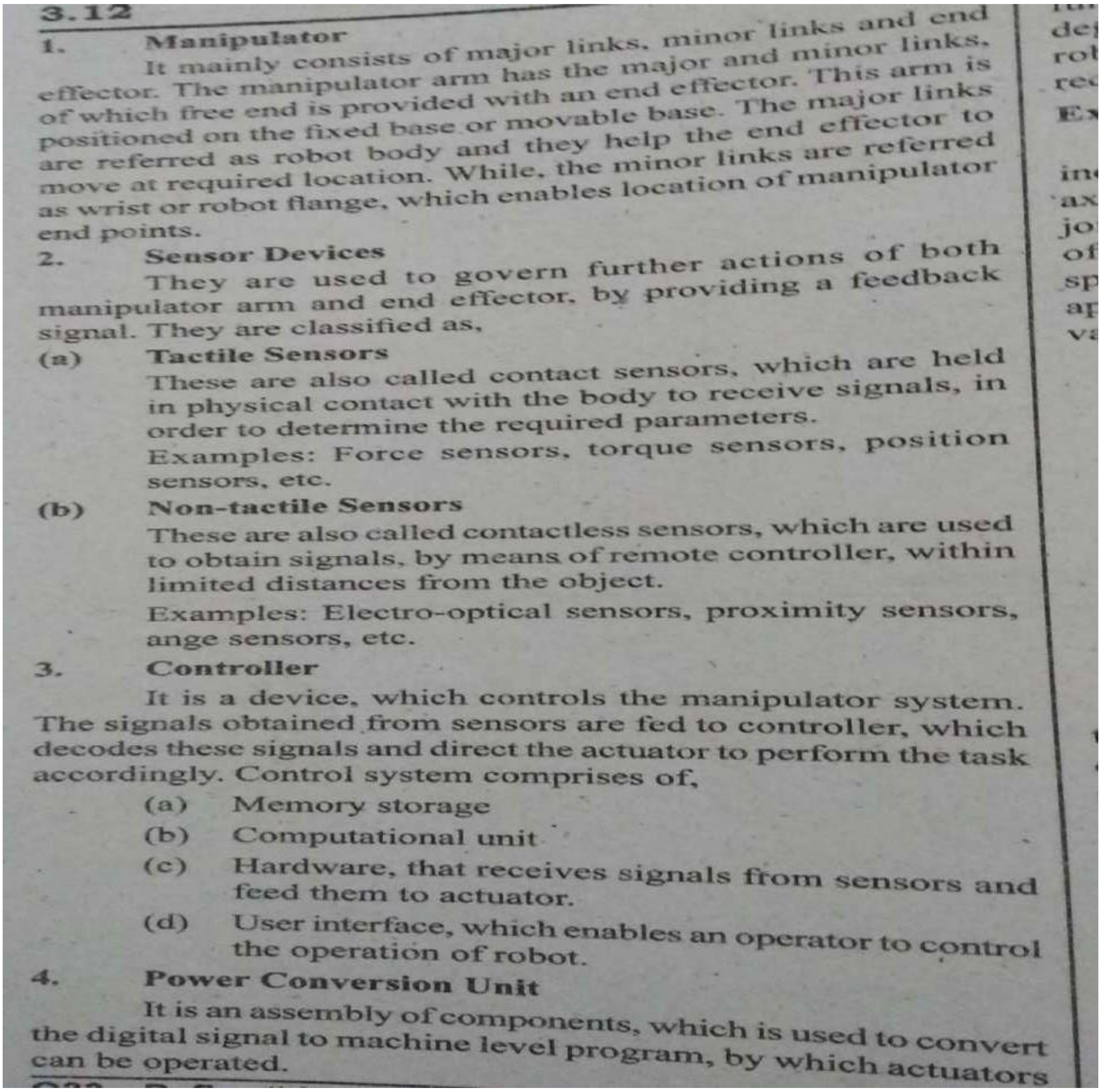
Robot Anatomy

Robot anatomy deals with the study of physical construction of a robot's structural parts such as body, arm and wrist. The body linked with arm assembly is connected to the base and wrist is provided at the end of arm. Series of joints are used to have relative motion (either rotating or sliding motion) between different components of body, arm and wrist. Also, assembly of body, arm and wrist may be referred as manipulator.

The basic components of a robot connected to a system are,

1. Manipulator
2. Sensor devices
3. Controller
4. Power conversion unit.

Figure : Robot Anatomy



1. Manipulator

It mainly consists of major links, minor links and end effector. The manipulator arm has the major and minor links, of which free end is provided with an end effector. This arm is positioned on the fixed base or movable base. The major links are referred as robot body and they help the end effector to move at required location. While, the minor links are referred as wrist or robot flange, which enables location of manipulator end points.

2. Sensor Devices

They are used to govern further actions of both manipulator arm and end effector, by providing a feedback signal. They are classified as,

(a) Tactile Sensors

These are also called contact sensors, which are held in physical contact with the body to receive signals, in order to determine the required parameters.

Examples: Force sensors, torque sensors, position sensors, etc.

(b) Non-tactile Sensors

These are also called contactless sensors, which are used to obtain signals, by means of remote controller, within limited distances from the object.

Examples: Electro-optical sensors, proximity sensors, ange sensors, etc.

3. Controller

It is a device, which controls the manipulator system. The signals obtained from sensors are fed to controller, which decodes these signals and direct the actuator to perform the task accordingly. Control system comprises of,

(a) Memory storage

(b) Computational unit

(c) Hardware, that receives signals from sensors and feed them to actuator.

(d) User interface, which enables an operator to control the operation of robot.

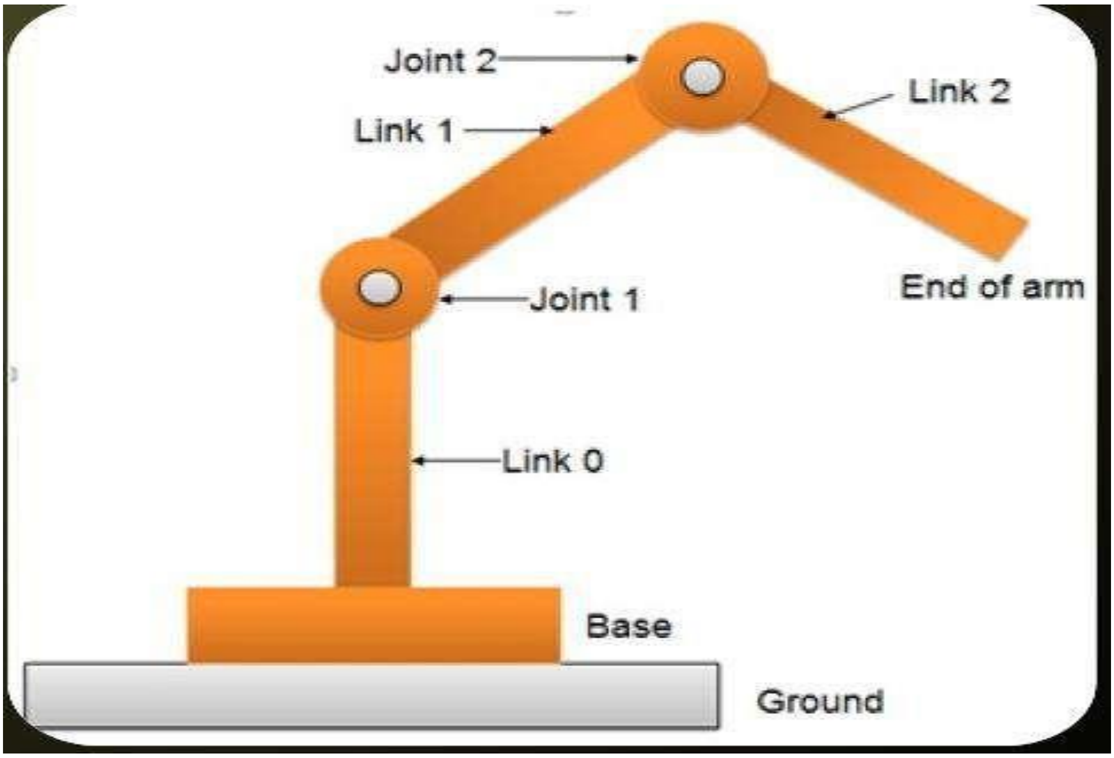
4. Power Conversion Unit

It is an assembly of components, which is used to convert the digital signal to machine level program, by which actuators can be operated.

JOINTS AND LINKS

- The manipulator of an industrial robot consists of a series of joints and links.
- Robot anatomy deals with the study of different joints and links and other aspects of the manipulator's physical construction.
- A robotic joint provides relative motion between two links of the robot.
- Each joint, or axis, provides a certain degree-of-freedom (dof) of motion.
- In most of the cases, only one degree-of-freedom is associated with each joint.
- Each joint is connected to two links, an input link and an output link.

- The robotic base and its connection to the first joint are termed as link-0.
- The first joint in the sequence is joint-1.
- Link-0 is the input link for joint-1, while the output link from joint-1 is link-1 which leads to joint-2.
- Link 1 is the output link for joint-1 and the input link for joint-2.
- This joint-link-numbering scheme is further followed for all joints and links in the robotic systems.



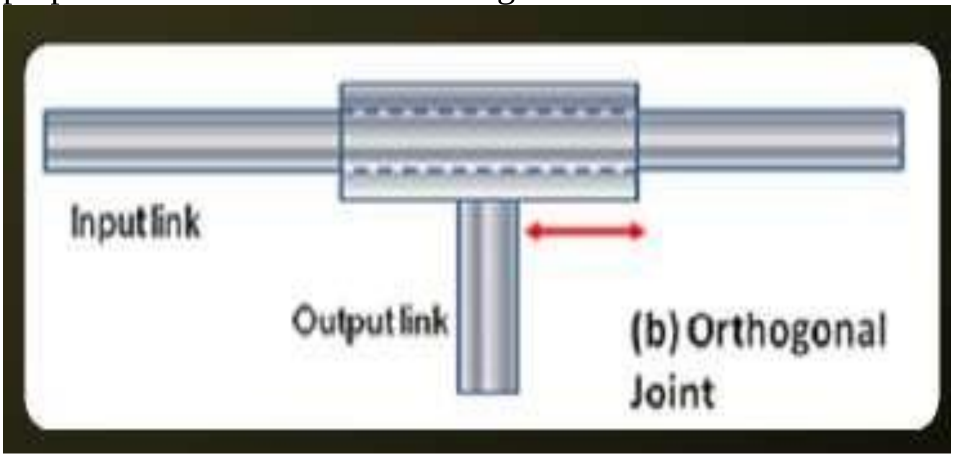
Nearly all industrial robots have mechanical joints that can be classified into following five types

a) Linear joint (type L joint)

- The relative movement between the input link and the output link is a translational sliding motion, with the axes of the two links being parallel.

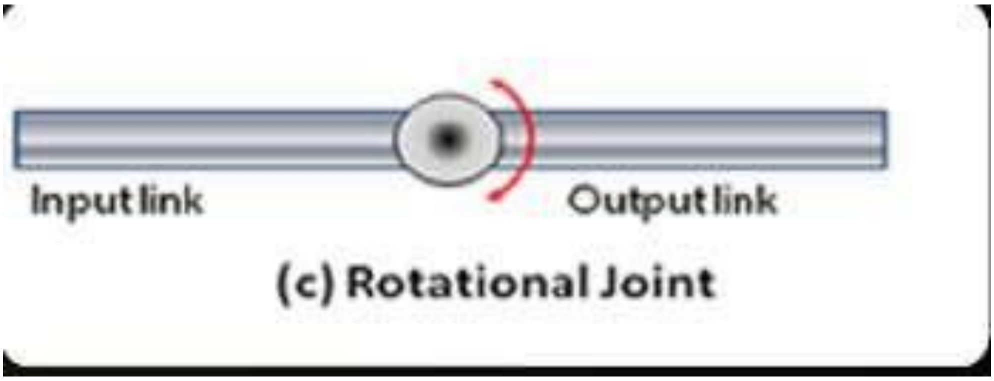
b) Orthogonal joint (type U joint)

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



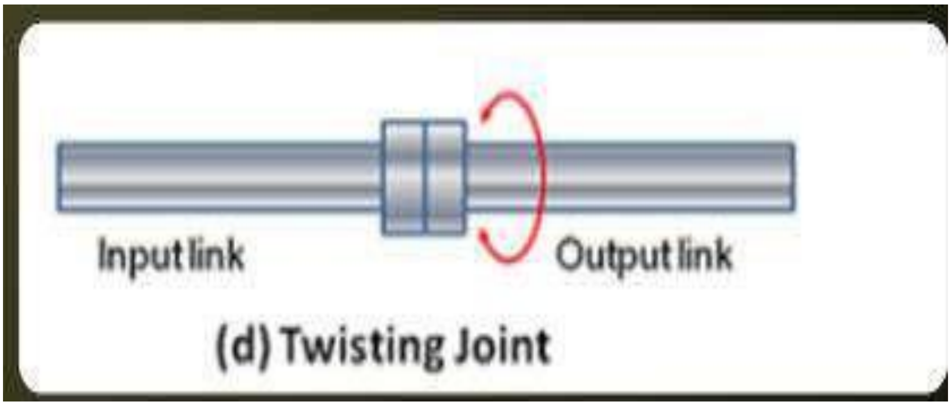
c) Rotational joint (type R joint)

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



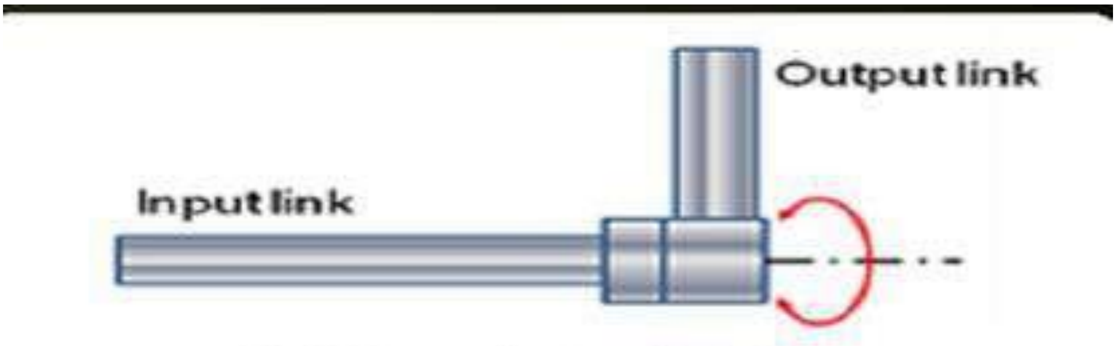
d) Twisting joint (type T joint)

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



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

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



(e) Revolving Joint

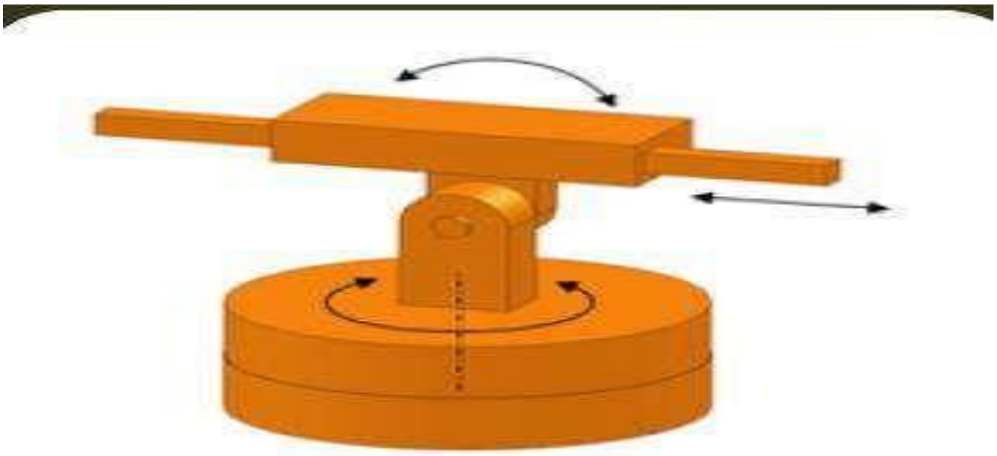
Coordinate System or Common Robot configurations

A coordinate system defines a plane or space by axes from a fixed point called the origin.
Robot targets and positions are located by measurements along the axes of coordinate systems. A robot uses several coordinate systems, each suitable for specific types of jogging or programming.
The Robots are mostly divided into four major configurations based on their appearances,
sizes, etc. such as:

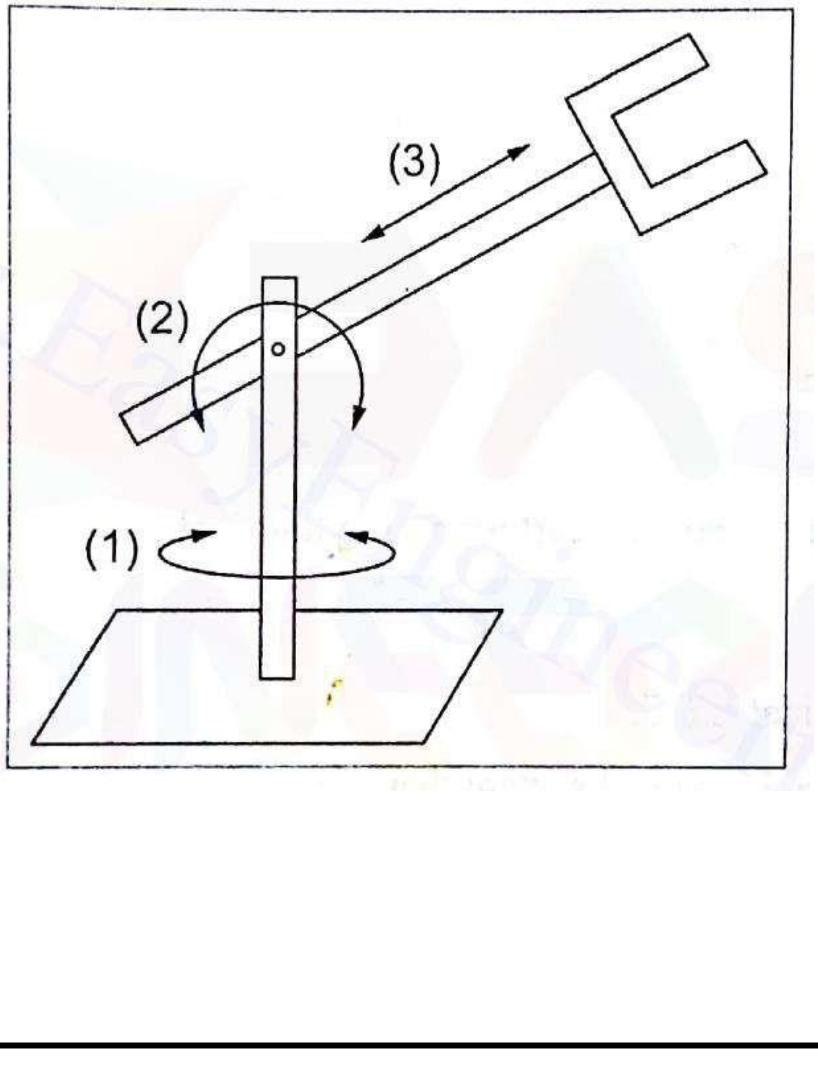
i. Polar Configuration
ii. Cylindrical Configuration,
iii. Cartesian Co-ordinate Configuration
iv. Jointed Arm Configuration, and
v. SCARA

(i) Polar configuration

• It consists of a sliding arm L-joint, actuated relative to the body, which rotates around both a vertical axis (T-joint) and horizontal axis (R-joint).

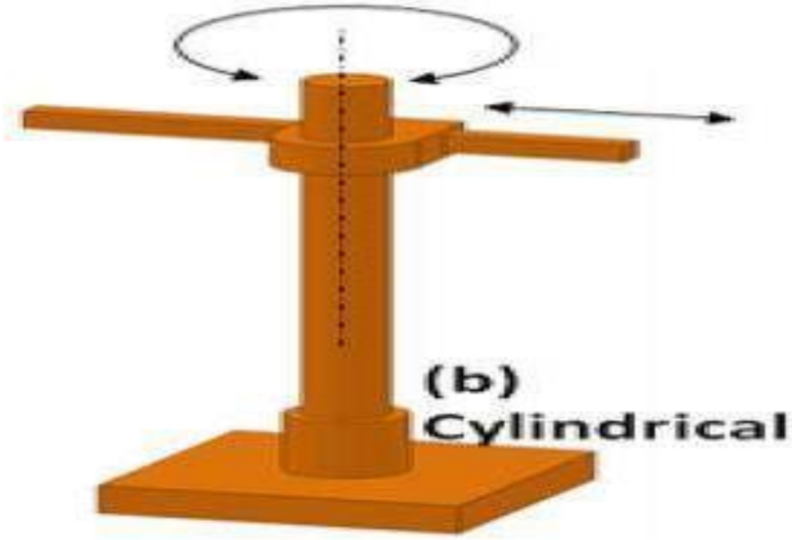


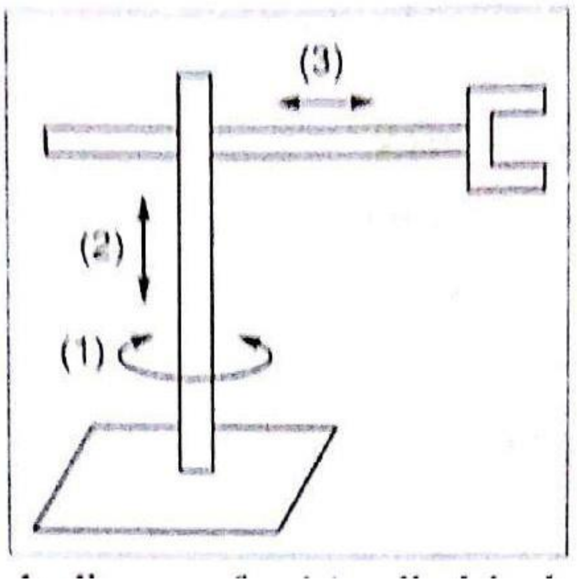
(a) Polar



(ii) Cylindrical configuration

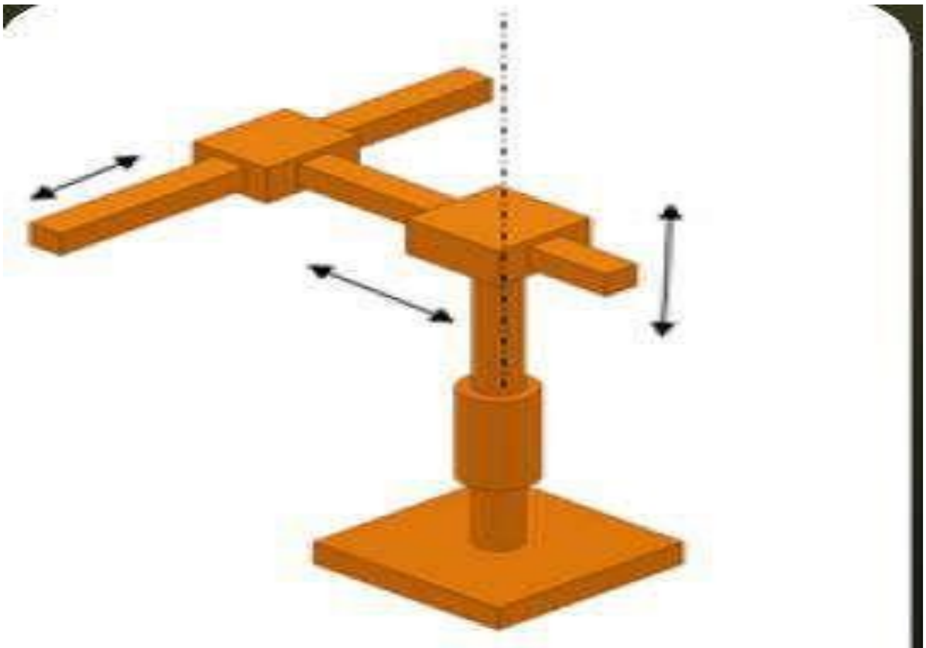
- It consists of a vertical column. An arm assembly is moved up or down relative to the vertical column.
- Arm can be moved in and out relative to the axis of the column. Common configuration is to use a T-joint to rotate the column about its axis.
- An L-joint is used to move the arm assembly vertically along the column, while an O joint is used to achieve radial movement of the arm.



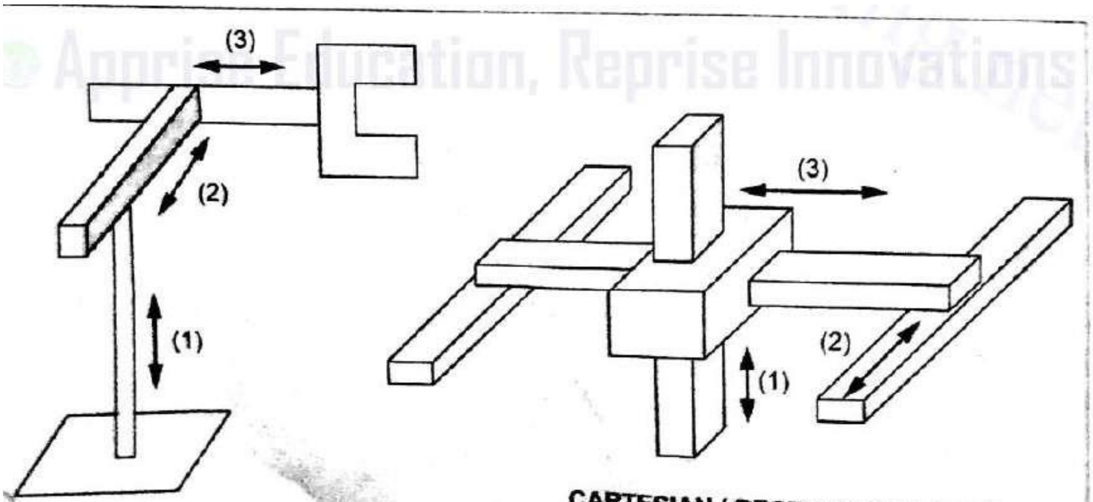


(iii) Cartesian co-ordinate robot

- It is also known as rectilinear robot and x-y-z robot. It consists of three sliding joints, two of which are orthogonal O-joints.



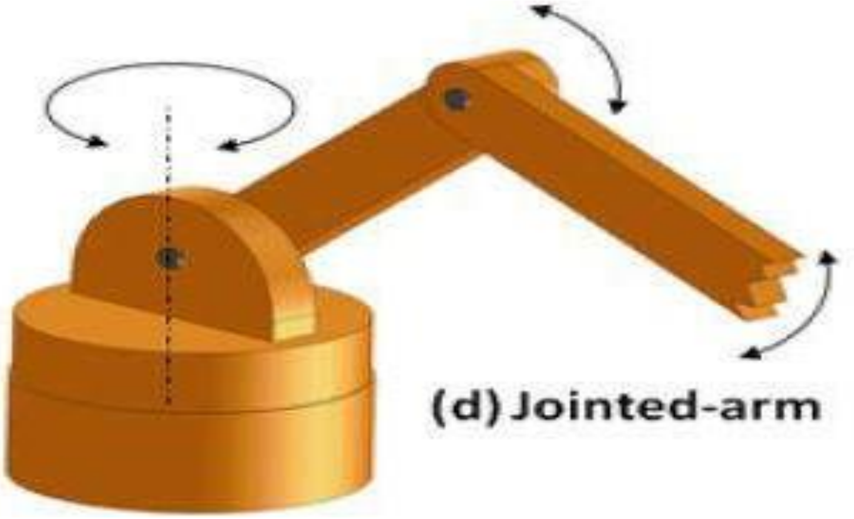
(c) Cartesian

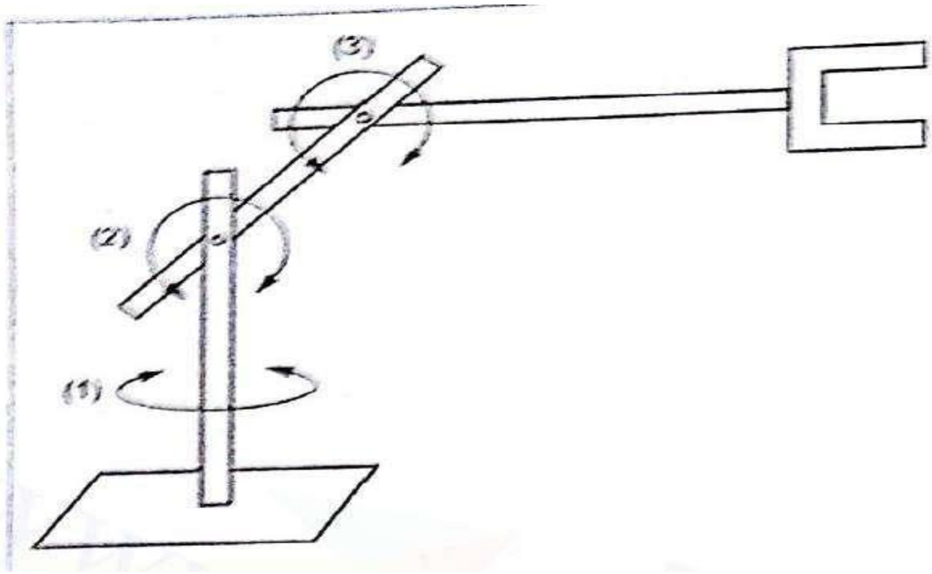


CARTESIAN / RECTILINEAR / GANTRY

(iv) Jointed-arm robot

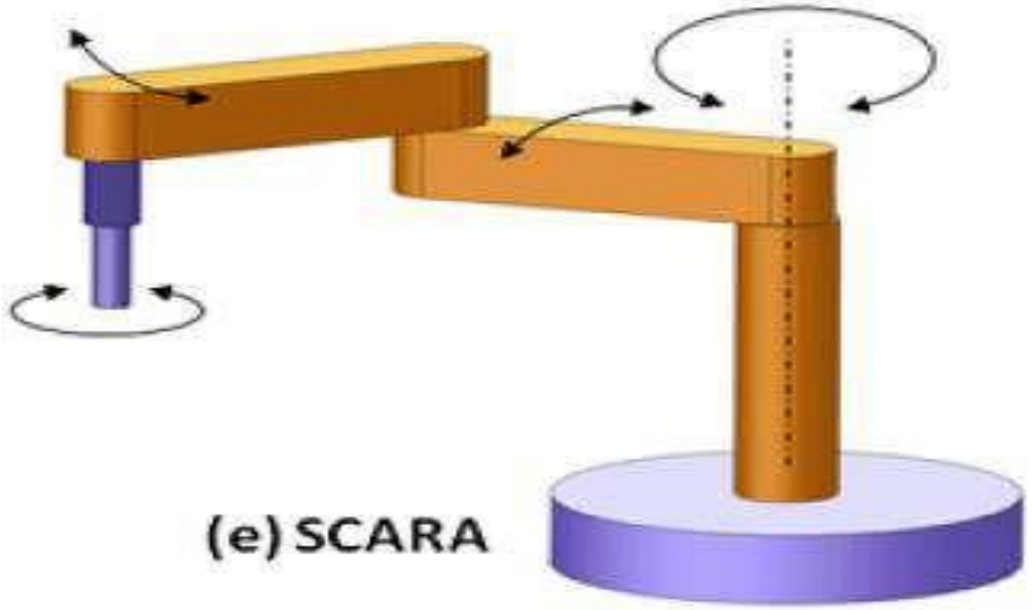
- It is similar to the configuration of a human arm.
- It consists of a vertical column that swivels about the base using a T-joint. Shoulder joint (R-joint) is located at the top of the column.
- The output link is an elbow joint (another R joint).


(d) Jointed-arm

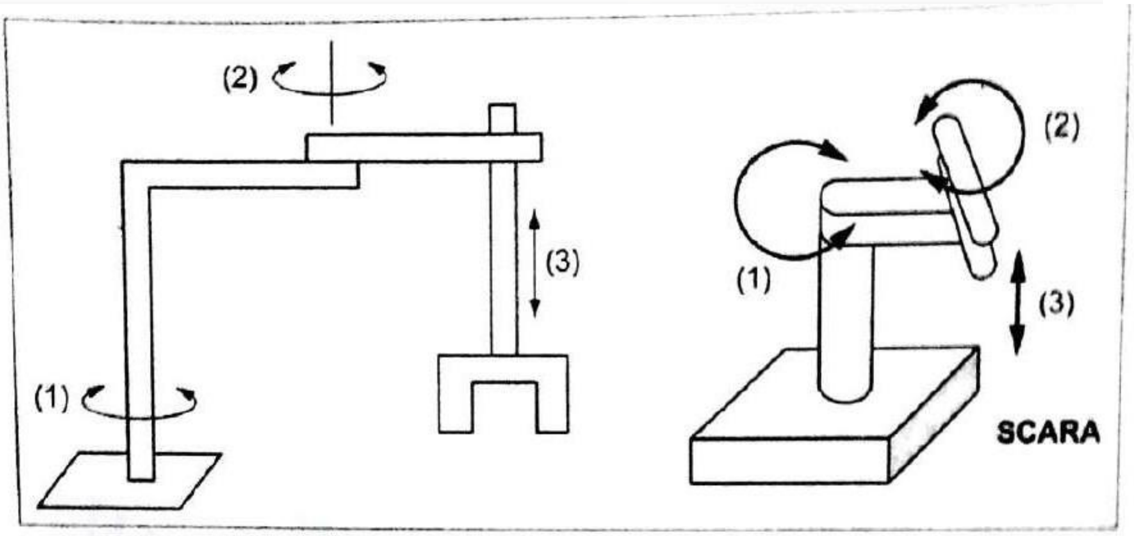


(v) SCARA

- Its full form is ‘Selective Compliance Assembly Robot Arm'.
- It is similar in construction to the jointer-arm robot, except the shoulder and elbow rotational axes are vertical.
- The arm is very rigid in the vertical direction, but compliant in the horizontal direction. Robot wrist assemblies consist of either two or three degrees-of freedom.
- A typical three-degree-of-freedom wrist joint is depicted in Figure.
- Roll joint is accomplished by use of a T-joint.
- Pitch joint is achieved by recourse to an R-joint. Yaw joint, a right-and-left motion, is gained by deploying a second R-joint.



(e) SCARA



work envelope:

***Work envelope** is defined as the envelope (or) space within which the robot can manipulate the end of the wrist.*

Figure 1.16 shows robot on design configuration.

- ✓ A robot's work envelope is its range of movement.
- ✓ The shape of the reachable work area of the robot.
- ✓ Space defined by the geometry of the robot; *i.e.,* Cartesian, cylindrical, spherical, revolute.
- ✓ It is the shape created when a manipulator reaches forward, backward, up and down.

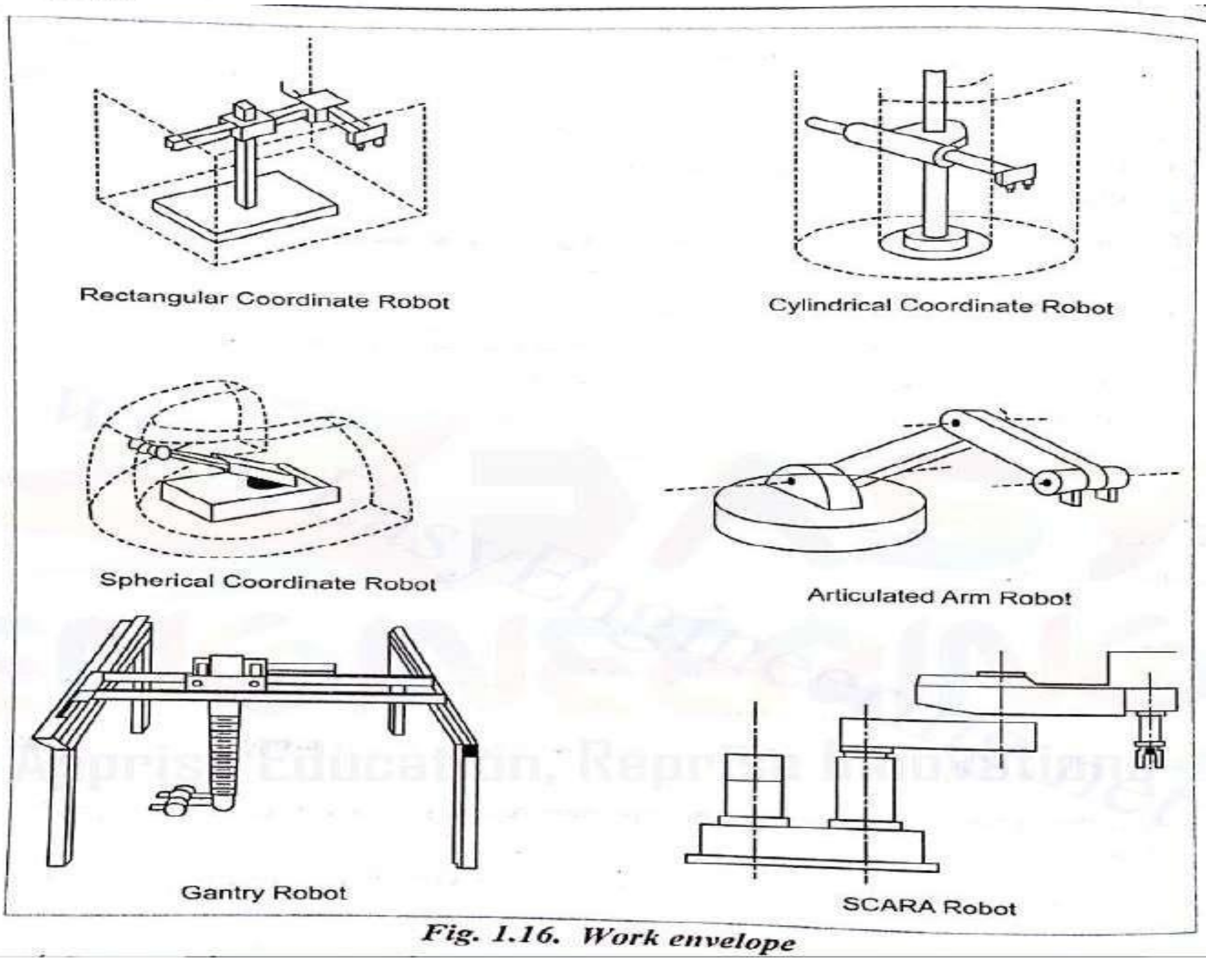

Rectangular Coordinate Robot
Cylindrical Coordinate Robot
Spherical Coordinate Robot
Articulated Arm Robot
Gantry Robot
SCARA Robot

Fig. 1.16. Work envelope

- ✓ The occurrence of this might not be predictable by maintenance or programming personnel working with the robot.
- ✓ A component malfunction could also cause an unpredictable movement and/or robot arm velocity.

Reach Envelope: A three-dimensional shape that defines the boundaries that the robot manipulator can reach. It also known as reach envelope.

Maximum envelope: The envelope that encompasses the maximum designed movements of all robot parts, including the end effector, work piece and attachments.

Restricted envelope is that portion of the maximum envelope which a robot is restricted by limiting devices.

Operating envelope: The restricted envelope that is used by the robot, while performing its programmed motions.

D ifferent types of robots.

are follows:

(a) Industrial Robot

- ✓ They have arms with gripper attached, which are fingers like and can grip or pick up various objects.
- ✓ They are used to pick and place.
- ✓ These robots can be programmed and computerized.
- ✓ Sensory, welding and assembly robots usually have a self contained micro or minicomputer.

(b) Laboratory Robot

- ✓ They take many shapes and many things.
- ✓ They have micro computers brain, multi joined arms, or advanced vision or tactile senses.
- ✓ Some of these may be mobile and others stationary.

(c) Explorer Robots

- ✓ They are used to go where human cannot go or fear to tread, *e.g.* to explore caves, dive far deeper underwater and rescue people in sunken ships.

(c) Explorer Robots

✓ They are used to go where human cannot go or fear to tread, *e.g.* to explore caves, dive far deeper underwater and rescue people in sunken ships.

✓ They are sophisticated machine that have sensory systems and remotely controlled.

(d) Hobbyist Robots

✓ Most of the hobbyist robots are mobile and made to operate by rolling around on wheels propelled by electric motors controlled by an on board microprocessor.

✓ Most hobbyist robots are equipped with speach synthesis and speed recognition systems.

✓ They have an arm or arms and resemble a person in appearance.

(e) Class Room Robots

✓ They are developed to assist the instructor in various aspects of the teaching learning processors.

(f) Educational Robot

✓ They have the ability to speak and respond to the spoken word.

✓ They can be used to entertain the people at various events or operate as a revoking advertisement.

(g) Tele-Robots

✓ Tele robots are guided by human operators through remote control.

1.10.1. TYPES OF INDUSTRIAL ROBOTS

1. Sequence Robot

✓ A manipulator which progresses successively through the various stages of an operation according to the predetermined sequence.

2. Playback Robot

✓ A manipulator which is able to perform an operation by reading out stored information for an operating sequence, which it learned before hand by being taken manually through the routine.

3. Intelligent Robot

- ✓ A Robot which can determine its own behaviour/conduct through its functions of sense and recognition.

4. Repeating Robot

- ✓ A manipulator performing an operation repeatedly, according to a rememorized work programme.

1.10.2. TELEROBOT

Telerobotics is the area of robotics concerned with the control of robots from a distance, chiefly using wireless connections "tethered" connections, or the Internet.

- ✓ It is a combination of two major subfields, teleoperation and telepresence.

Teleoperation

- ✓ ***Teleoperation*** means "doing work at a distance", although "work" may mean almost anything.

Classification of robots:

The robots can be classified according to the configuration, types of control, drive, movement, application, degree of freedom and sensory system.

1. Physical Configuration

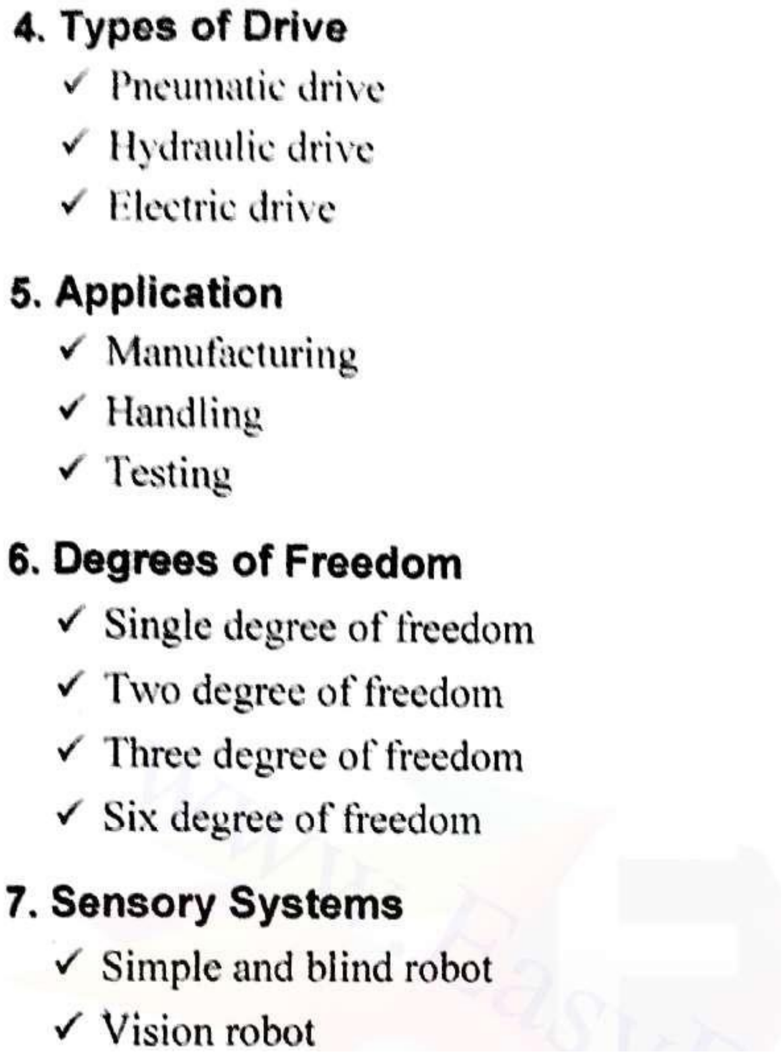
- ✓ Cartesian coordinate configuration:
- ✓ Cylindrical coordinate configuration:
- ✓ Polar coordinate configuration:
- ✓ Jointed arm configuration:
- ✓ SCARA.

2. Control System

- ✓ Point to point robots
- ✓ Straight line robots
- ✓ Continuous robot

3. Movement

- ✓ Fixed robot
- ✓ Mobile robot
- ✓ Walking or legged robot



4. Types of Drive

- ✓ Pneumatic drive
- ✓ Hydraulic drive
- ✓ Electric drive

5. Application

- ✓ Manufacturing
- ✓ Handling
- ✓ Testing

6. Degrees of Freedom

- ✓ Single degree of freedom
- ✓ Two degree of freedom
- ✓ Three degree of freedom
- ✓ Six degree of freedom

7. Sensory Systems

- ✓ Simple and blind robot
- ✓ Vision robot

Technical specification in Robotics.

1.14.1. Accuracy

- ✓ Accuracy can be defined as the ability of a robot to position its wrist end at desired target point within its reach.
- ✓ How closely the robot arm is able to move to a specific coordinate in the work cell.
- ✓ In terms of control resolution, the accuracy can be defined as one-half of the control resolution.
- ✓ This definition of accuracy applies in the worst case when the target point is between two control points.

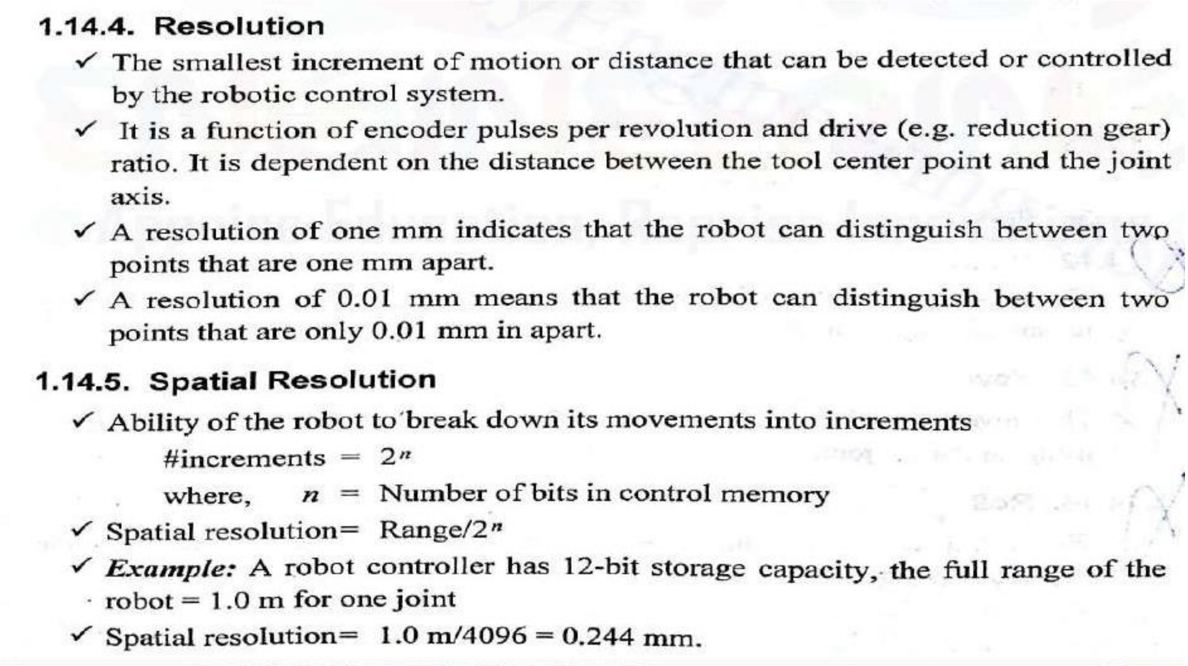
1.14.2. Repeatability

- ✓ Repeatability refers to robot's ability to return to the programmed point when it is commanded to do so.
- ✓ Degree to which the robot is able to return to a previously taught position.

- ✓ Repeatability is often smaller than accuracy.
- ✓ A repeatability of 0.25 mm indicates that once a manipulator has been taught to reach a certain point, it will continually return to that same point within 0.25 mm.

1.14.3. Reliability

- ✓ Reliability identifies the percentage of time that the robot is expected to operate without being taken out of service for maintenance or repair.
- ✓ Manufacturers estimate the reliability of their robots to be between 96% and 98%.
- ✓ Although this estimate is not true in all cases, most robot users have found their robots to be very reliable.



1.14.4. Resolution

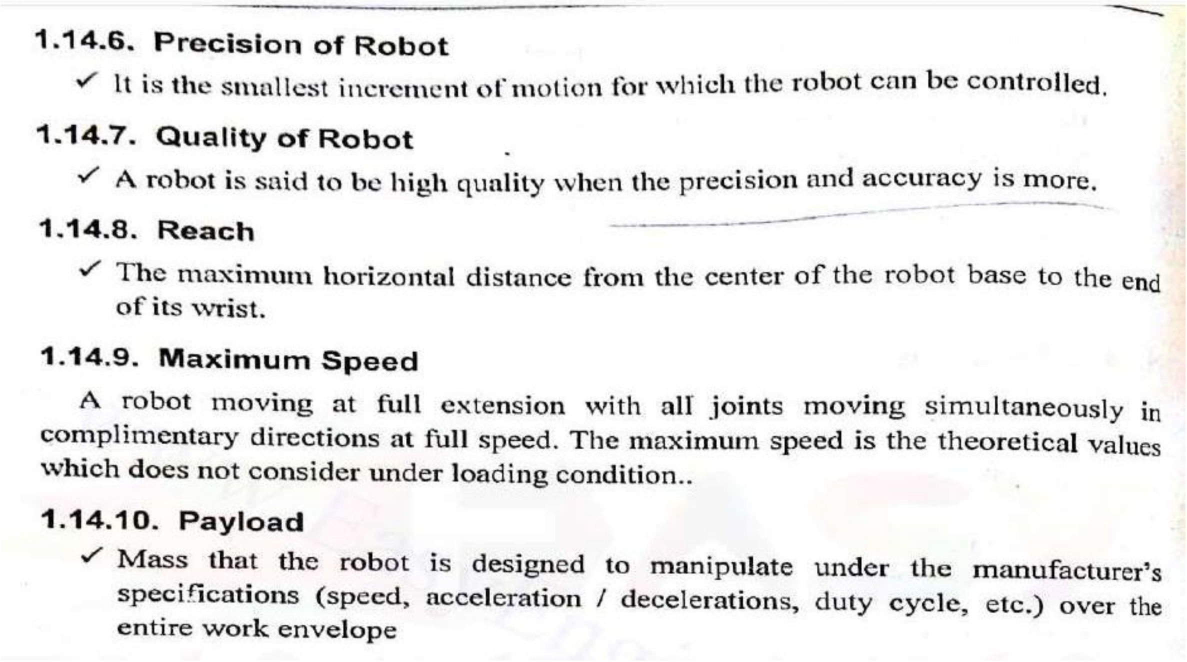
- ✓ The smallest increment of motion or distance that can be detected or controlled by the robotic control system.
- ✓ It is a function of encoder pulses per revolution and drive (e.g. reduction gear) ratio. It is dependent on the distance between the tool center point and the joint axis.
- ✓ A resolution of one mm indicates that the robot can distinguish between two points that are one mm apart.
- ✓ A resolution of 0.01 mm means that the robot can distinguish between two points that are only 0.01 mm in apart.

1.14.5. Spatial Resolution

- ✓ Ability of the robot to break down its movements into increments

  #increments = 2^n

  where, n = Number of bits in control memory
- ✓ Spatial resolution= Range/2^n
- ✓ *Example:* A robot controller has 12-bit storage capacity, the full range of the robot = 1.0 m for one joint
- ✓ Spatial resolution= 1.0 m/4096 = 0.244 mm.



1.14.6. Precision of Robot

- ✓ It is the smallest increment of motion for which the robot can be controlled.

1.14.7. Quality of Robot

- ✓ A robot is said to be high quality when the precision and accuracy is more.

1.14.8. Reach

- ✓ The maximum horizontal distance from the center of the robot base to the end of its wrist.

1.14.9. Maximum Speed

A robot moving at full extension with all joints moving simultaneously in complimentary directions at full speed. The maximum speed is the theoretical values which does not consider under loading condition..

1.14.10. Payload

- ✓ Mass that the robot is designed to manipulate under the manufacturer's specifications (speed, acceleration / decelerations, duty cycle, etc.) over the entire work envelope

Payload = End effector weight (or Tooling weight) + Part weight

1.14.11. Pay Load Capability of Robot

- ✓ The maximum load which can be carried by the manipulator at low (or) normal speed.

1.14.12. Pitch

- ✓ This involves the up and down of rotation of the object, typically done by means of a rotary or 'R' type joint.

1.14.13. Yaw

- ✓ This involves right to left rotation of the object, also accomplished typically using an R-type joint.

1.14.14. Roll

- ✓ This D.O.F can be accomplished by a twisting or T-type joint to rotate the object about the arm axis.

1.14.15. Duty Cycle

- ✓ Ratio of run time to total operational time that a robot can continuously work at the rated payload without overheating or degrading the robot specifications.

1.14.16. Offset

- ✓ Point of action for the tool mounted to the robot tool plate (or tool center point - TCP).
- ✓ Consider offset in computer programming of the robot.

1.15. BASIC ROBOT MOTIONS

There are six basic motions, or degree of freedom, which provide the robot, with capability to move the end effector through the required sequence of motions.

- ✓ The six degree of freedom are intended to emulate the versatility of movement possessed by the human arm. Not all robots are equipped with ability to move in all six degrees.

- ✓ The six basic motions consist of three arm and body motions and three wrist motions are illustrated in Fig.1.18 for the polar type robot. These motions are described below.

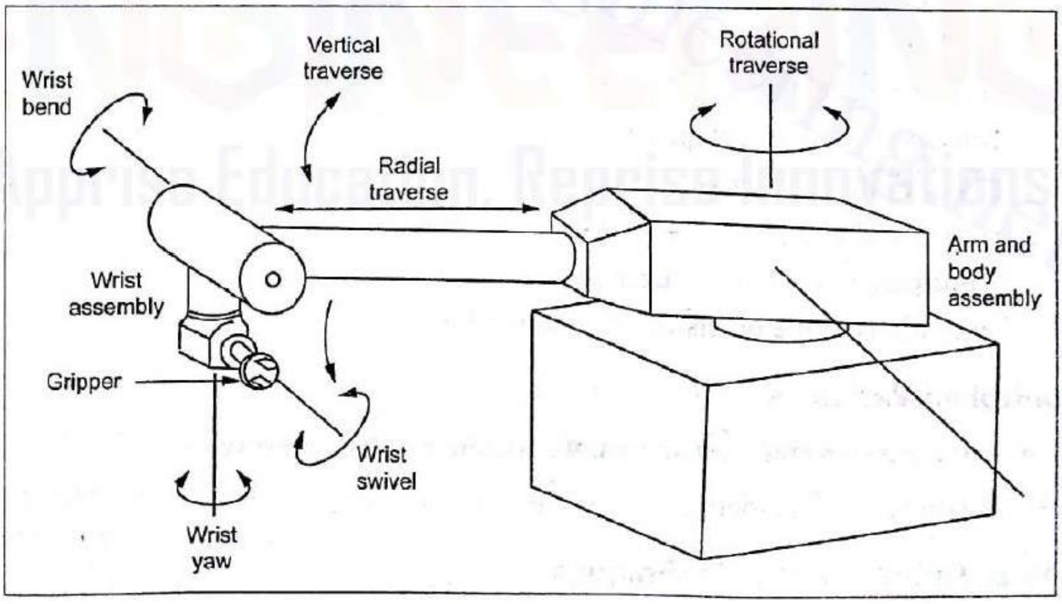


Fig. 1.18. Robot motion

The six basic robot motions are:

1. ***Rotational transverse*** - Movement about a vertical axis.
2. ***Radial transverse*** - Extension and retraction of arm.
3. ***Vertical transverse*** - Up and down motion.
4. ***Pitch*** - Up and down movement of the wrist.
5. ***Yaw*** - Side to side movement of wrist.
6. ***Roll*** - Rotation of wrist.

Four types of robot control.

- ✓ Industrial robots can be programmed from a distance to perform their required and preprogrammed operations with different types of paths generated through different control techniques.
- ✓ The Four different types of paths generated are

Path Control

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

1.17.2. Point-to-Point

- ✓ Robots programmed and controlled in this manner are programmed to move from one discrete point to another within the robot's working envelope.
- ✓ In the automatic mode of operation, the exact path taken by the robot will vary slightly due to variations in velocity, joint geometries, and point spatial locations.
- ✓ This difference in paths is difficult to predict and therefore can create a potential safety hazard to personnel and equipment.
- ✓ Primary programming device - teach pendant. Tooling or gripper moved into position using the teach pendant and controller records the coordinate values for the joint positions.
- ✓ The path robot takes when programming two consecutive points has no effect on the final program, only end points are recorded.
- ✓ Controller changes each axis at maximum rate. .

Advantages

- ✓ Relatively large and complex problems obtained at moderate cost.
- ✓ Reliability.

Disadvantages

- ✓ Lack of straight-line control.

1.17.4. Continuous Path

- A robot whose path is controlled by storing a large number or close succession of spatial points in memory during a teaching sequence is a continuous path controlled robot.
- When the robot is placed in the automatic mode of operation, the program is replayed from memory and a duplicate path is generated.

Advantages

- Very complex tasks can be performed.
- Duplicates movement of the operator.

Disadvantages

- Expensive
- High level of control

Applications

- Spray painting

1.17.3. Controlled Path

- The path or mode of movement ensures that the end of the robot's arm will follow a predictable (controlled) path and orientation as the robot travels from point to point.
- The coordinate transformations required for this hardware management are calculated by the robot's control system computer.
- Observations that result from this type of programming are less likely to present a hazard to personnel and equipment.
- Point-to-point system with added capability of providing control of the end effector.
- Axis actuators driven ,so that the path between points is a straight line

Advantages

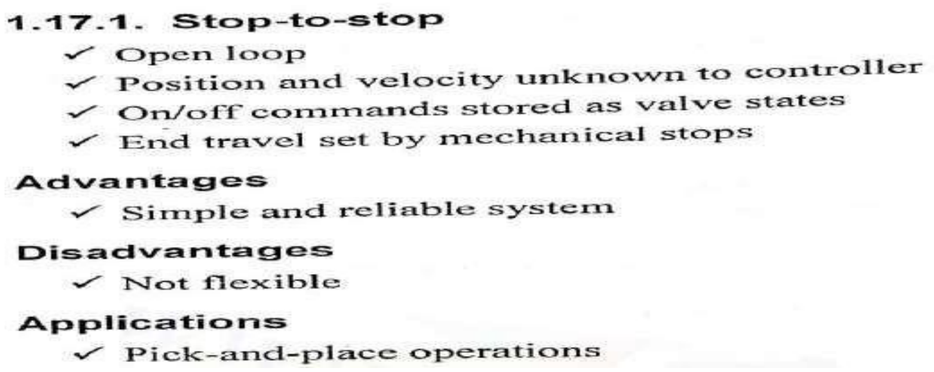
- Path control
- Complex tasks

Disadvantages

- Increase in controller intelligence

Applications

- Operations requiring path control
- Welding, etc.



1.17.1. Stop-to-stop

- ✓ Open loop
- ✓ Position and velocity unknown to controller
- ✓ On/off commands stored as valve states
- ✓ End travel set by mechanical stops

Advantages

- ✓ Simple and reliable system

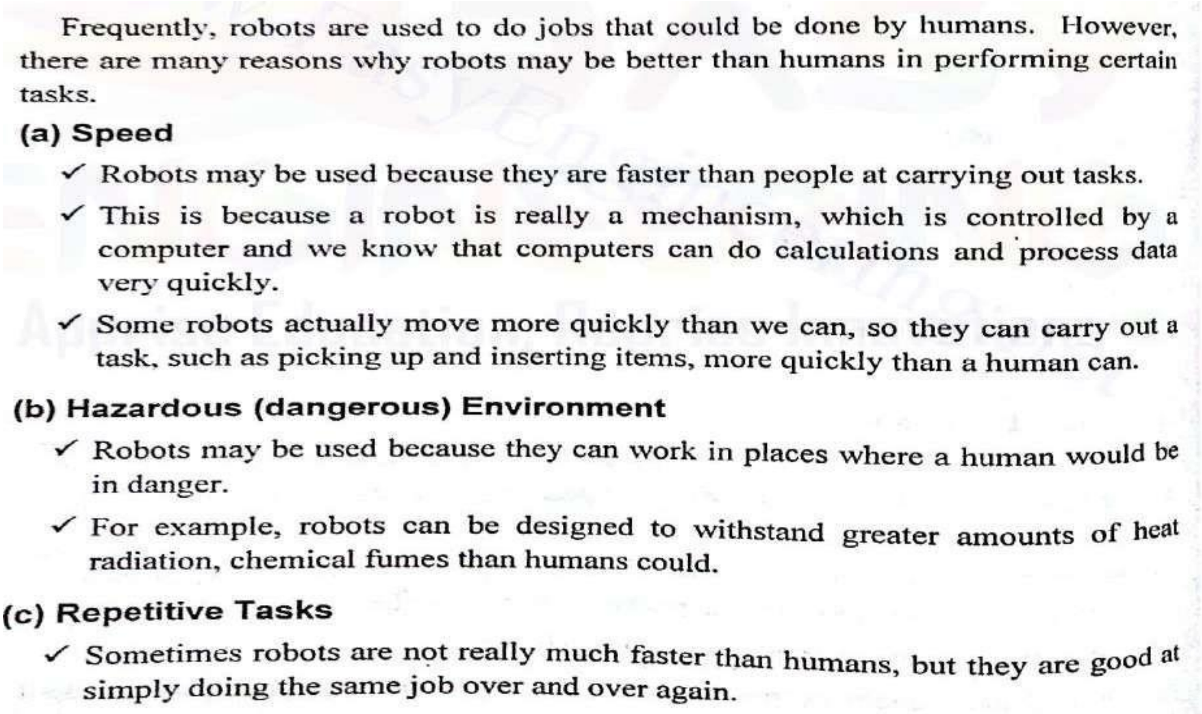
Disadvantages

- ✓ Not flexible

Applications

- ✓ Pick-and-place operations

Need for robots



Frequently, robots are used to do jobs that could be done by humans. However, there are many reasons why robots may be better than humans in performing certain tasks.

(a) Speed

- ✓ Robots may be used because they are faster than people at carrying out tasks.
- ✓ This is because a robot is really a mechanism, which is controlled by a computer and we know that computers can do calculations and process data very quickly.
- ✓ Some robots actually move more quickly than we can, so they can carry out a task, such as picking up and inserting items, more quickly than a human can.

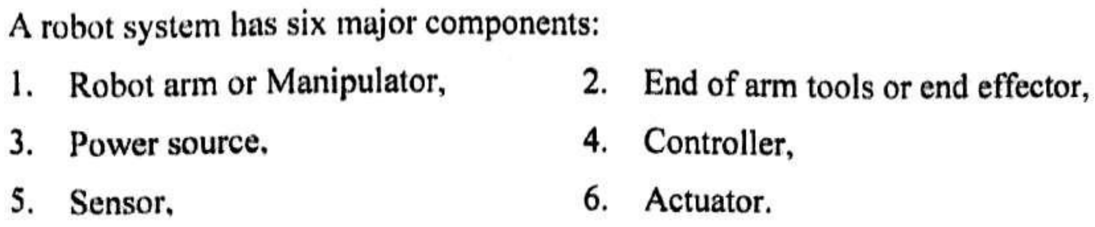
(b) Hazardous (dangerous) Environment

- ✓ Robots may be used because they can work in places where a human would be in danger.
- ✓ For example, robots can be designed to withstand greater amounts of heat radiation, chemical fumes than humans could.

(c) Repetitive Tasks

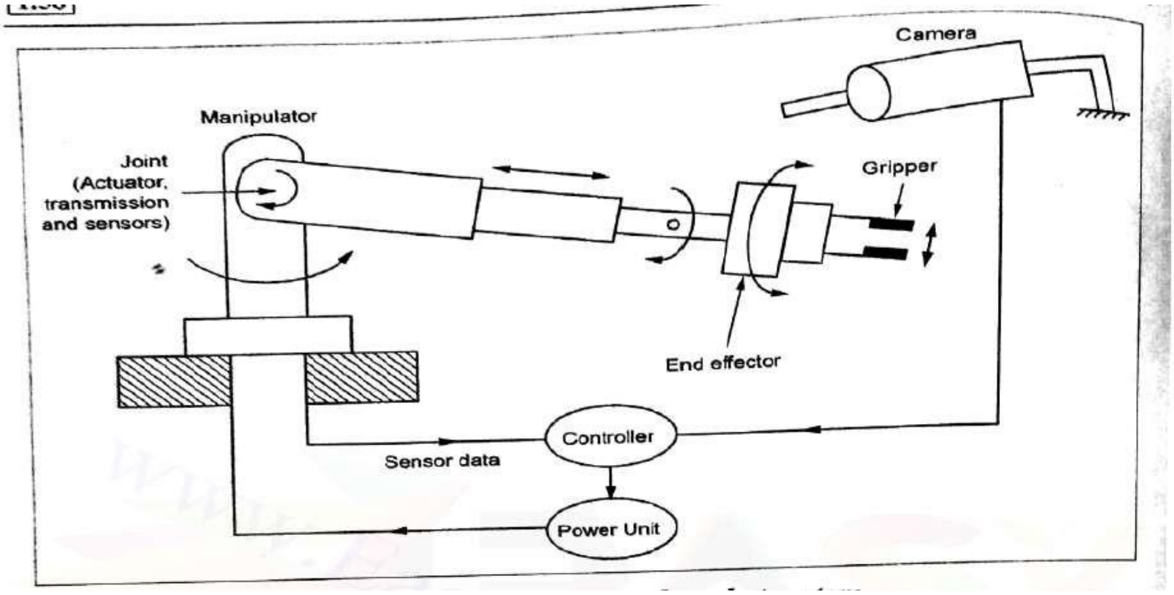
- ✓ Sometimes robots are not really much faster than humans, but they are good at simply doing the same job over and over again.

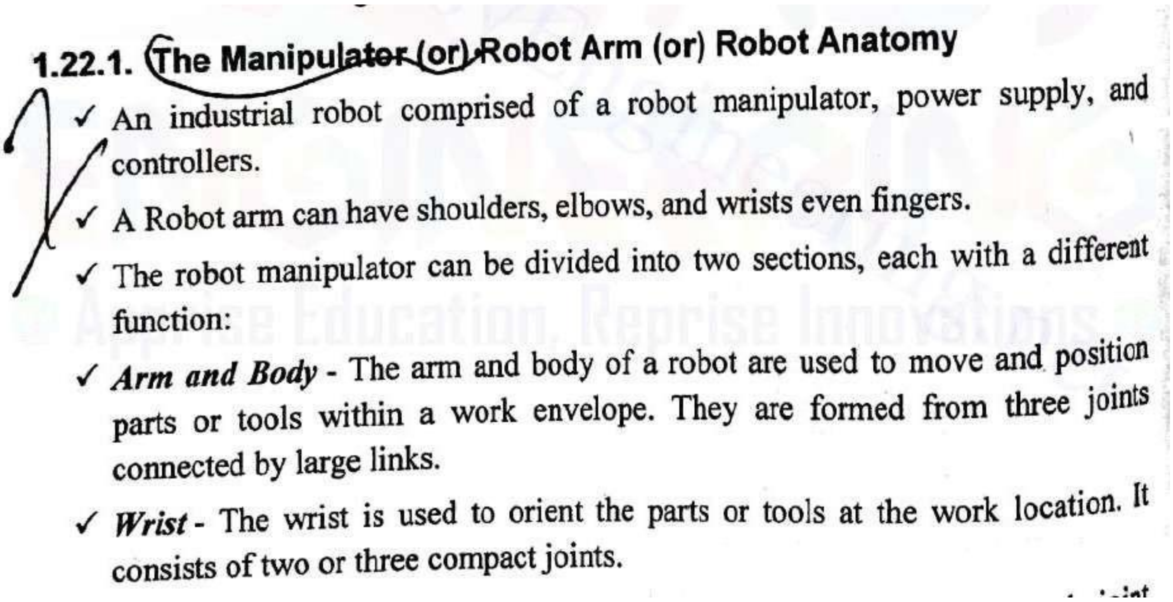
Robot parts and functions



A robot system has six major components:

1. Robot arm or Manipulator,
2. End of arm tools or end effector,
3. Power source,
4. Controller,
5. Sensor,
6. Actuator.





1.22.1. The Manipulator (or) Robot Arm (or) Robot Anatomy

- ✓ An industrial robot comprised of a robot manipulator, power supply, and controllers.
- ✓ A Robot arm can have shoulders, elbows, and wrists even fingers.
- ✓ The robot manipulator can be divided into two sections, each with a different function:
- ✓ ***Arm and Body*** - The arm and body of a robot are used to move and position parts or tools within a work envelope. They are formed from three joints connected by large links.
- ✓ ***Wrist*** - The wrist is used to orient the parts or tools at the work location. It consists of two or three compact joints.

- ✓ The arm-and-body section of the manipulator is based on one of four configurations. Each of these anatomies provides a different work envelope and is suited for different applications.
- ✓ ***Gantry*** - These robots have linear joints and are mounted overhead. They are also called Cartesian and rectilinear robots.
- ✓ ***Cylindrical*** - Named for the shape of its work envelope, cylindrical anatomy robots are fashioned from linear joints that connect to a rotary base joint.
- ✓ ***Polar*** - The base joint of a polar robot allows for twisting and the joints are a combination of rotary and linear types. The work space created by this configuration is spherical.

1.22.2. End-Effector

The end-effector (commonly known as robot hand) mounted on the wrist enables the robot to perform specified tasks. Various types of end-effectors are designed for the same robot to make it more flexible and versatile.

End-effectors are categorized into two major types:

1. Grippers
2. Tools

1) Grippers

Grippers are generally used to grasp and hold an object and place it at a desired location.

- ✓ Mechanical grippers
- ✓ Vacuum or suction cups
- ✓ Magnetic grippers
- ✓ Adhesive grippers
- ✓ Hooks, scoops, and so forth

2) Tools

At times, a robot is required to manipulate a tool to perform an operation on a workpiece. In such applications the end-effector is a tool itself.

- ✓ Spot-welding tools
- ✓ Arc-welding tools
- ✓ Spray-painting nozzles
- ✓ Rotating spindles for drilling
- ✓ Rotating spindles for grinding

1.22.3. Power Source/Drives

The power source is the unit that supplies power to controller and the manipulator. Almost all modern robots are driven by brushless AC servo motors, but many of the robots existing in industry use other drives. The controller is operated by an AC power. The manipulator is controlled by hydraulic or pneumatic drives.

1.22.3.1. Pneumatic Supply/Pneumatic Drives

- ✓ Pneumatic power can be readily adapted to the actuation of piston devices to provide translational movement of sliding joints.

1.22.3.2. Hydraulic Supply/Hydraulic Drives

- ✓ Hydraulic drives were used on a large number of the early robots as it was more rigid and controllable than pneumatics and it could provide more power than the electric drives then available.
- ✓ Hydraulic drive is generally associated with large robots, such as the Unimate 2000 series.

1.22.3.3. Electric Supply/Electric Drives

Electric

- ✓ There are three major types of electric drive that have been used for robots.

Stepper Motors

- ✓ These are used mainly for simple pick and place mechanisms where cheapness is more important than power or controllability.

DC Servos

- ✓ For the early electric robots the DC servo drive was used extensively. It gave good power output with a high degree of control of both speed and position.

AC Servos

- ✓ In recent years the AC servo has taken over from the DC servo as the standard drive. These modern motors give higher power output and are almost silent in operation. As they have no brushes they are very reliable and require almost no maintenance in operation.
- ✓ In general, each motor requires appropriate reduction gear systems to provide proper output force or torque.

1.22.4. Actuators

What are Actuators?

- ✓ Actuators are the devices used for converting hydraulic energy, (or) electrical energy into mechanical energy.
- ✓ In other words, actuators perform a function just opposite to that of the pumps.
- ✓ The pressurized hydraulic fluid delivered by the hydraulic pump is supplied to the actuators, which converts the energy of the fluid into mechanical energy. This mechanical energy is used to get the work done.
- ✓ The hydraulic actuators produce linear, rotary, or oscillating motion.
- ✓ They can be used for lifting, tilting, clamping, opening, closing, metering, mixing, turning, swinging, counterbalancing, bending and for many other operations.
- ✓ Special applications are on rollover devices, conveyors, valve operations, printing presses, rock drills, dies, clamps, machine tools, etc.

1.22.5. Sensors

A sensor is an electronic device that transfers a physical phenomenon (temperature, pressure, humidity, etc.) into an electrical signal.

Sensors in robotics are used for both internal feedback control and external interaction with the outside environment.

The Purpose of a Sensor

Sensor is used for an element which produces a signal relating to the quantity being measured i.e., an electrical resistance temperature element the quantity being measured is temperature and the sensors transforms an input of temperature in to a change in resistance.

- ✓ Analogous to human sensory organs Eyes, Ears, Nose, Tongue, Skin.
- ✓ Sensors help the robot knowing its surroundings better.
- ✓ Improves its actions and decision-making ability.
- ✓ Provides feedback control.

Examples

- ✓ Light Dependent Resistor
- ✓ Thermistor
- ✓ IR Photo Sensor

Drive:

The drive is the "engine" that drives the links (the sections between the joints into their desired position. Without a drive, a robot would just sit there, which is not often helpful. Most drives are powered by air, water pressure, or electricity

The robot’s capacity to move its body, arm, wrist and joints are provided by drive system

The common drive systems used in robotics are

1. Mechanical drives
2. Pneumatic drives
3. Hydraulic drives
4. Electrical drives

2. Pneumatic drives

✓ Pneumatic actuators utilise pneumatic energy provided by a compressor and transforms it into mechanical energy by means of pistons (or) turbines.

✓ Pressurised air is used to transmit and control power.

✓ Pneumatic actuators are the devices that cause things to move by taking the advantage of potential energy.

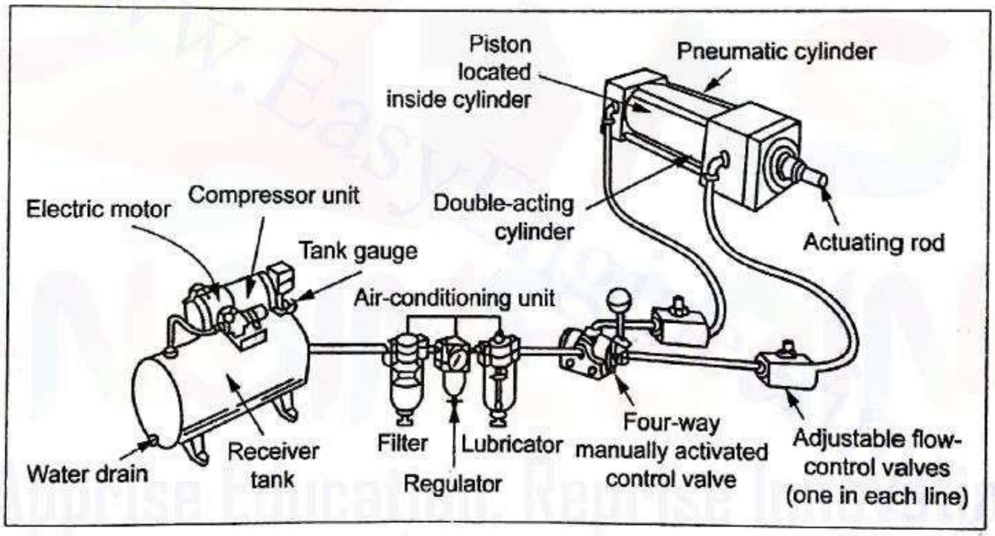
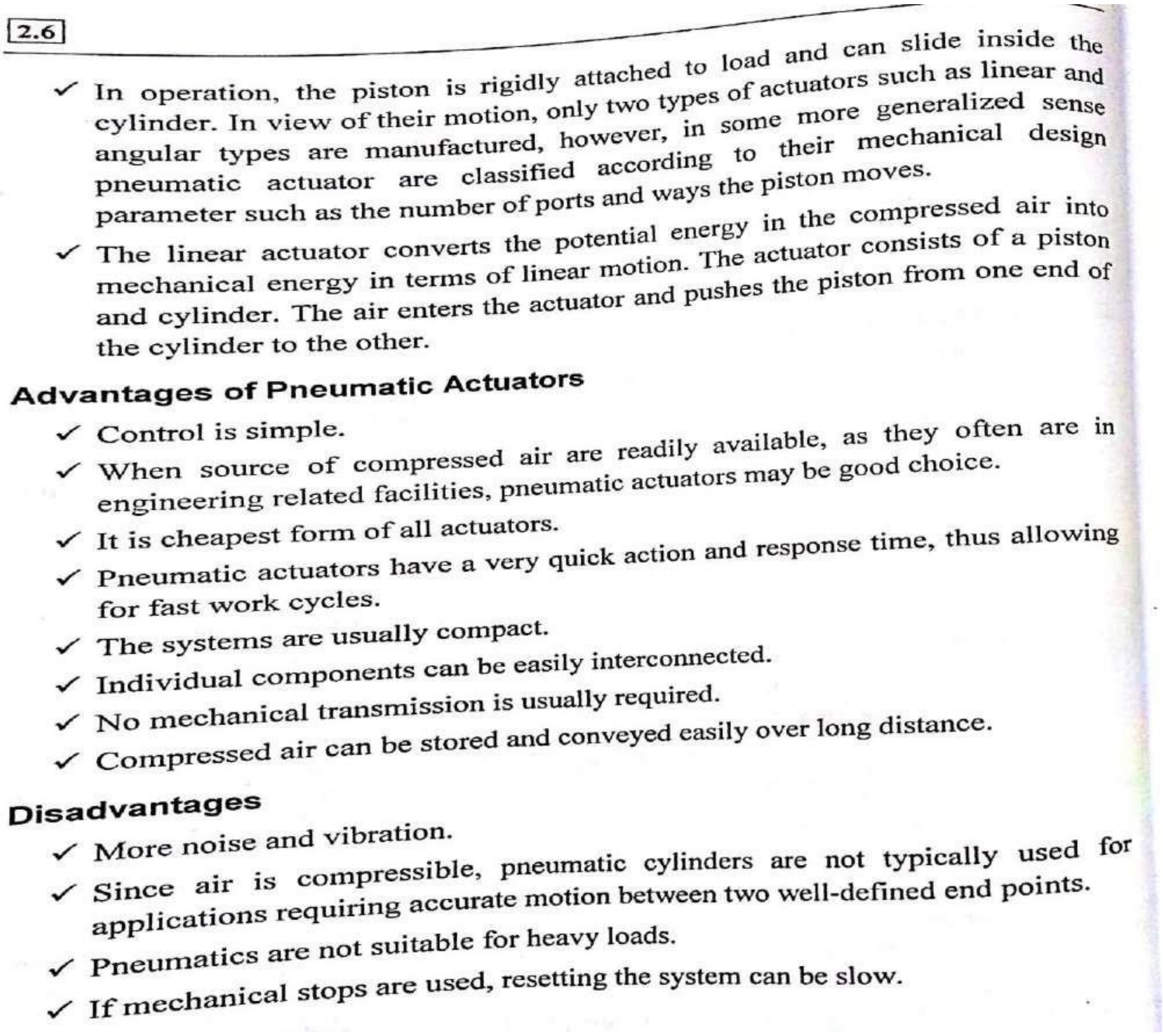


Fig. 2.2. A pneumatic actuator

✓ The actuators in their conventional form are basically called pneumo-mechanical device and have been used to automate industrial tasks of iterative nature.

- ✓ The actuator has three components namely: 1. Cylinder, 2. Piston, 3. Valve.
- ✓ The cylinder is hollow chamber into which the external compressed air is allowed to enter, so as to enable the piston to move.
- ✓ The air enters through a hole usually called port and a valve, which is considered as an actuator, controls the rate of flow of air into the chamber. The valve is a controlling element and it is an electromechanical device.



- ✓ In operation, the piston is rigidly attached to load and can slide inside the cylinder. In view of their motion, only two types of actuators such as linear and angular types are manufactured, however, in some more generalized sense pneumatic actuator are classified according to their mechanical design parameter such as the number of ports and ways the piston moves.
- ✓ The linear actuator converts the potential energy in the compressed air into mechanical energy in terms of linear motion. The actuator consists of a piston and cylinder. The air enters the actuator and pushes the piston from one end of the cylinder to the other.

Advantages of Pneumatic Actuators

- ✓ Control is simple.
- ✓ When source of compressed air are readily available, as they often are in engineering related facilities, pneumatic actuators may be good choice.
- ✓ It is cheapest form of all actuators.
- ✓ Pneumatic actuators have a very quick action and response time, thus allowing for fast work cycles.
- ✓ The systems are usually compact.
- ✓ Individual components can be easily interconnected.
- ✓ No mechanical transmission is usually required.
- ✓ Compressed air can be stored and conveyed easily over long distance.

Disadvantages

- ✓ More noise and vibration.
- ✓ Since air is compressible, pneumatic cylinders are not typically used for applications requiring accurate motion between two well-defined end points.
- ✓ Pneumatics are not suitable for heavy loads.
- ✓ If mechanical stops are used, resetting the system can be slow.

3. Hydraulic drives

- ✓ Hydraulic actuators transform the hydraulic energy stored in a reservoir into mechanical energy by means of suitable pumps.
- ✓ Hydraulic actuators are also fluid power device for industrial robots which utilise high pressure fluid such as oil to transmit forces to the point of application desired. Hydraulic actuator as shown in Fig.2.1.

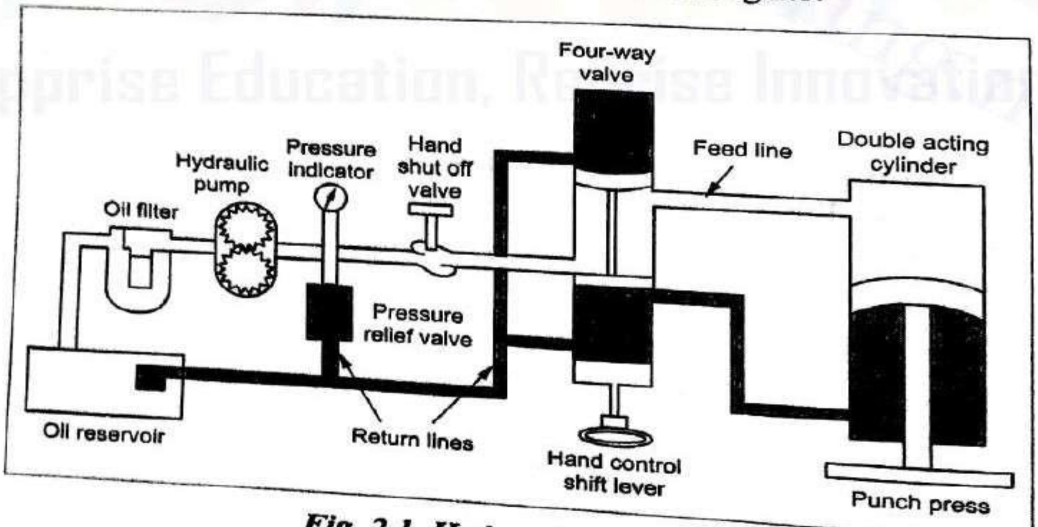


Fig. 2.1. Hydraulic actuator

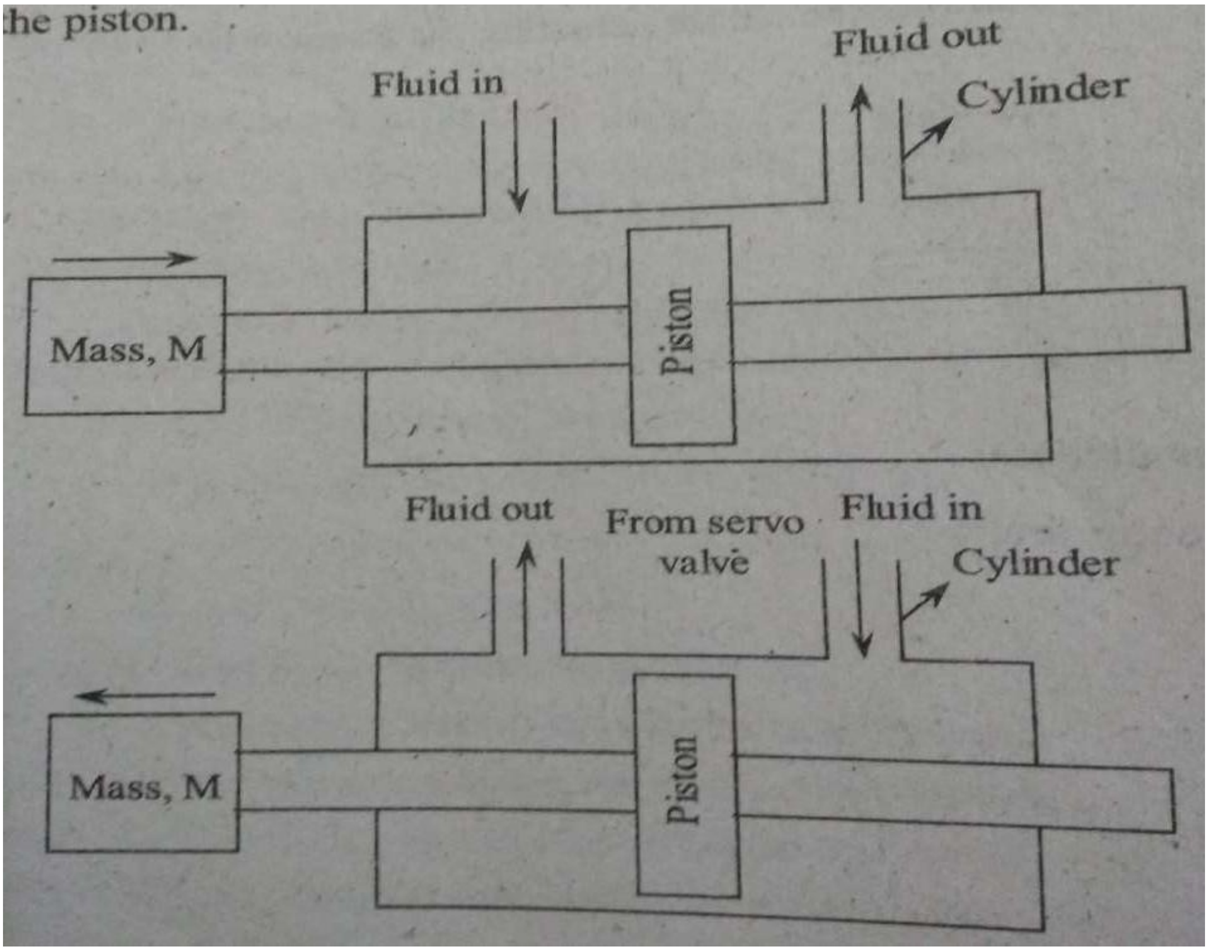
- ✓ Principle and working of hydraulic actuation system is similar to pneumatic system, except that instead of air, fluid such as water or oil supplies the inlet power. Although the working principle remains the same, the structural design varies.
- ✓ These devices utilize pressurized fluid to produce linear motion and force (or) rotary motion and torque.
- ✓ Hydraulic actuators are used in a variety of power transfer application.
- ✓ The pressure that is transmitted when a quantity of fluid such as water (or) oil, is forced through a comparatively small orifice (or) through tube, operate hydraulic actuator. Based on the principle, a handful number of hydraulic actuating components are designed.
- ✓ They are hydraulic accumulator, hydraulic cylinders, hydraulic flow controls, hydraulic motors, hydraulic power units, hydraulic pumps, hydraulic pressure regulators, rod less hydraulic cylinder and vacuum pressure regulators.

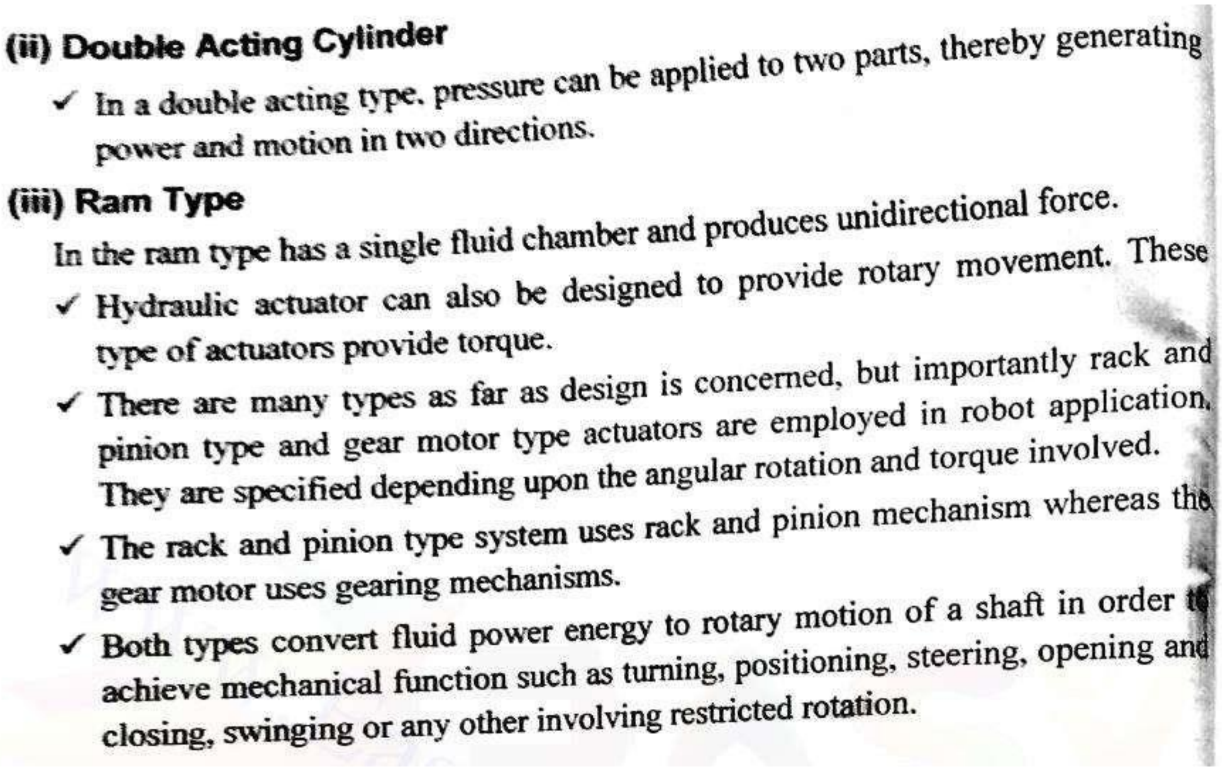
- ✓ Hydraulic actuators, mainly are classified into three type.
  - (*i*) Single acting spring return type
  - (*ii*) Double acting cylinder
  - (*iii*) Ram type

i) Single Acting Spring Return Type

- ✓ The single acting cylinder is pressurized on only one end. An internal spring is compressed by pressure on the cap end, and a rod extends. A reduction of pressure allows for the retraction of the rod by spring.

he piston.





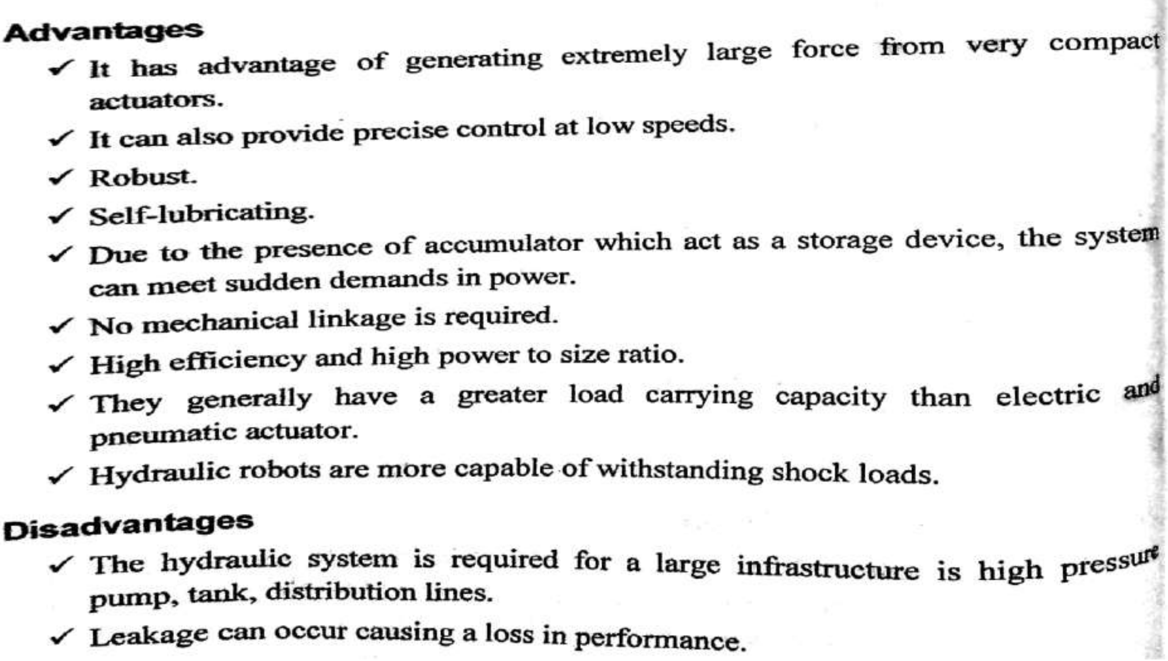
(ii) Double Acting Cylinder

- ✓ In a double acting type, pressure can be applied to two parts, thereby generating power and motion in two directions.

(iii) Ram Type

In the ram type has a single fluid chamber and produces unidirectional force.

- ✓ Hydraulic actuator can also be designed to provide rotary movement. These type of actuators provide torque.
- ✓ There are many types as far as design is concerned, but importantly rack and pinion type and gear motor type actuators are employed in robot application. They are specified depending upon the angular rotation and torque involved.
- ✓ The rack and pinion type system uses rack and pinion mechanism whereas th gear motor uses gearing mechanisms.
- ✓ Both types convert fluid power energy to rotary motion of a shaft in order t achieve mechanical function such as turning, positioning, steering, opening and closing, swinging or any other involving restricted rotation.



Advantages

- ✓ It has advantage of generating extremely large force from very compact actuators.
- ✓ It can also provide precise control at low speeds.
- ✓ Robust.
- ✓ Self-lubricating.
- ✓ Due to the presence of accumulator which act as a storage device, the system can meet sudden demands in power.
- ✓ No mechanical linkage is required.
- ✓ High efficiency and high power to size ratio.
- ✓ They generally have a greater load carrying capacity than electric and pneumatic actuator.
- ✓ Hydraulic robots are more capable of withstanding shock loads.

Disadvantages

- ✓ The hydraulic system is required for a large infrastructure is high pressure pump, tank, distribution lines.
- ✓ Leakage can occur causing a loss in performance.

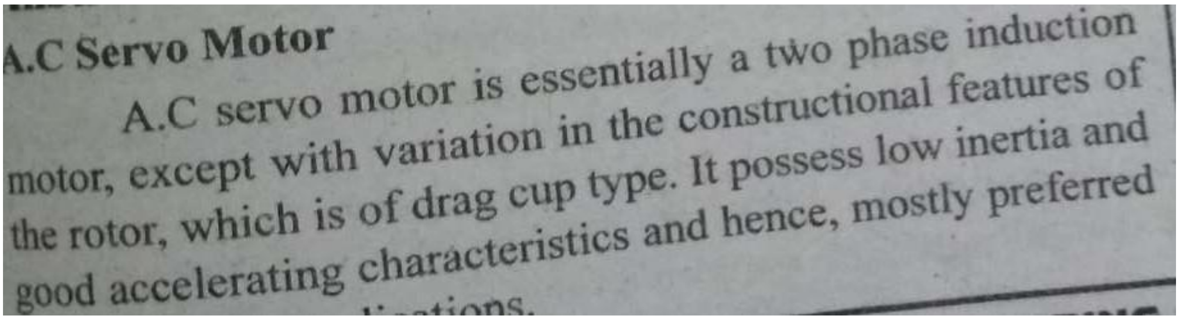
4. Electrical drives

Electric actuator is a device, which uses electrical energy to impart motion.

Electric actuators classified in to 3 types

1. A.C. Servo Motors,
2. D.C. Servo Motors,
3. Stepper Motor.

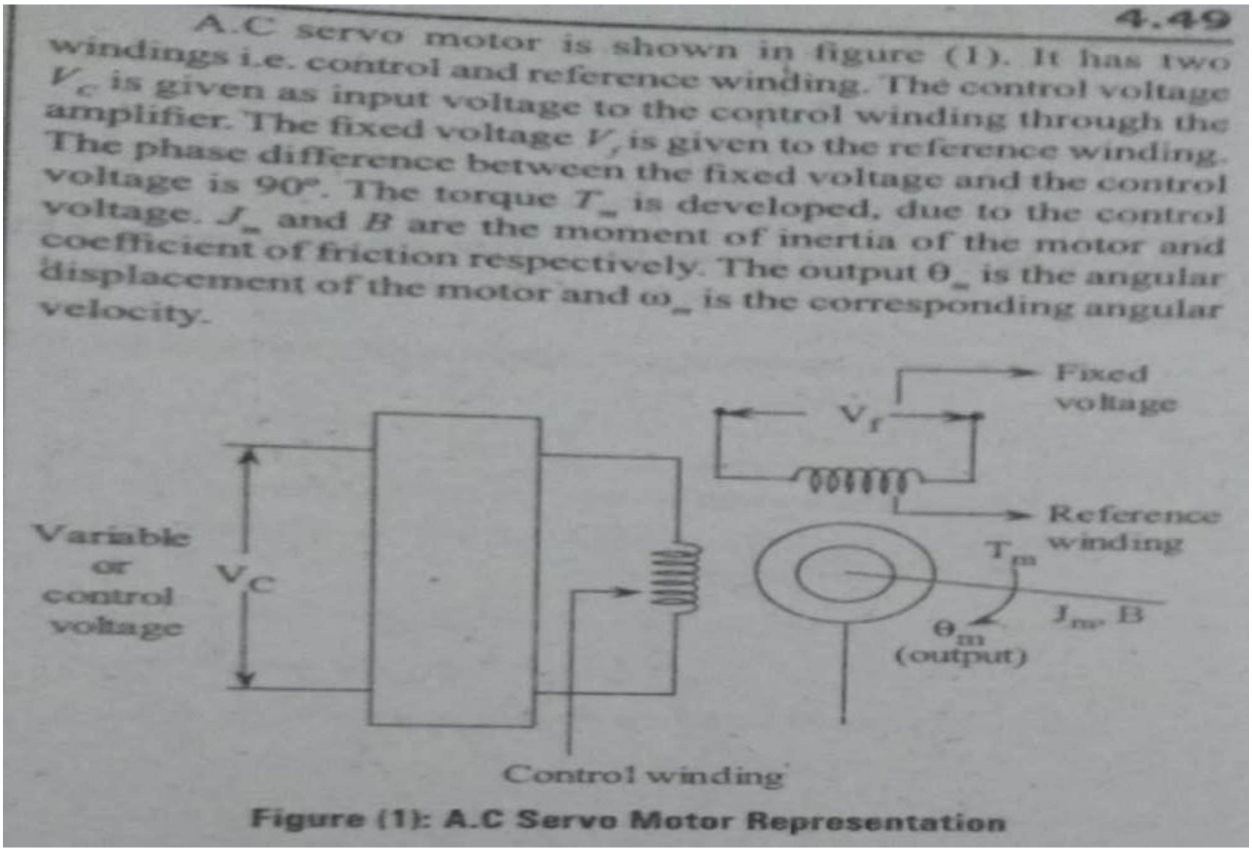
1. A.C. Servo Motors



A.C Servo Motor

A.C servo motor is essentially a two phase induction motor, except with variation in the constructional features of the rotor, which is of drag cup type. It possess low inertia and good accelerating characteristics and hence, mostly preferred

Mostly preferred for low power applications.

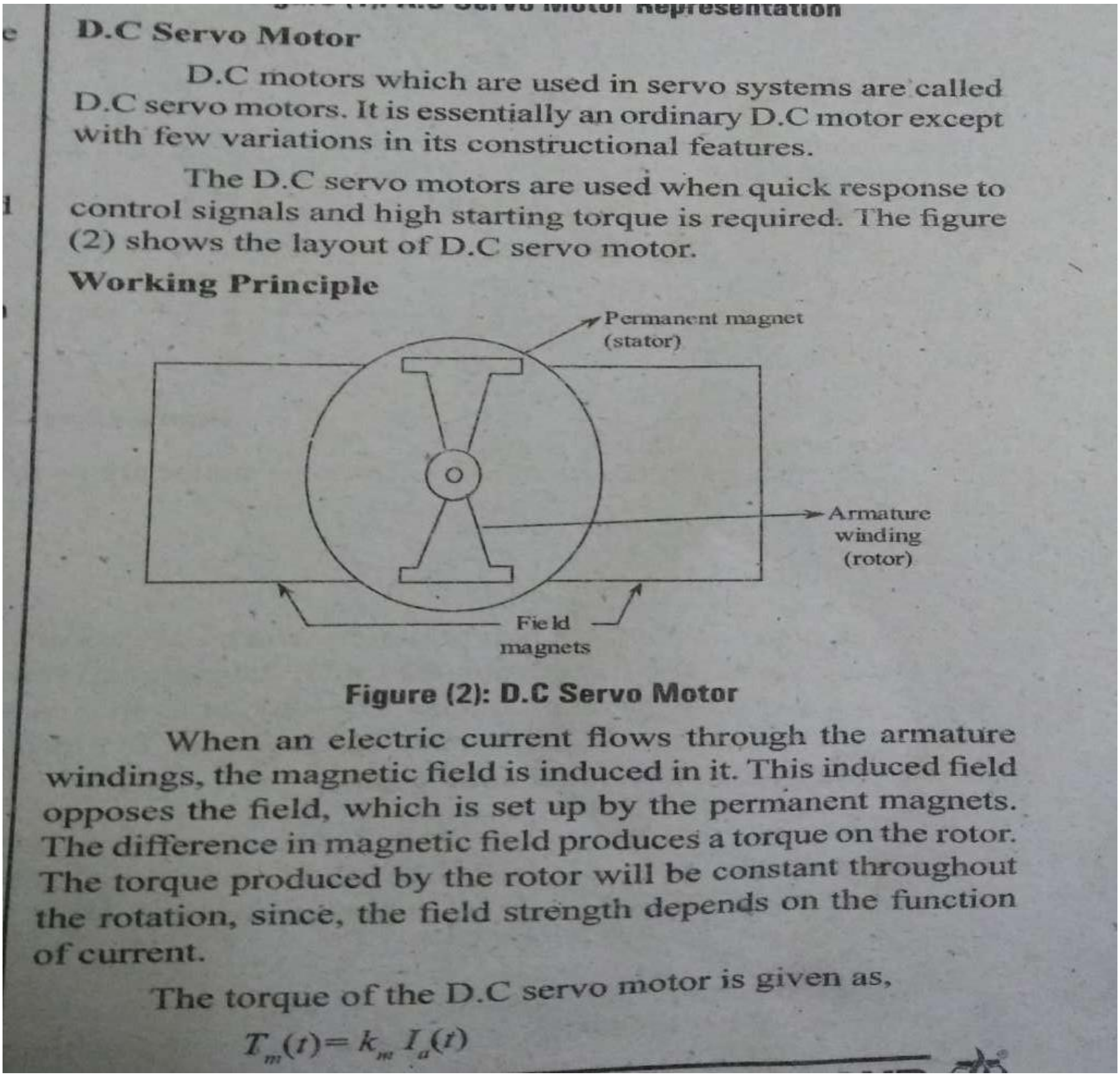


4.49

A.C servo motor is shown in figure (1). It has two windings i.e. control and reference winding. The control voltage V_c is given as input voltage to the control winding through the amplifier. The fixed voltage V_f is given to the reference winding. The phase difference between the fixed voltage and the control voltage is 90°. The torque T_m is developed, due to the control voltage. J_m and B are the moment of inertia of the motor and coefficient of friction respectively. The output θ_m is the angular displacement of the motor and ω_m is the corresponding angular velocity.

Figure (1): A.C Servo Motor Representation

2. D.C. Servo Motors



D.C Servo Motor

D.C motors which are used in servo systems are called D.C servo motors. It is essentially an ordinary D.C motor except with few variations in its constructional features.

The D.C servo motors are used when quick response to control signals and high starting torque is required. The figure (2) shows the layout of D.C servo motor.

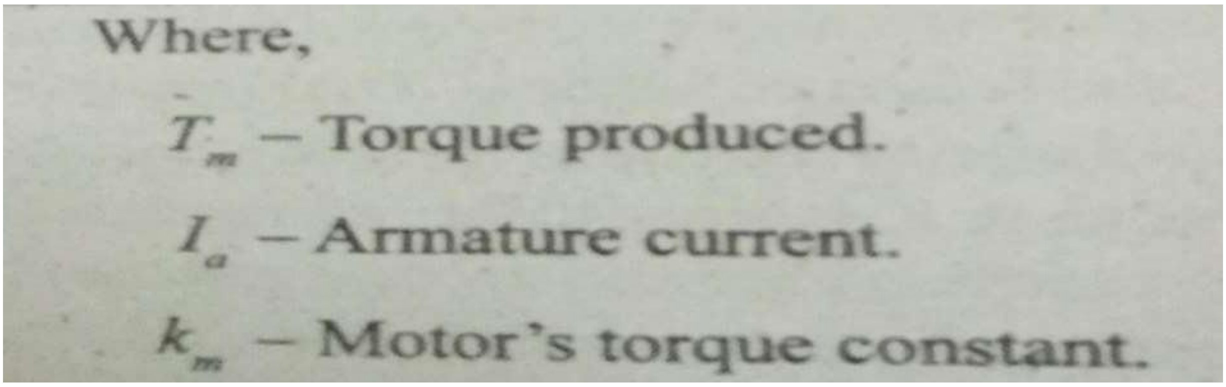
Working Principle

Figure (2): D.C Servo Motor

When an electric current flows through the armature windings, the magnetic field is induced in it. This induced field opposes the field, which is set up by the permanent magnets. The difference in magnetic field produces a torque on the rotor. The torque produced by the rotor will be constant throughout the rotation, since, the field strength depends on the function of current.

The torque of the D.C servo motor is given as,

$$T_m(t) = k_m \, I_a(t)$$

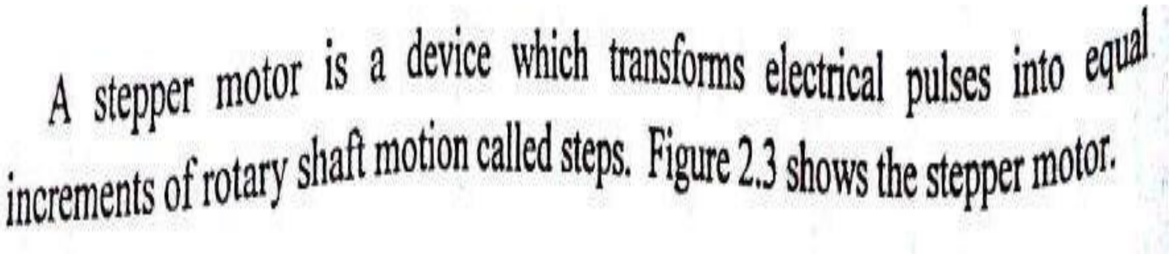

Where,

T_m – Torque produced.

I_a – Armature current.

k_m – Motor's torque constant.

3. Stepper Motor.


A stepper motor is a device which transforms electrical pulses into equal increments of rotary shaft motion called steps. Figure 2.3 shows the stepper motor.

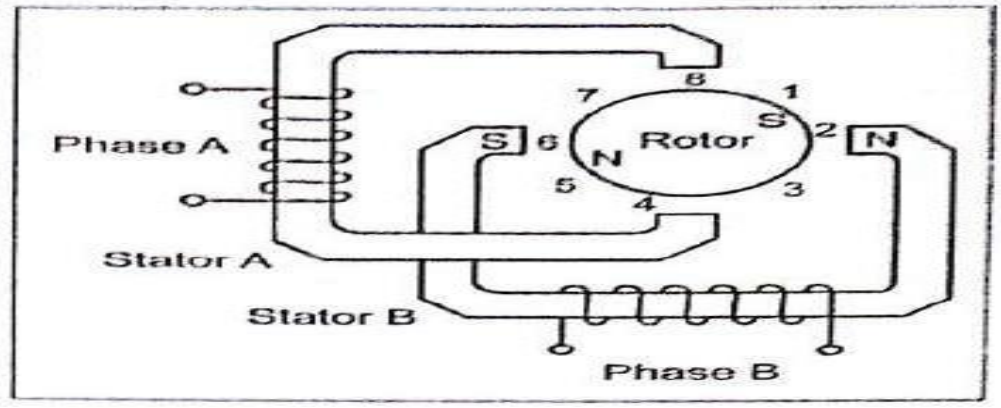


Fig. 2.3. Stepper motor

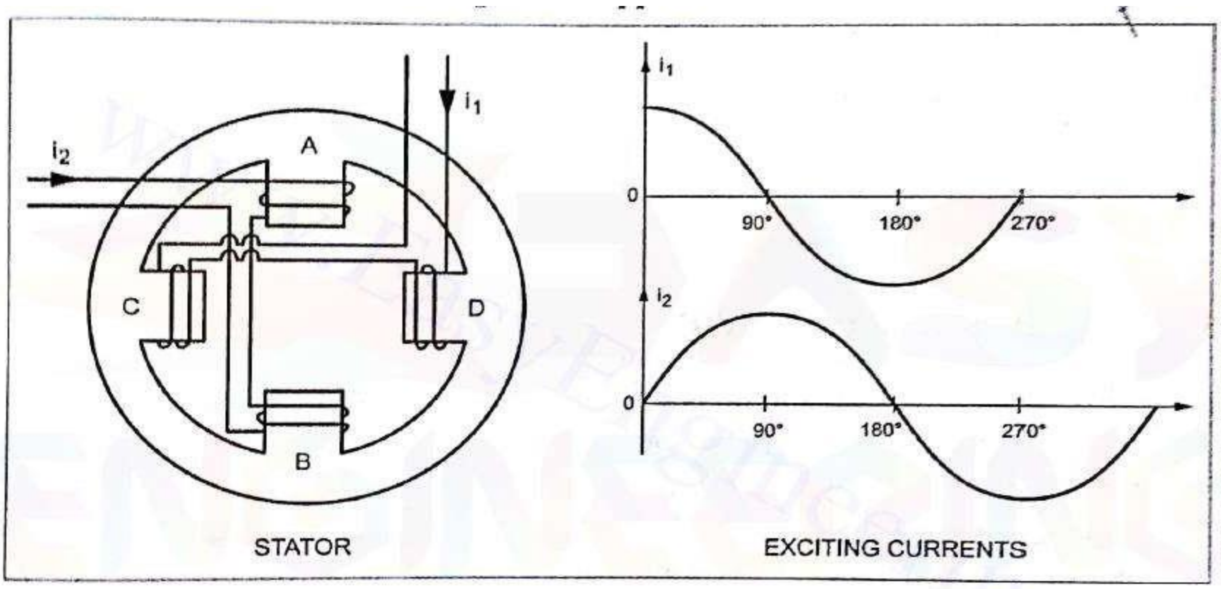
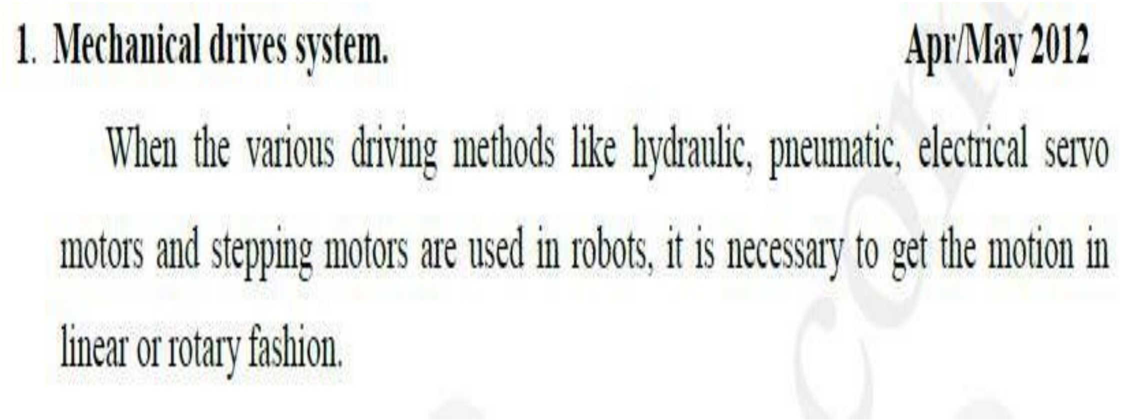


Fig. 2.4. Magnetic flux path through a two pole stepper motor with lag between the rotor and stator

Principle

- ✓ The shaft or spindle of a stepper motor rotates indiscrete step increments when electrical command pulses are applied to it in the proper sequence.
- ✓ The motors rotation has several direct relationships to these applied input pulses. The sequence of the applied pulses is directly related to the direction of motor shafts rotation.
- ✓ The speed of the motor shafts rotation is directly related to the frequency of the input pulses and the length of rotation is directly related to the number of input pulses applied.



1. Mechanical drives system. Apr/May 2012

When the various driving methods like hydraulic, pneumatic, electrical servo motors and stepping motors are used in robots, it is necessary to get the motion in linear or rotary fashion.

mechanical drives are mainly classified as following

a) Rack and Pinion Mechanism

b) Ratchet and Pawl Mechanism

c) Cam Mechanism

d) Geneva Mechanism

e) Harmonic drive system

f) Ball and Roller Screws or Screw Driven Nut System or Re-Circulating Ball screw

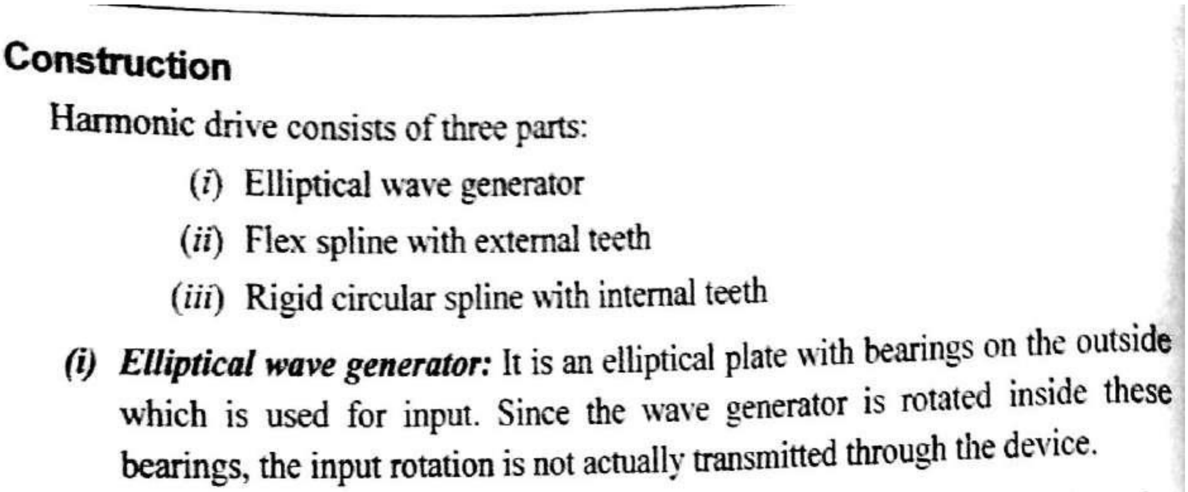
up to Geneva mechanism refer in unit 1

e) Harmonic drive system

For speed reduction, standard gear transmission gives sliding friction and backlash. Moreover, it takes more space.

Harmonic drive due to its natural preloading eliminates backlash and greatly reduces tooth wear.

Harmonic drives are suitable for robot drives due to their smooth and efficient action.



Construction

Harmonic drive consists of three parts:

(*i*) Elliptical wave generator
(*ii*) Flex spline with external teeth
(*iii*) Rigid circular spline with internal teeth

(i) ***Elliptical wave generator:*** It is an elliptical plate with bearings on the outside which is used for input. Since the wave generator is rotated inside these bearings, the input rotation is not actually transmitted through the device.

(ii) ***Flex spline with external teeth*** which is a thin-walled cup. It has teeth on its outside. The flex spline fits over the bearings on the wave generator, such that when the wave generator is rotated, the flex spline deforms to the shape of a rotating ellipse. But does not actually rotate itself.

(iii) ***Rigid circular spline with internal teeth:*** It is a circular cup which has teeth on the inside of the cup, and is identical to an internal gear. These teeth engage the teeth on the outside of the flex spline, but only at the ends of the elliptical shape. Figure 2.16 illustrates the circular spline with internal teeth.

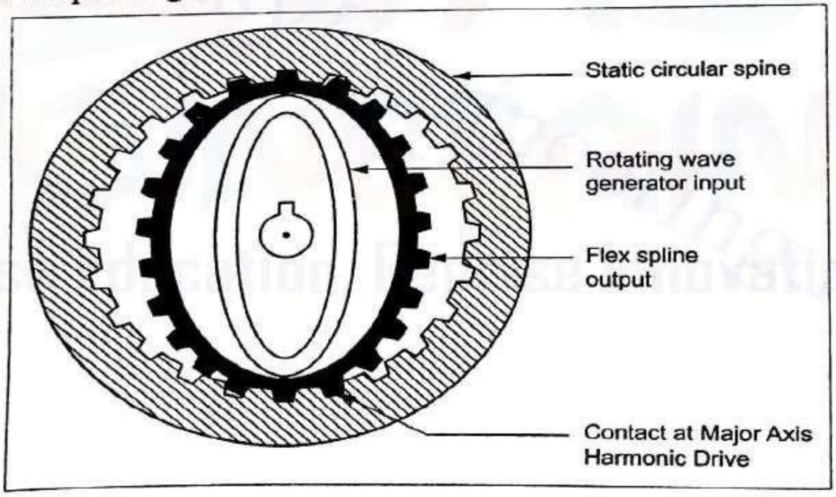


Fig. 2.16. Harmonic drive

Working Principle

- ✓ The harmonic drive theory is based on elastic dynamics and utilizes the flexibility of metal. More complex versions will have a fourth component normally used to shorten the overall length or to increase the gear reduction within a smaller diameter, but still follows the same basic principles.

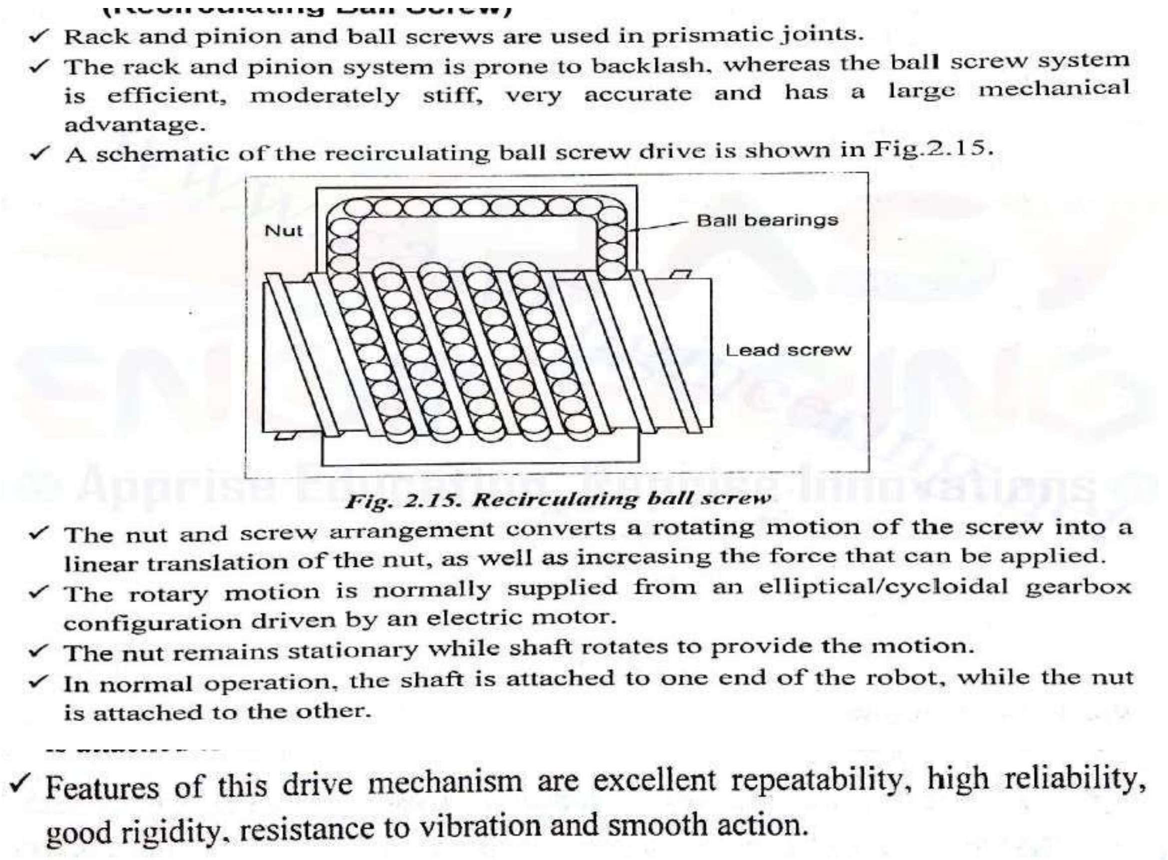
- ✓ The end result is that the wave generator rotates within the flex spline, deforming it and thus shifting the flex spline along the circular spline opposite to the input rotation.
- ✓ Since the wave generator and flex spline are elliptical, the flex spline engages the circular spline at two points on opposite sides of the gear.
- ✓ This allows almost 30% of the teeth to be engaged at any time, providing high torque capabilities and other benefits.
- ✓ When the input shaft is rotated 90 degrees clockwise, the wave generator rotates and deforms the flex spline accordingly.
- ✓ Because of the deformation, the flex spline turns slightly (about half a tooth) counterclockwise.
- ✓ When the input shaft is rotated a full 360 degrees clockwise, the flex spline will have turned about two teeth counterclockwise. This is because the circular spline, with its larger circumference, has two more teeth than the flex spline.
- ✓ In a harmonic drive mechanism, the reduction ratio can be calculated from the number of teeth on each gear:

Reduction = (Flex spline teeth – Circular spline teeth) / Flex spline teeth)

Advantage of Harmonic Drive

- ✓ Zero backlash
- ✓ High reduction ratio with single stage
- ✓ Compact & Light weight
- ✓ High torque capability
- ✓ Coaxial input & output shaft

f) Ball and Roller Screws



- ✓ Rack and pinion and ball screws are used in prismatic joints.
- ✓ The rack and pinion system is prone to backlash, whereas the ball screw system is efficient, moderately stiff, very accurate and has a large mechanical advantage.
- ✓ A schematic of the recirculating ball screw drive is shown in Fig.2.15.

Fig. 2.15. Recirculating ball screw

- ✓ The nut and screw arrangement converts a rotating motion of the screw into a linear translation of the nut, as well as increasing the force that can be applied.
- ✓ The rotary motion is normally supplied from an elliptical/cycloidal gearbox configuration driven by an electric motor.
- ✓ The nut remains stationary while shaft rotates to provide the motion.
- ✓ In normal operation, the shaft is attached to one end of the robot, while the nut is attached to the other.
- ✓ Features of this drive mechanism are excellent repeatability, high reliability, good rigidity, resistance to vibration and smooth action.

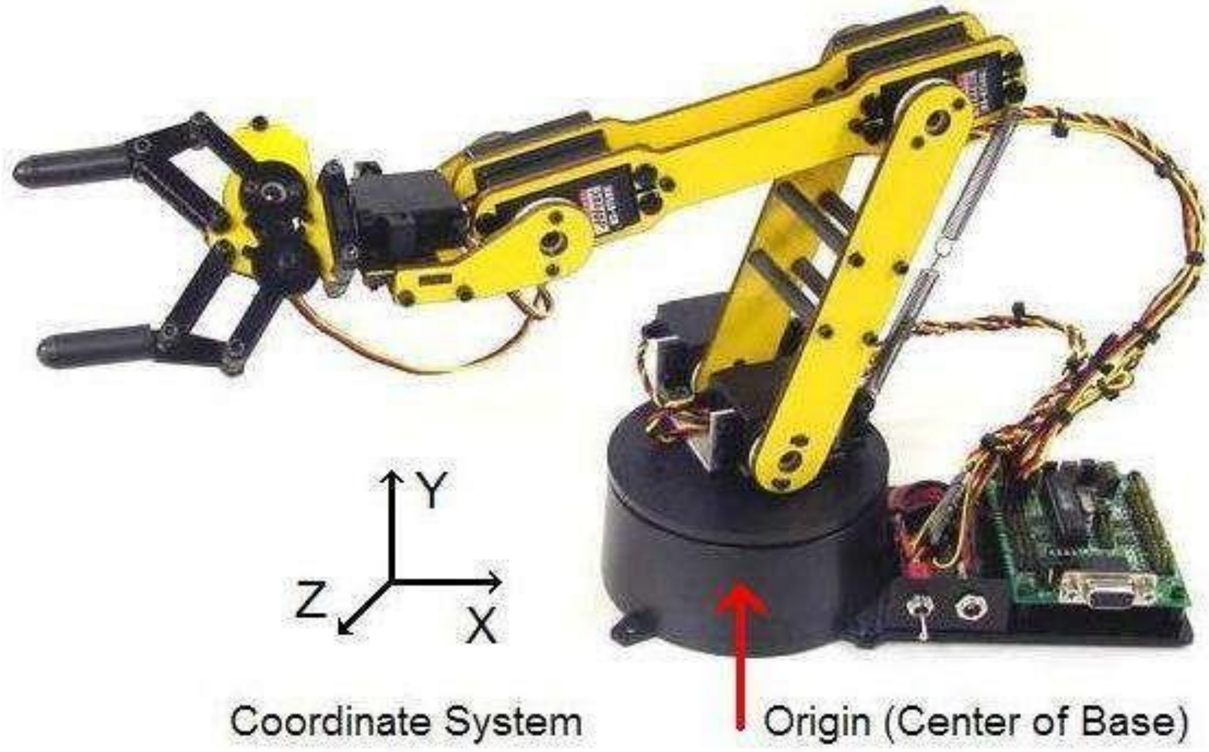
END EFFECTORS

In robotics, an **end effector** is the device at the end of a robotic arm, designed to interact with the environment.

An end effector is a component, which is attached to the robot’s wrist, to enable completion of tasks like gripping cutting etc.,

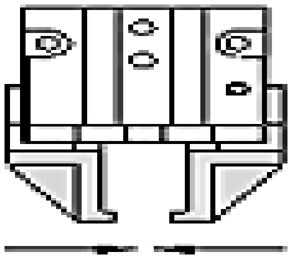
It is also called as gripper

End effectors may consist of a gripper or a tool. The gripper can be of two fingers, three fingers or even five fingers.

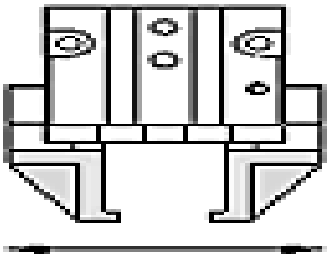


Pneumatic Gripper

Pneumatic grippers, as the name proposes, works with compressed air. The gripper is connected to a compressed air supply network. When air pressure is applied on the pistons, the gripper closes. When the pressure is released the gripper opens. The only way to manage the force in the gripper is to manage the air pressure in the air intake (or valve).

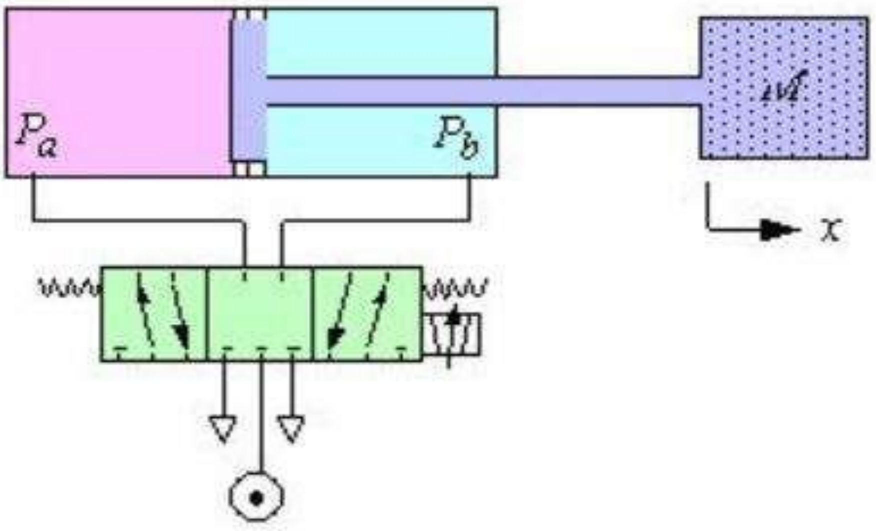


Parallel Gripper (closed)

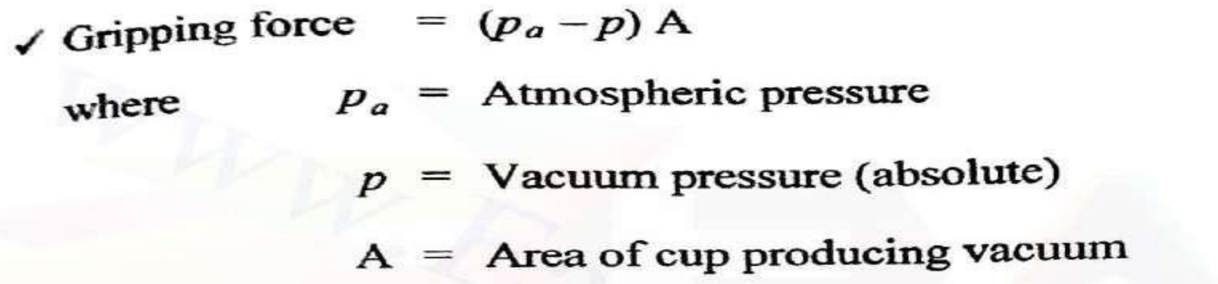


Parallel Gripper (open)

To further elaborate on this concept, imagine that the gripper is two pneumatic actuators placed in opposite directions. Referring to the figure below. When the robot program asks the gripper to close against the part, first the valve (coloured in green) is moving right to let the air pressure enter into the left portion of the pneumatic actuator (coloured in pink). As the pressure builds up in this section, the piston moves in the "x" direction. The piston will then apply a force according to the pressure on the piston (Force = Pressure * Surface). To keep a constant force on the part, the valve can be closed or remains open and must keep a constant air pressure on the piston.



When the program requests the release of the part, the valve then moves left and the air pressure goes into the right section of the cylinder (coloured in blue), at the same time the air in the left section is released. This operation brings the piston back to its initial position. This way, the part is also released.
As both actuators are attached to each individual finger in direct opposition to each other, the piston controlling the fingers will close against each other in perfect synchronization. This example is a simple representation of how it works, however, a lot of different design exist. The disadvantage of using this kind of gripper is that there are very few settings that can be controlled on the fly. In fact, the stroke is fixed for a given gripper and the force has to be adjusted with the pressure that flows into the valve. It takes a couple of tests to figure out the amount of air pressure that will work well for each particular application

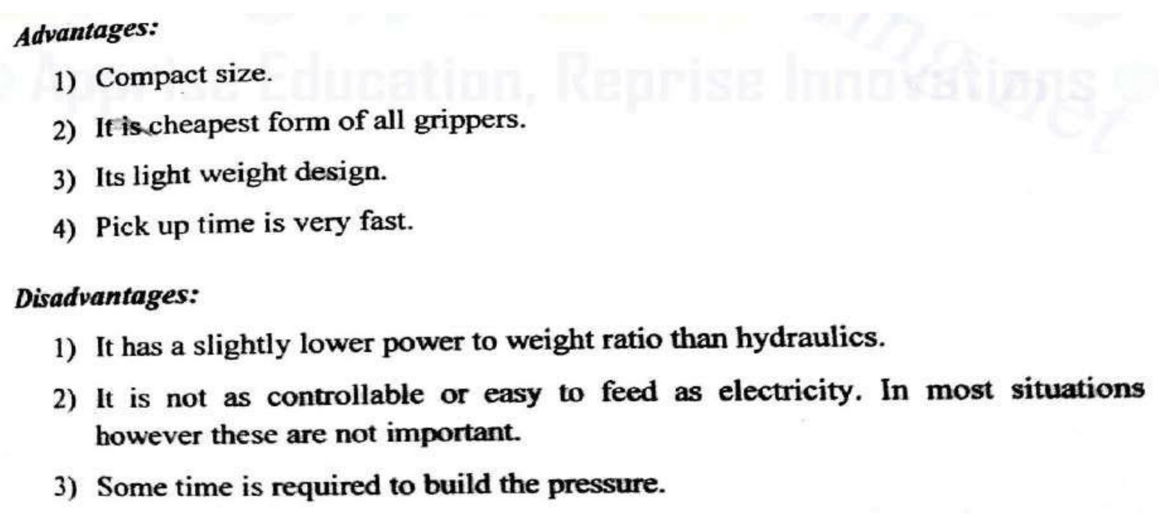


✓ Gripping force $= (p_a - p)\,A$

where $p_a =$ Atmospheric pressure

$p =$ Vacuum pressure (absolute)

$A =$ Area of cup producing vacuum



Advantages:

1) Compact size.
2) It is cheapest form of all grippers.
3) Its light weight design.
4) Pick up time is very fast.

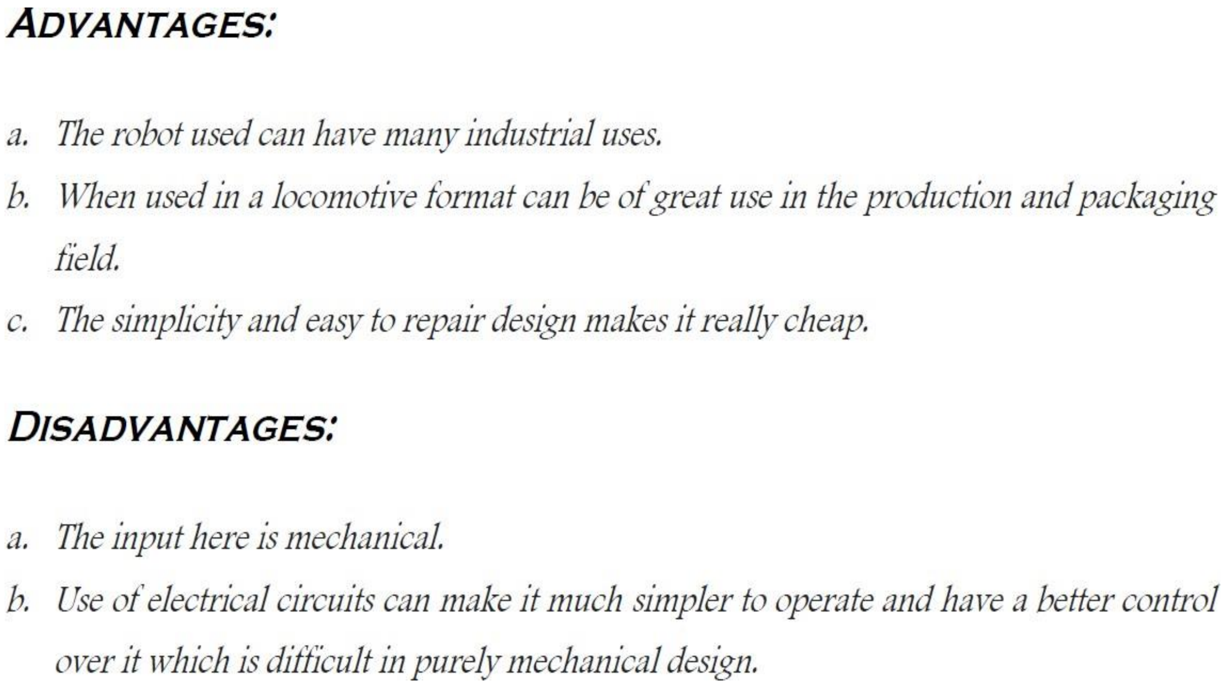
Disadvantages:

1) It has a slightly lower power to weight ratio than hydraulics.
2) It is not as controllable or easy to feed as electricity. In most situations however these are not important.
3) Some time is required to build the pressure.

Hydraulic Gripper

In general, hydraulic and pneumatic grippers have the same basic actuation principle. They include direct acting piston designs as well as piston wedge designs

The direct acting piston design is used when a hydraulic force acts directly on a piston that is directly connected to the jaw or finger that is touching or gripping the part.



ADVANTAGES:

a. The robot used can have many industrial uses.
b. When used in a locomotive format can be of great use in the production and packaging field.
c. The simplicity and easy to repair design makes it really cheap.

DISADVANTAGES:

a. The input here is mechanical.
b. Use of electrical circuits can make it much simpler to operate and have a better control over it which is difficult in purely mechanical design.

When selecting a hydraulic gripper, it is important to consider the following:

1. Part weight and size to be lifted
2. Part material
3. Clearance issues around the part that could interfere with the gripping part
4. The environment the gripper will be used in (corrosive, food or beverage, etc.)
5. The motion path of the robot or linear device that is moving the gripper
6. The power supply that will be available and the pressure ratings available

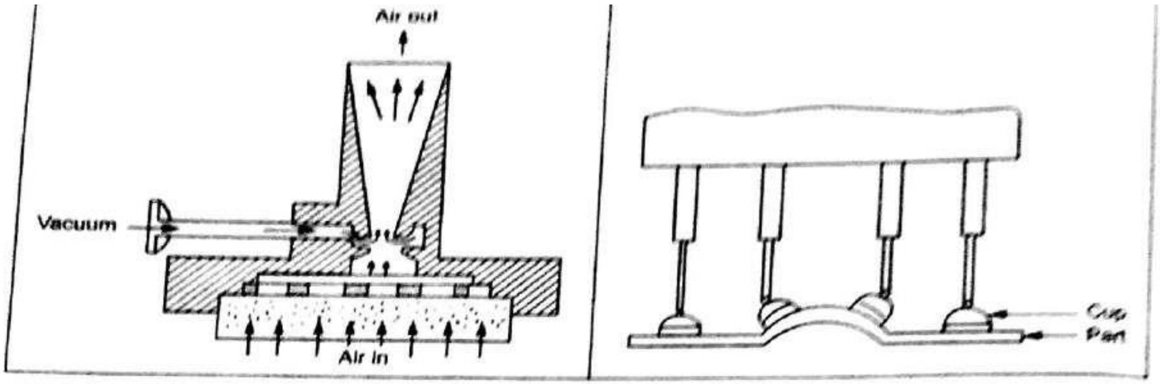
Vacuum Gripper

The vacuum gripper has two components:

(*a*) The vacuum gripper cups

(*b*) The vacuum system

- ✓ The vacuum cups consist of a flexible-rubber cup and a hard-rubber cup.
- ✓ Cups are made of elastic material and round in shape.
- ✓ The cup creates negative pressure, which in turn, create the vacuum and the necessary lifting power.
- ✓ The vacuum is created between cup and the object.
- ✓ The vacuum can be generated by a vacuum pump or a venturi system. After lifting and placing the part at the desired place the vacuum is released.
- ✓ Number of grippers (cups) determines the size and weight of object to be grasped.
- ✓ Vacuum gripper is used for handling of fragile parts.
- ✓ Positioning of parts not as critical as with other grippers.
- ✓ In some applications where the objects are too thin to be handled, they can be held by vacuum grippers.
- ✓ Fig.3.10 illustrates Vacuum gripper.
- ✓ The lifting capacity of suction pump depends upon the effective area of the cup and negative air pressure (vacuum) between the cup and the object.



(a) Ventury device for flat surface gripping *(b) Gripper for contoured surface*

Fig. 3.10. The vacuum gripper

Uses of Vacuum Grippers

- ✓ It is used for picking of metal parts and large light weight boxes.

Lift Capacity of Suction Pump

Lift capacity of suction pump depends upon:

1. Effective area of the cup.
2. Negative air pressure between cup and object.

$$\text{Force (F)} = K \cdot p \cdot A_{eff} = K \cdot A_{eff} \cdot p_a$$

where, F = Lift capacity (Newton)

K = Coefficient

A_{eff} = Effective area

p = Negative pressure

p_a = Atmospheric pressure

p_{res} = Residual pressure in vacuum cup

Advantages

1. The Gripper is lighter in weight.
2. Distribute the pressure entirely in some area.

Disadvantages

1. It is not suitable for components having curved surface and holes.
2. More time is required to build the vacuum in the cup.

Magnetic Gripper

Grippers in which a magnetic substance performs the grasping action for handling ferrous material are called magnetic grippers.

The types of magnetic grippers are:

- (*i*) Electromagnetic grippers
- (*ii*) Permanent magnet grippers

3.5.1. Permanent Magnet Type Grippers

- ✓ The magnetic gripper employs the effect of a magnetic field coming into contact with a ferrous metal.
- ✓ The magnetic field is developed by passing constant current through an electromagnet.
- ✓ The Fig.3.12 illustrates permanent magnet type magnetic gripper.

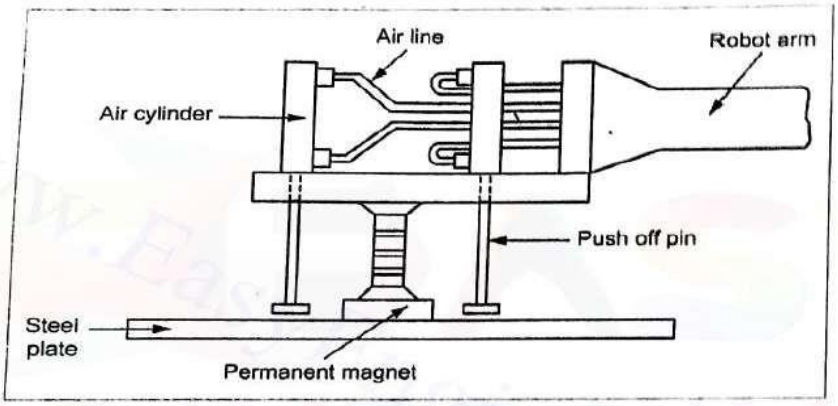


Fig. 3.12. Magnetic gripper – Permanent magnet type

- ✓ This field causes the molecules of the ferrous metal to align and develop smaller magnetic fields in the part.
- ✓ These smaller magnetic fields have a polarity that is opposite to the polarity of the electromagnetic field. The two poles of opposite polarity attract each other, allowing the gripper to lift the part.
- ✓ The electric current is turned off after the part has been lifted and placed at the desired place.

Advantage:

- ✓ Variety of part size can be handled.
- ✓ Pickup times are very fast.
- ✓ Variations in part size can be tolerated.
- ✓ The grippers do not have to be designed for one particular work part.
- ✓ They have the ability to handle metal parts with holes.
- ✓ Requires only one surface for gripping.
- ✓ A magnetic gripper, despite in compact size, can sustain enormous holding power.

Disadvantage:

- ✓ Residual magnetism remaining in the workpiece may cause problems.
- ✓ Side slippage.
- ✓ More than one sheet will be lifted by the magnet from a stack.
- ✓ Lack of control during some duration of the cycle.

3.6. ELECTROMAGNETIC GRIPPERS

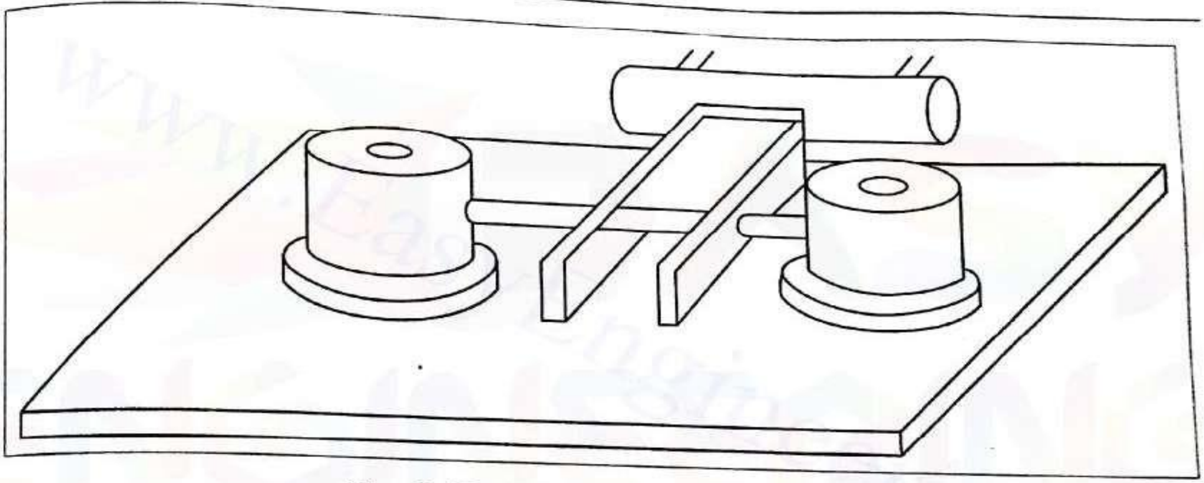


Fig. 3.13. Electromagnetic grippers

✓ Electromagnetic grippers can be employed for holding magnetic materials Fig.3.13.

✓ When the objects to be handled are too large and ferromagnetic in nature pneumatic grippers may be employed.

✓ This is more suitable for flat materials and holding force in such case will be high.

✓ Whenever magnetic grippers are used, it is to be ensured that power to gripper is always available. Otherwise the job may fall against power failure.

Attractive Force of an Electromagnet

The attractive force P of an electromagnet can be found by using Maxwell's equation

$$P = \frac{[I \times N]^2}{25 \times A \times (S_a + S_m)}$$

where I = Current (A)
N = Number of turns of coil
S_a = Reluctance of magnetic paths through air
S_m = Reluctance of magnetic paths through the metal

S_m

Advantage

- ✓ Electromagnet grippers are easier to control, but they require a source of electric power.

3.7. ADHESIVE GRIPPER

- ✓ In a device an adhesive substance is used to hold a flexible material such as a fabric. An adhesive substance can be used for grasping action in gripper design.
- ✓ The requirement on the items to be handled are that they must be gripped on one side only.
- ✓ The reliability of this gripping device is diminished with each successive operation cycle as the adhesive substance loses its tackiness on repeated use.
- ✓ To overcome this limitation, the adhesive material can be loaded in the form of a continuous ribbon into a feeding mechanism attached to the robot wrist.
- ✓ Employed to handle fabric and light weight material.

Limitations of adhesive grippers:

- ✓ Adhesive substances losses his tackiness on repeated usage.
- ✓ Reliability is diminished with successive operations.

Mechanical Gripper

- ✓ A mechanical gripper is an end effector that uses mechanical finger actuated by mechanism to grasp an object.
- ✓ Mechanical grippers are used to transfer parts from one location to another or to assemble parts.
- ✓ These grippers are of many types.
- ✓ Most common, can be angular or parallel.

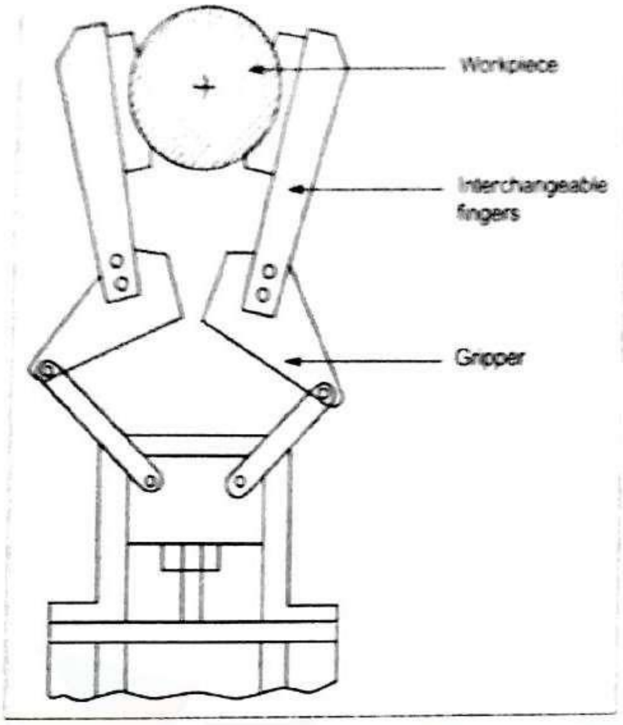


Fig. 3.2. Mechanical gripper with interchangeable finger

- ✓ They are used to perform some special tasks.
- ✓ Mechanical grippers, actuated by pneumatic / hydraulic / solenoid / motor are designed based on strength consideration and is made as light as possible. Otherwise it will have heavy loading on other drive equipments.

- ✓ Gripping by mechanical type finger is less versatile and less dextrose than holding by universal fingers as the grippers with mechanical fingers have fewer numbers of joints and less flexibility.
- ✓ The grippers can be sub grouped according to finger classification, for example, the number of figures typically two, three, and five-finger types.
- ✓ The two finger gripper is the most popular.

3.2.3. Finger Grippers

- ✓ These will generally have two opposing fingers or three fingers like a lathe chuck.
- ✓ The fingers are driven together such that once gripped any part is centred in the gripper. This gives some flexibility to the location of components at the pick-up point.
- ✓ Two finger grippers can be further split into parallel motion or angular motion fingers.
- ✓ Robot end effectors can be classified on the basis of the mode of gripping as external and internal gripping.

3.2.4. A Single Gripper

- ✓ The robot must reach into the production machine twice, once to unload the finished part from the machine, and the second time to load the next part into the machine.

3.2.5. Dual Gripper

- ✓ The robot picks up the next work part. while the machine is still processing the preceding part.
- ✓ When the machine finishes, the robot reaches into the machine once to remove the finished part and load the next part. This reduces the cycle time per part.

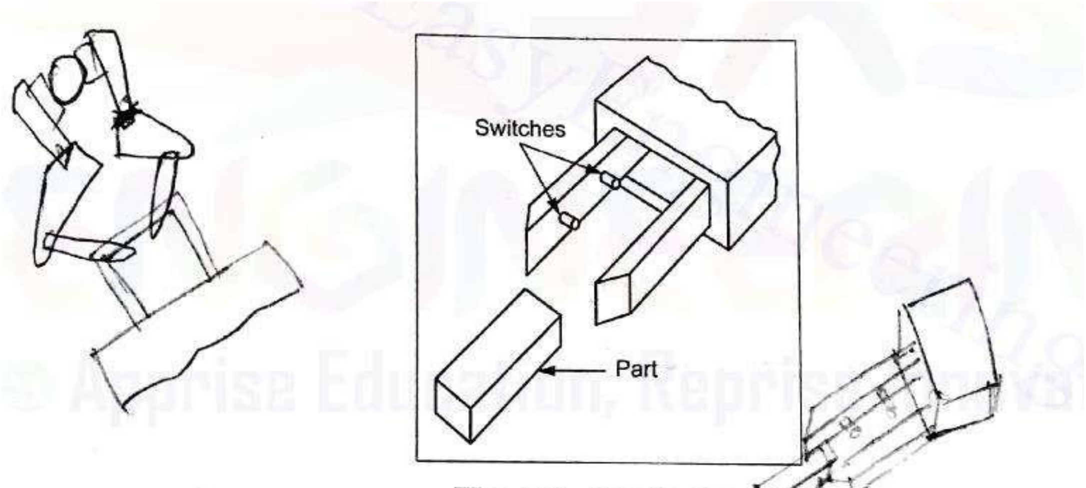


Fig. 3.3. Dual gripper

3.2.6. Mechanical Grippers with Two Fingers

(1) Pivoting

- ✓ This is the most popular mechanical gripper for industrial robots. It can be designed for limited shapes of an object, especially cylindrical workplace.
- ✓ If actuators that produce linear movement are used, like pneumatic piston-cylinders, the device contains a pair of slider-crank mechanisms.

- ✓ In the slider crank mechanism shown in Fig.3.4 when the piston 1 is pushed by pneumatic pressure to the right, the elements in the cranks 2 and 3, rotate counter clockwise with the fulcrum F_1 and clockwise with the fulcrum F_2 respectively, when 8 < 180°.
- ✓ These rotations make the grasping action at the extended end of the crank elements 2 and 3.
- ✓ The releasing action can be obtained by moving the piston to the left. An angle & ranging from 160° to 170° is commonly used.

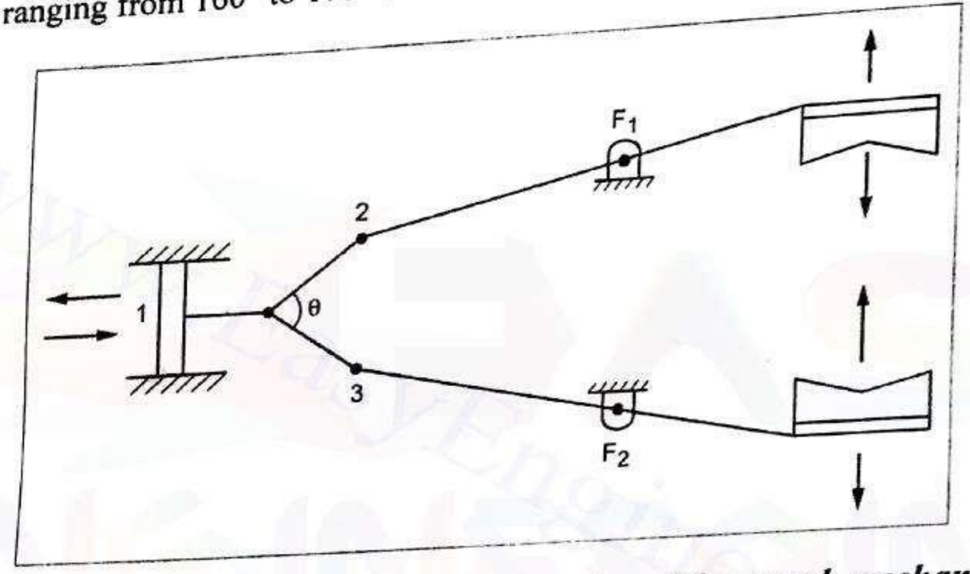


Fig. 3.4. Schematic diagram of a gripper using slider-crank mechanism

(2) Swinging Gripper Mechanisms

- ✓ Figure 3.5 is another example of swinging gripper that uses the piston-cylinder. This is the swing-block mechanism.
- ✓ The sliding rod 1, actuated by the pneumatic piston transmits motion by way of the two symmetrically arranged swing-block linkages 1-2-3-4 and 1-2-3'-4' to grasp or release the object by means of the subsequent swinging motions of links 4 and 4' at their pivots F_1 and F_2.

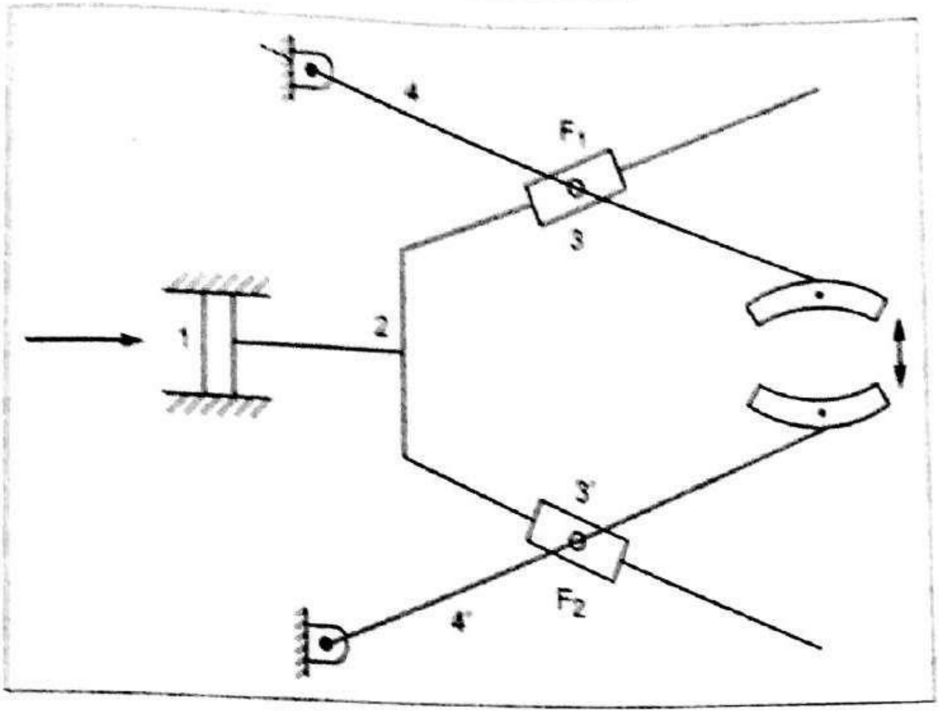


Fig. 3.5. *Schematic diagram of a gripper using swing block mechanism*

3.2.7. Mechanical Grippers with Three Fingers

Figure 3.6 Gripper using three point chuck mechanism.

- ✓ 3-Finger grippers consists of simulate action of thumb, index finger and third finger.
- ✓ The increase of the number of fingers and degrees of freedom will greatly aid the versatility of grippers.
- ✓ The main reason for using the three-finger gripper is its capability of grasping the object in three spots, enabling both a tighter grip and the holding of spherical objects of different size keeping the centre of the object at a specified position.

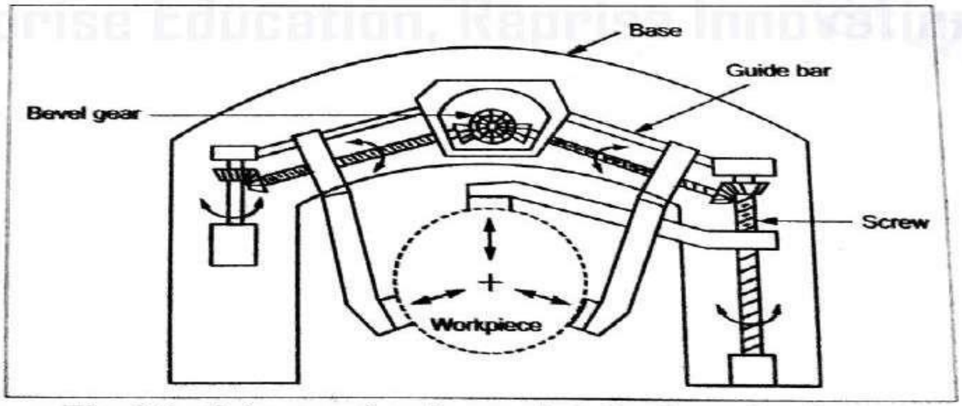
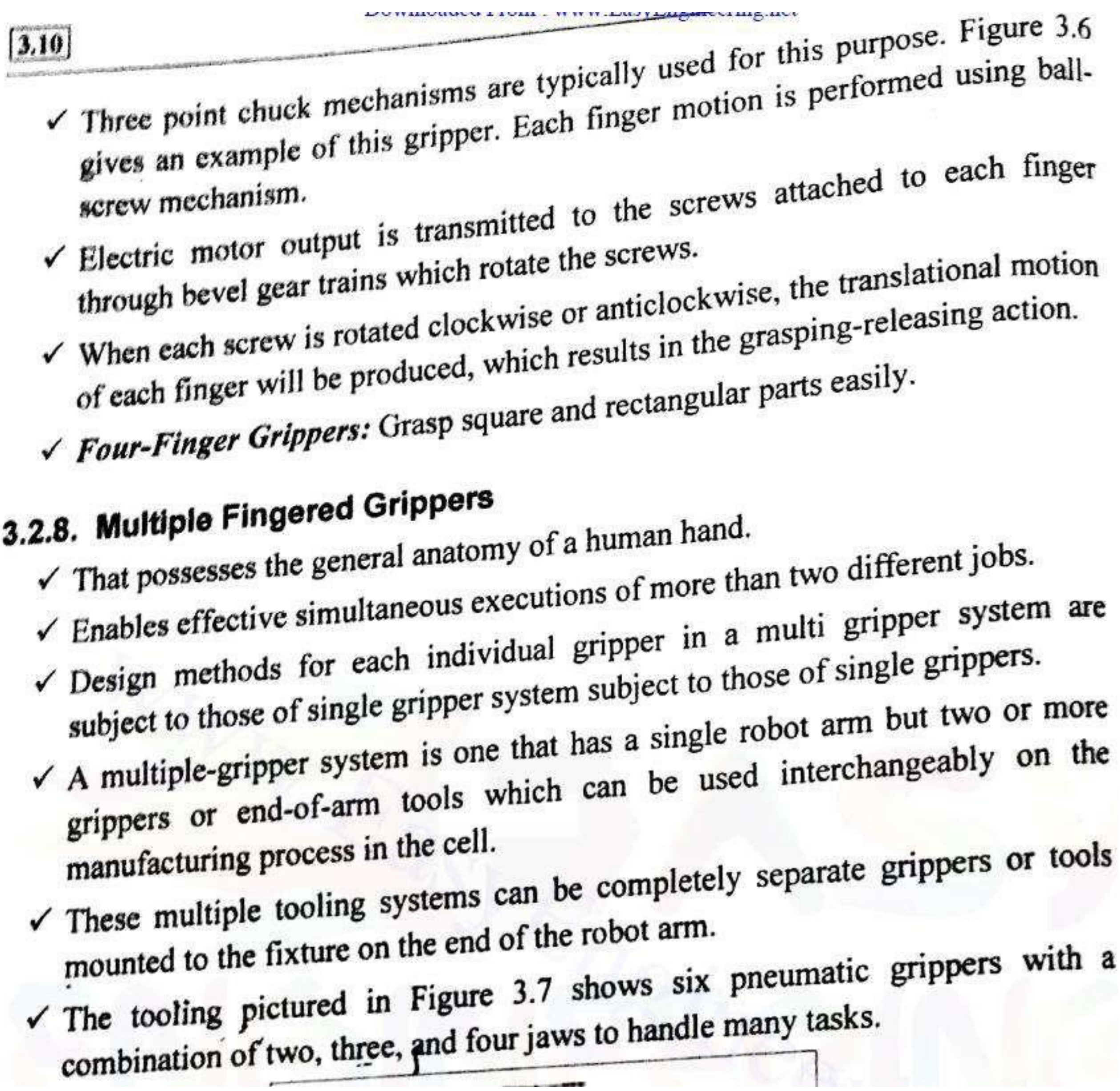


Fig. 3.6. Gripper using three point chuck mechanism



- ✓ Three point chuck mechanisms are typically used for this purpose. Figure 3.6 gives an example of this gripper. Each finger motion is performed using ball-screw mechanism.
- ✓ Electric motor output is transmitted to the screws attached to each finger through bevel gear trains which rotate the screws.
- ✓ When each screw is rotated clockwise or anticlockwise, the translational motion of each finger will be produced, which results in the grasping-releasing action.
- ✓ ***Four-Finger Grippers:*** Grasp square and rectangular parts easily.

3.2.8. Multiple Fingered Grippers

- ✓ That possesses the general anatomy of a human hand.
- ✓ Enables effective simultaneous executions of more than two different jobs.
- ✓ Design methods for each individual gripper in a multi gripper system are subject to those of single gripper system subject to those of single grippers.
- ✓ A multiple-gripper system is one that has a single robot arm but two or more grippers or end-of-arm tools which can be used interchangeably on the manufacturing process in the cell.
- ✓ These multiple tooling systems can be completely separate grippers or tools mounted to the fixture on the end of the robot arm.
- ✓ The tooling pictured in Figure 3.7 shows six pneumatic grippers with a combination of two, three, and four jaws to handle many tasks.

of two, three, and

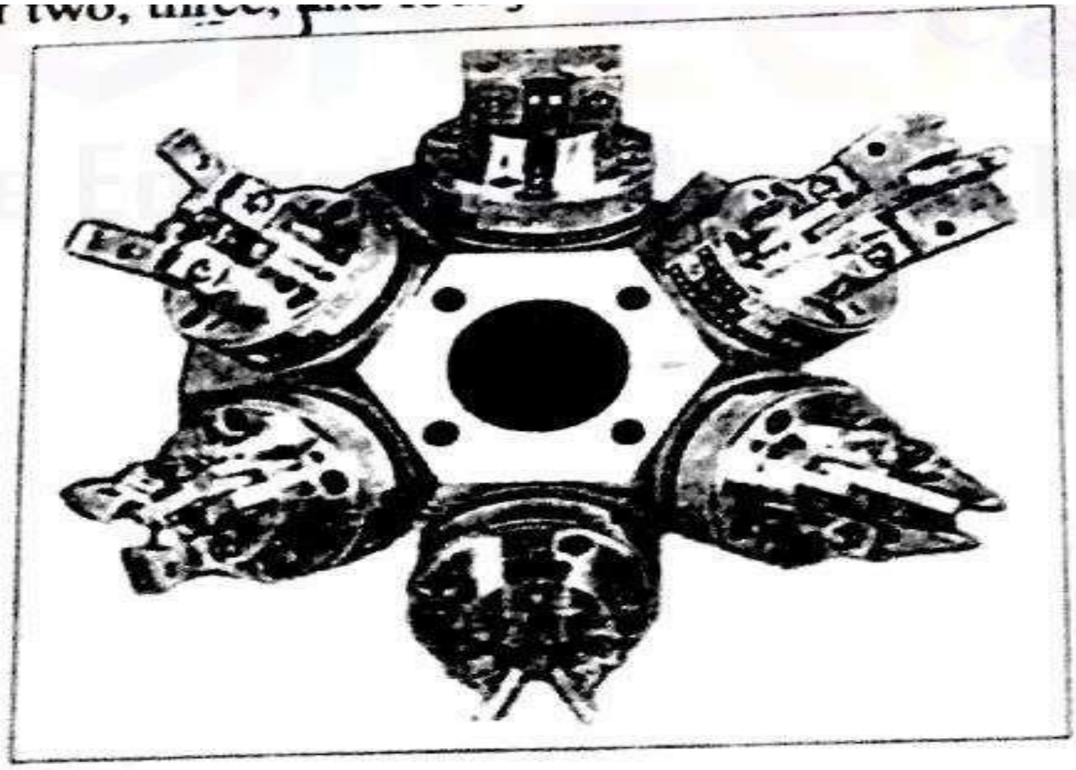


Fig. 3.7. Multiple fingered grippers

3.2.11. Internal Gripper

- ✓ In these grippers, the finger pads are mounted on the outside of the fingers.
- ✓ This mounting allows the pads to fit into the inside diameter of the part that it must lift. The pads are pressed against the inside walls of the part.
- ✓ The frictional force developed allows the fingers to hold the part securely when the gripper lifts the part.
- ✓ The contact may be either two-point contact or captivation or flexible, grip with polyurethane pads.

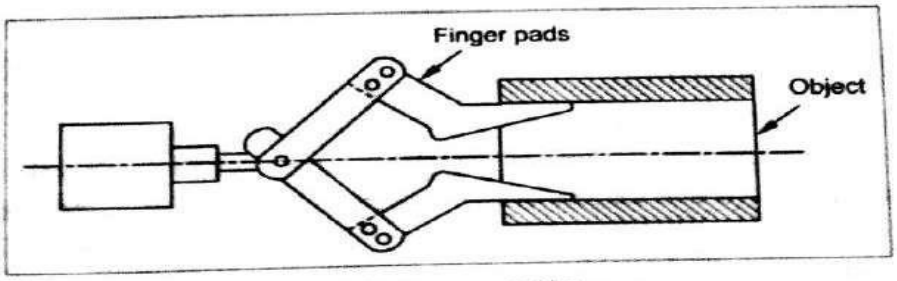


Fig. 3.8. Internal Gripper

3.2.12. External Gripper

- ✓ This type of gripper is designed so that the finger pads press against the outside of the component.
- ✓ Grips the exterior surface of the objects with closed finger.
- ✓ The pads develop the frictional force required to lift the part. The pads are made of polyurethane bonded to steel.
- ✓ These grippers are generally of four-point contact V-block type.
- ✓ External grippers are shown in Fig.3.9.

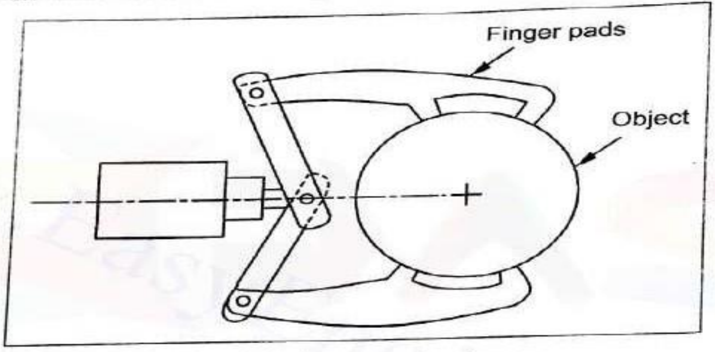
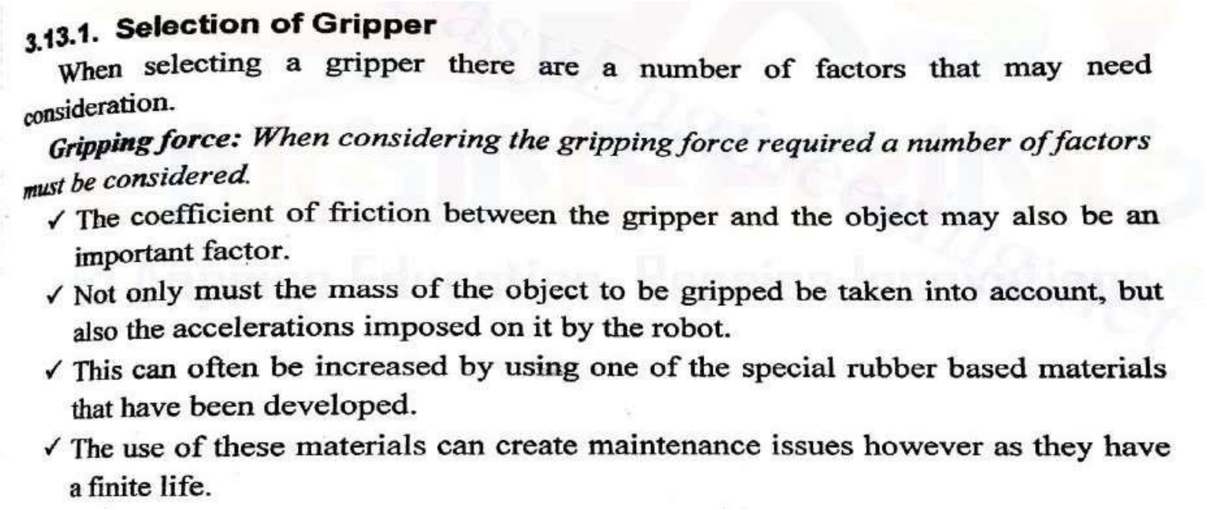


Fig. 3.9. External gripper

selection and design considerations in robot grippers

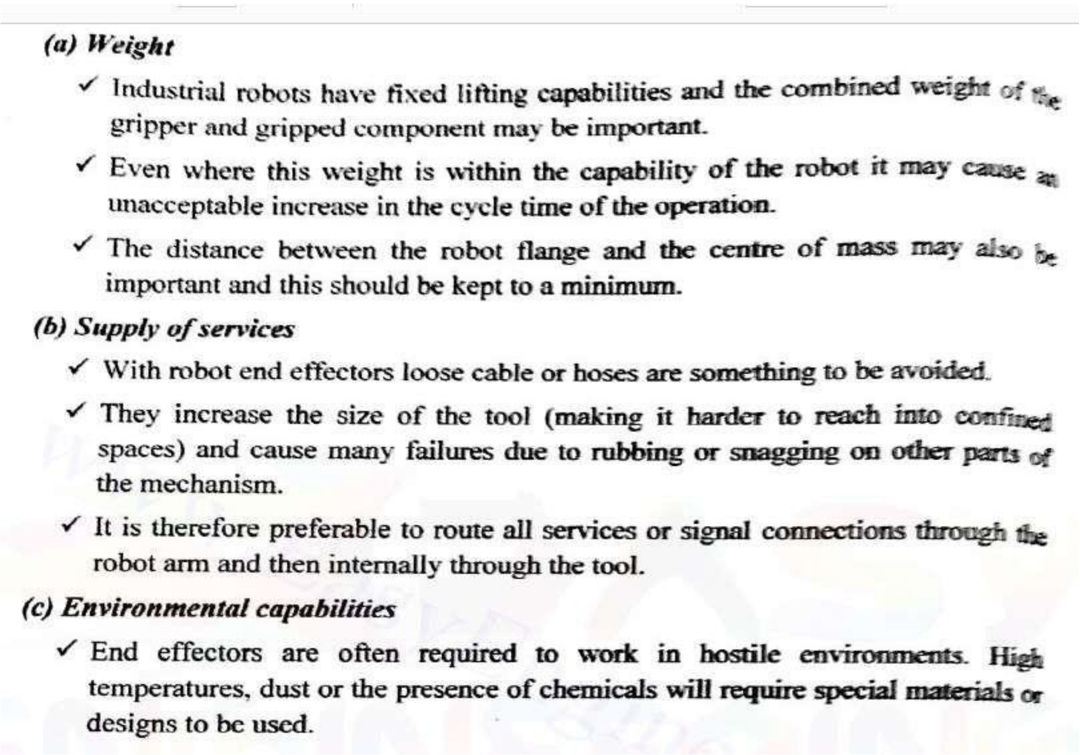


3.13.1. Selection of Gripper

When selecting a gripper there are a number of factors that may need consideration.

Gripping force: *When considering the gripping force required a number of factors must be considered.*

- ✓ The coefficient of friction between the gripper and the object may also be an important factor.
- ✓ Not only must the mass of the object to be gripped be taken into account, but also the accelerations imposed on it by the robot.
- ✓ This can often be increased by using one of the special rubber based materials that have been developed.
- ✓ The use of these materials can create maintenance issues however as they have a finite life.



(a) Weight

- ✓ Industrial robots have fixed lifting capabilities and the combined weight of the gripper and gripped component may be important.
- ✓ Even where this weight is within the capability of the robot it may cause an unacceptable increase in the cycle time of the operation.
- ✓ The distance between the robot flange and the centre of mass may also be important and this should be kept to a minimum.

(b) Supply of services

- ✓ With robot end effectors loose cable or hoses are something to be avoided.
- ✓ They increase the size of the tool (making it harder to reach into confined spaces) and cause many failures due to rubbing or snagging on other parts of the mechanism.
- ✓ It is therefore preferable to route all services or signal connections through the robot arm and then internally through the tool.

(c) Environmental capabilities

- ✓ End effectors are often required to work in hostile environments. High temperatures, dust or the presence of chemicals will require special materials or designs to be used.

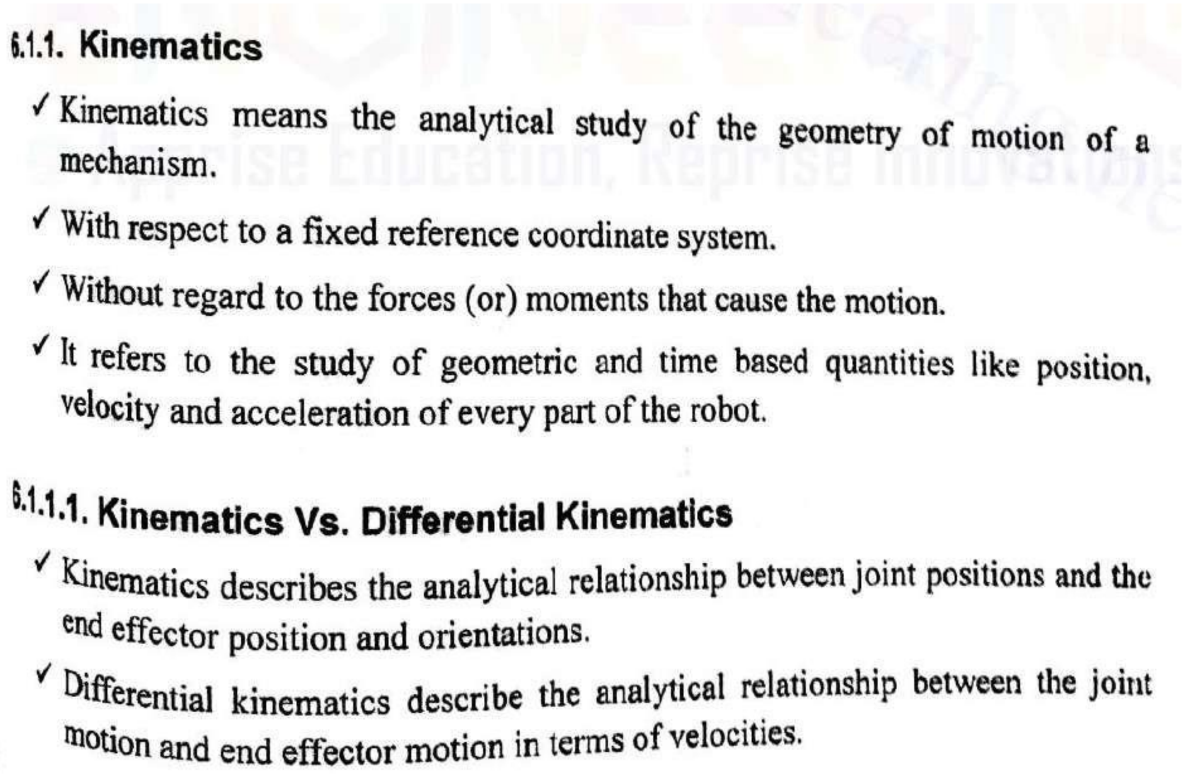
(d) Sensor capabilities

- For certain applications some degree of sensory feedback from the gripper is necessary.
- This may be measurement of insertion or gripping forces or may simply be a proximity sensor to say if anything is between the jaws of the gripper.
- Some standard grippers are provided with feedback to show the separation of the jaws but most grippers have no feedback.

(e) Others

- Other factors to be considered include the speed of the gripper jaws and the range of sizes of component they can grip.
- The amount of maintenance required is also important though most modern mechanisms require little or no maintenance. For some situations the behaviour of the gripper on power failure may be critical.
- Some but not all use either springs to apply the gripping force or non return valves to ensure that pressure is maintained.

UNIT – 4: KINEMATICS AND DYNAMICS OF ROBOTS

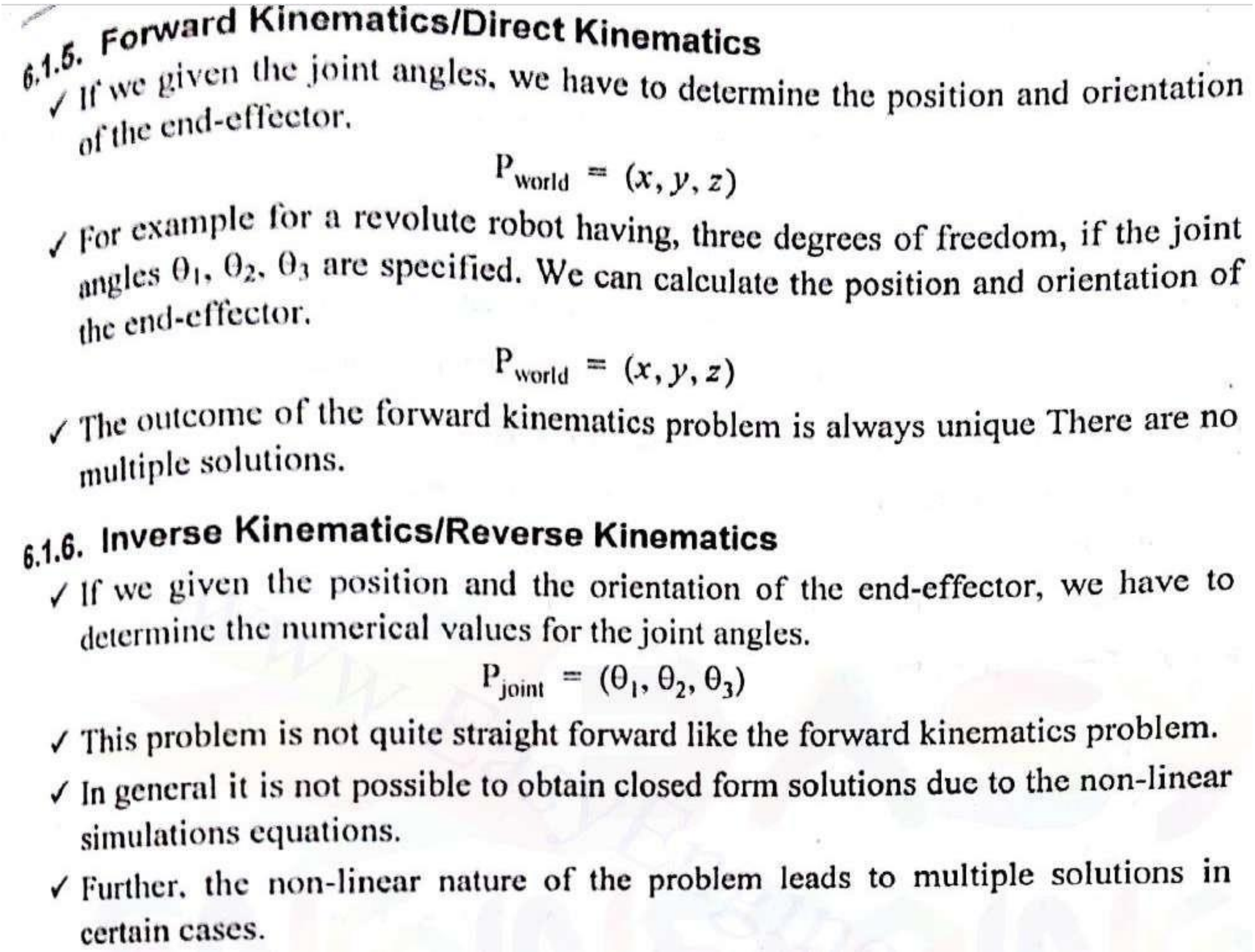


6.1.1. Kinematics

- ✓ Kinematics means the analytical study of the geometry of motion of a mechanism.
- ✓ With respect to a fixed reference coordinate system.
- ✓ Without regard to the forces (or) moments that cause the motion.
- ✓ It refers to the study of geometric and time based quantities like position, velocity and acceleration of every part of the robot.

6.1.1.1. Kinematics Vs. Differential Kinematics

- ✓ Kinematics describes the analytical relationship between joint positions and the end effector position and orientations.
- ✓ Differential kinematics describe the analytical relationship between the joint motion and end effector motion in terms of velocities.



6.1.5. Forward Kinematics/Direct Kinematics

- ✓ If we given the joint angles, we have to determine the position and orientation of the end-effector.

$$P_{world} = (x, y, z)$$

- ✓ For example for a revolute robot having, three degrees of freedom, if the joint angles θ_1, θ_2, θ_3 are specified. We can calculate the position and orientation of the end-effector.

$$P_{world} = (x, y, z)$$

- ✓ The outcome of the forward kinematics problem is always unique There are no multiple solutions.

6.1.6. Inverse Kinematics/Reverse Kinematics

- ✓ If we given the position and the orientation of the end-effector, we have to determine the numerical values for the joint angles.

$$P_{joint} = (\theta_1, \theta_2, \theta_3)$$

- ✓ This problem is not quite straight forward like the forward kinematics problem.
- ✓ In general it is not possible to obtain closed form solutions due to the non-linear simulations equations.
- ✓ Further, the non-linear nature of the problem leads to multiple solutions in certain cases.

6.1.6.1. Difference Between Forward Kinematics and Inverse Kinematics

(a) Forward Kinematics:

- ✓ If we given joint angles, compute the transformation between world and gripper coordinates.

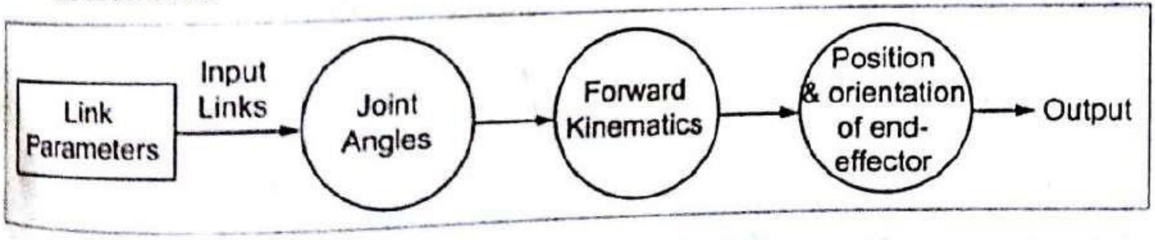


Fig. 6.2. Forward kinematics

- ✓ Relatively straight forward.

(b) Inverse (Reverse) Kinematics:

- ✓ If we given the transformation between world coordinates and an arbitrary frame, compute the joint angles that would line gripper coordinates up with that frame.

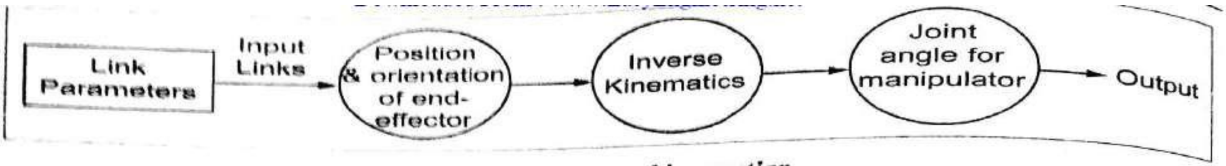


Fig. 6.3. Reverse kinematics

- ✓ For a kinematic mechanism, the inverse kinematic problems difficult to solve.
- ✓ The robot controller must solve a set of non-linear simultaneous algebraic.

6.1.6.2. Two Frames Kinematic Relationship

- ✓ There is a kinematic relationship between two frames, basically a translation and rotation.
- ✓ This relationship is represented by 4 × 4 homogeneous transformation.

6.1.7. Transformations

- ✓ Transformations of frames introduced to make modeling the relocation of objects easier.
- ✓ An object is described with respect to a frame located in the object, and this frame is relocated with a transformation.

- ✓ The transformation is the result of a sequence of rotations and translations, which are recorded with a transformation equation.

6.1.8. Homogeneous Transformation

1. Homogeneous Transformation Matrix

$$ {}^{A}T_{B} = \begin{bmatrix} \overset{\text{Rotation matrix}}{\boxed{R}}_{3\times3} & \overset{\text{Position matrix}}{\boxed{P}}_{3\times1} \\ 0 & \boxed{1} \end{bmatrix} \longleftarrow \text{Scaling} $$

2. Composite Homogeneous Transformation Matrix

Rules:

- ✓ Transformation (rotation/translation) with respect to (X,Y,Z) (OLD FRAME), using ***pre-multiplication.***
- ✓ Transformation (rotation/translation) with respect to (U,V,W) (NEW FRAME), using ***post-multiplication.***

6.1.9. Composite Rotation Matrix

A sequence of finite rotations matrix multiplications do not commute rules:

- ✓ If rotating coordinate O-U-V-W is rotating about principal axis of OXYZ frame, then Pre-multiply the previous (resultant) rotation matrix with an appropriate basic rotation matrix.
- ✓ If rotating coordinate O-U-V-W is rotating about its own principal axes, then post-multiply the previous (resultant) rotation matrix with an appropriate basic rotation matrix.

6.1.10. Homogeneous Representation

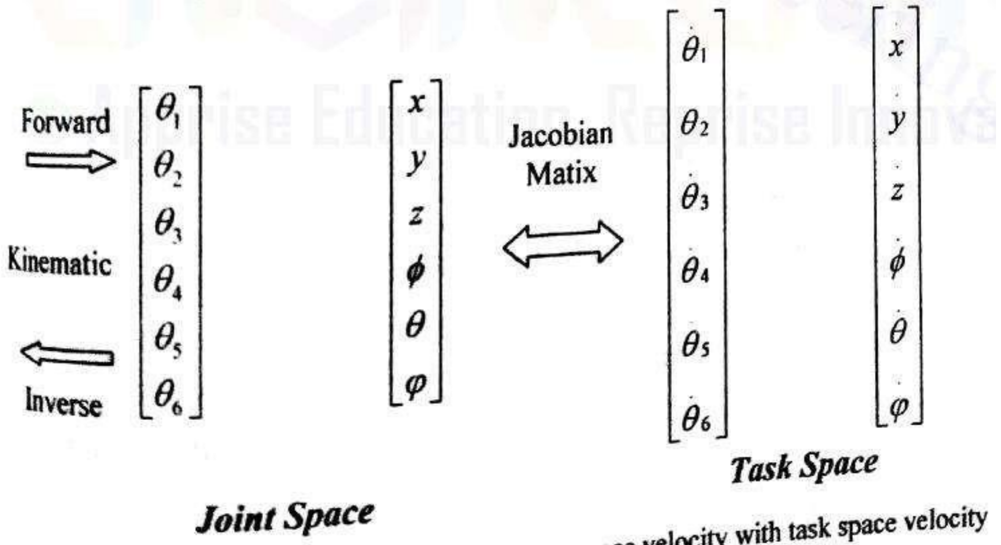
A frame in space (Geometric Interpretation)

$$F = \begin{bmatrix} R_{3\times3} & P_{3\times1} \\ 0 & 1 \end{bmatrix}$$

$$F = \begin{bmatrix} n_x & s_x & a_x & p_x \\ n_y & s_y & a_y & p_y \\ n_z & s_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Principal axis n with respect to the reference coordinate system

6.1.11. Manipulator Kinematics



Jacobian Matrix: Relationship between joint space velocity with task space velocity

6.1.12. Jacobian

Let the linear velocity and the angular velocity of the end-effector be represented in the vectorial form by

Let the joint angular velocities of a revolute robot be represented by

$$\frac{d\theta}{dt} = \begin{pmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_6 \end{pmatrix}$$

The vector V and $d\theta/dt$ can be connected by a matrix known as the Jacobian , i.e.,

$$V = J\frac{d\theta}{dt}$$

Where,

$J = J(\theta)$ is the Jacobian.

$$\boxed{V = J\frac{d\theta}{dt}}$$

Further

(−10 deg

6.2. ROBOT MOTION ANALYSIS

In robot motion analysis we study the geometry of the robot arm with respect to a reference coordinate system, while the end-effector moves along the prescribed path. This kinematic analysis involves two different kinds of problems:

1. Determining the coordinates of the end-effector or end of arm for a given set of joints coordinates.
2. Determining the joints coordinates for a given location of the end-effector or end of arm.

The position, V, of the end-effector can be defined in the cartesian coordinate system.

Generally, for robots the location of the end-effector can be defined in two systems:

(a) Joint space
(b) World space (also known as global space)

(a) Joint Space

In Joint space, the joint parameters such as rotating or variable link length and twisting joint angles are used to represent the position of the end-effector.

$V_j = (\theta, a)$ for RR robot (Rotating)
$V_j = (L_1, L_2)$ for LL robot (Variable link length)
$V_j = (\alpha, L_2)$ for TL robot (Twisting joint angles)

Where V_j refers to the position of the end-effector in joint space.

(b) World space

In world space, rectilinear coordinates with reference to the basic cartesian system are used to define the position of the end-effector.

Usually the origin of the cartesian axes is located in the robot's base.

$$VW = (x, y)$$

where VW refers to the position of the end-effector in world space.

— The transformation of coordinates from joint space to world space is known as Direct (or) Forward kinematic transformation.

— Similarly, the transformation of coordinates from world space to joint space is known as backward (or) reverse kinematic transformations.

6.3. FORWARD KINEMATIC TRANSFORMATION OF TWO DEGREES OF FREEDOM

The transformation of coordinates of the end-effector point from the joint space to the world space is known as ***forward kinematics transformation.***

6.3.1. LL Robot

Let us consider a Cartesian LL robot.

✓ Figure 6.4 illustrates the scheme of forward and reverse kinematics LL Robot.

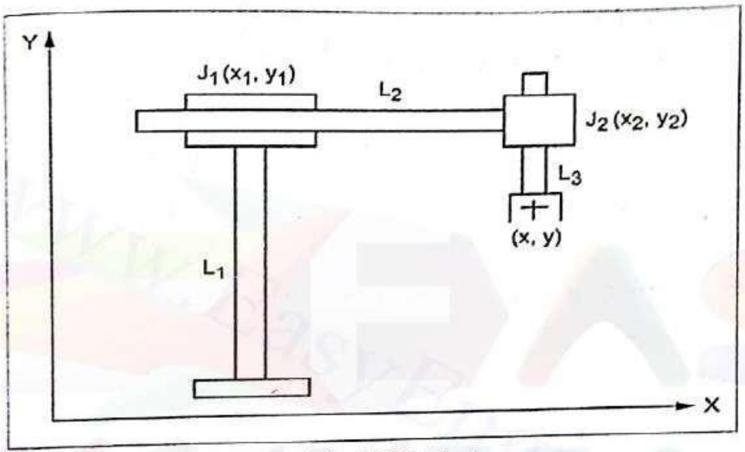


Fig. 6.4. LL Robot

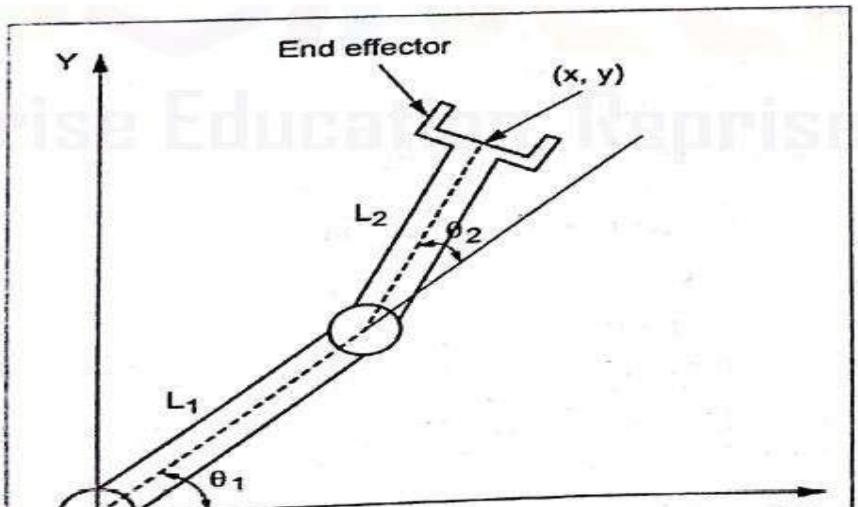


Fig. 6.5. Two manipulator with two degrees of freedom

Joints J1 and J2 are linear joints with links of variable lengths L1 and L2. Let joint J_1 be denoted by (x_1, y_1) and joint J_2 (x_2, y_2).

From geometry, we can easily get the following:

$$x_2 = x_1 + L_2 \qquad \cdots (6.1)$$

$$y_2 = y_1 \qquad \cdots (6.2)$$

These relations can be represented in homogeneous matrix form:

$$\begin{bmatrix} x_2 \\ y_2 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & L_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ y_1 \\ 1 \end{bmatrix}$$

or $$X_2 = T_1 X_1$$

Where, $$X_2 = \begin{bmatrix} x_2 \\ y_2 \\ 1 \end{bmatrix}; \quad T_1 = \begin{bmatrix} 1 & 0 & L_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}; \quad X_1 = \begin{bmatrix} x_1 \\ y_1 \\ 1 \end{bmatrix}$$

If the end-effector point is denoted by (x, y), then:

$$x = x_2 \qquad \ldots (6.3)$$

$$y = y_2 - L_3 \qquad \ldots (6.4)$$

therefore,

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & -L_3 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_2 \\ y_2 \\ 1 \end{bmatrix}$$

or $$X = T_2 X_2 \qquad \ldots (6.5)$$

Substitute X_2 value in equation (6.5), we get

$$X = T_2 (T_1 X_1) = T_{LL} X_1 \qquad [\because T_2 T_1 = T_{LL}]$$

Where, $$T_{LL} = T_2 T_1 \qquad \ldots (6.6)$$

And $$T_{LL} = \begin{bmatrix} 1 & 0 & L_2 \\ 0 & 1 & -L_3 \\ 0 & 0 & 1 \end{bmatrix} \qquad \ldots (6.6.1)$$

6.3.2. RR Robot

Let θ and α be the rotations at joints J_1 and J_2 respectively. Let J_1 and J_2 have the coordinates of (x_1, y_1) and (x_2, y_2) respectively.

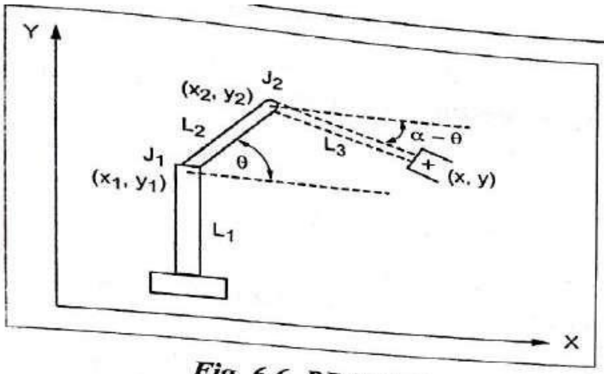


Fig. 6.6. ***RR Robot***

One can write the following from the geometry:

$$x_2 = x_1 + L_2 \cos(\theta) \qquad \dots (6.7)$$

$$y_2 = y_1 + L_2 \sin(\theta) \qquad \dots (6.8)$$

Equation (6.7) and (6.8) can be written in matrix form

$$\begin{bmatrix} x_2 \\ y_2 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & L_2 \cos(\theta) \\ 0 & 1 & L_2 \sin(\theta) \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ y_1 \\ 1 \end{bmatrix}$$

$$[\because x = x_1 + y_1 + z_1;\ y = x_1 + y_1 + z_1]$$

or $$X_2 = T_1 X_1 \qquad \dots (6.9)$$

On the other end: $$x = x_2 + L_3 \cos(\alpha - \theta)$$

$$[\because x = x_1 + y_1 + z_1;\ y = x_1 + y_1 + z_1]$$

or $$X_2 = T_1 X_1 \qquad \dots (6.9)$$

On the other end: $$x = x_2 + L_3 \cos(\alpha - \theta) \qquad \dots (6.10)$$

$$y = y_2 - L_3 \sin(\alpha - \theta) \qquad \dots (6.11)$$

Equation (6.9) and (6.10) can be written in matrix form,

$$X = T_2 X_2 \qquad \dots (6.12)$$

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & L_3 \cos(\alpha - \theta) \\ 0 & 1 & -L_3 \sin(\alpha - \theta) \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_2 \\ y_2 \\ 1 \end{bmatrix}$$

Substitute X_2 value in equation (6.12), we get

Combining the two equation gives,

$$X = T_2 (T_1 X_1) = T_{RR} X_1 \qquad [\because T_2 T_1 = T_{RR}]$$

$$T_{RR} = \begin{bmatrix} 1 & 0 & L_2 \cos(\theta) + L_3 \cos(\alpha - \theta) \\ 0 & 1 & L_2 \sin(\theta) - L_3 \sin(\alpha - \theta) \\ 0 & 0 & 1 \end{bmatrix} \qquad \dots (6.12.1)$$

6.3.3. TL Robot

Let α be the rotation at twisting joint J_1 and L_2 be the variable link length at linear joint J_2.

One can write that:

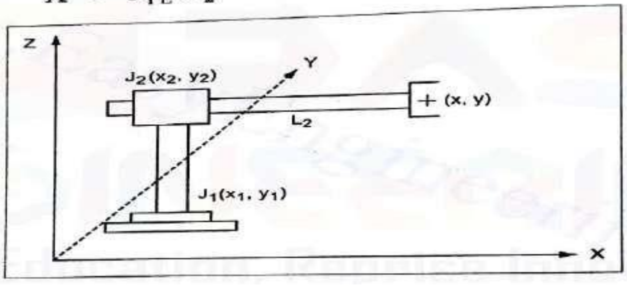
$$x = x_2 + L_2 \cos(\alpha) \quad \ldots (6.13)$$

$$y = y_2 + L_2 \sin(\alpha) \quad \ldots (6.14)$$

Equation (6.13) and (6.14) can be written in matrix form

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & L_2 \cos(\alpha) \\ 0 & 1 & L_2 \sin(\alpha) \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_2 \\ y_2 \\ 1 \end{bmatrix} \quad \ldots (6.14.1)$$

or $$X = T_{TL} X_2 \qquad [\because x = x_2 + y_2 + z_2; y = x_2 + y_2 + z_2]$$



6.4. BACKWARD KINEMATIC TRANSFORMATION – 2 DEGREES OF FREEDOM

6.4.1. LL Robot

In backward kinematic transformation, the objective is to drive the variable link lengths from the known position of the end-effector in world space.

$$x = x_1 + L_2(\alpha) \quad \ldots (6.15)$$

$$y = Y_1 - L_3 \quad \ldots (6.16)$$

$$y_1 = y_2 \quad \ldots (6.17)$$

By combining equations (6.15) & (6.16), we can get

$$L_2 = x - x_1$$
$$L_3 = -y + y_2$$

6.4.2. RR Robot

$$x = x_1 + L_2 \cos(\theta) + L_3 \cos(\alpha - \theta) \quad \text{... (6.18)}$$
$$y = y_1 + L_2 \sin(\theta) - L_3 \sin(\alpha - \theta)(\theta) \quad \text{... (6.19)}$$

Combine the equations (6.18) & (6.19) easily, we can get the angles.

$$\cos(\alpha) = \frac{[(x - x_1)^2 + (y - y_1)^2 - L_2^2 - L_3^2}{2 L_2 L_3} \quad \text{... (6.19.1)}$$

and
$$\tan(\theta) = \frac{(y - y_1)(L_2 + L_3 \cos(\alpha)) + (x - x_1) L_3 \sin(\alpha)}{(x - x_1)(L_2 + L_3 \cos(\alpha)) - (y - y_1) L_3 \sin(\alpha)} \quad \text{... (6.19.2)}$$

6.4.3. TL Robot

$$x = x_2 + L \cos(\alpha)(\theta) \quad \text{... (6.20)}$$
$$y = y_2 + L \sin(\alpha)(\theta) \quad \text{... (6.21)}$$

One can easily get the equations for length and angle:

$$L = \sqrt{(x - x_2)^2 + (y - y_2)^2} \quad \text{... (6.22)}$$

Substitute equations (6.20), (6.21) values in equation (6.22), we get

$$\sin(\alpha) = \frac{y - y_2}{L}$$

6.6. DETERMINE THE FORWARD AND REVERSE KINEMATICS SOLUTION OF A SPHERICAL ROBOT CONFIGURATION (RRL) (THREE DOF 2D MANIPULATOR)

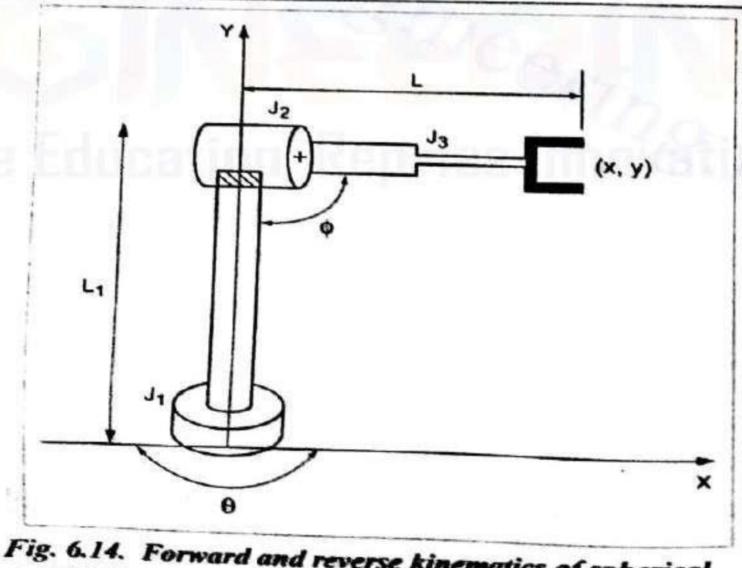


Fig. 6.14. Forward and reverse kinematics of spherical Robot RRL Configuration with three DOF with 2D manipulator

- In the forward kinematics, if we are given the joint angles, we have to find out the position of the end effector.
- A manipulator with three degrees of freedom, two rotation and one linear motion.
- The arm and body (RR) provides position of the end of the arm and wrist 'L' provide the orientation.
- The robot is still limited to the XY plane.

Forward Kinematics:

✓ For the forward kinematics, we can compute the x, y and z coordinates.

$$x = \cos\theta\,(L\cos\phi) + L_3\cos\phi$$

$$y = \sin\theta\,(L\cos\phi) + L_1 + L_3 + L_3\cos\phi$$

Backward (or) Reverse Kinematics:

✓ In the backward kinematics, we have given world coordinates x, y, ϕ and we want to calculate the joint angles θ_1, θ_2 and θ_3.

✓ This is accomplished by first determining the coordinates of joint 3. *i.e.,* x_3, y_3.

$$x_3 = x - L_3\cos\phi \qquad \ldots (6.27)$$

$$y_3 = y - L_3\cos\phi \qquad \ldots (6.28)$$

Substituting the 'x' values and 'y' values in the equation (6.27) and (6.28) respectively.

$$x_3 = \cos\theta\,(L\cos\phi) + L_3\cos\phi - L_3\cos\phi$$

$$\boxed{x_3 = \cos\theta\,(L\cos\phi)} \qquad [\because L_3\cos\phi - L_3\cos\phi = 0] \qquad \ldots (6.28.1)$$

$$y_3 = y - L_3\cos\phi$$

$$y_3 = \sin\theta\,(L\cos\phi) + L_1 + L_3 + L_3\cos\phi - L_3\cos\phi \quad [\because L_3\cos\phi - L_3\cos\phi = 0]$$

$$\boxed{y_3 = \sin\theta\,(L\cos\phi) + L_1 + L_3}$$

$$\boxed{y_3 = \sin\theta\,(L\cos\phi) + L_1 + L_3}$$

It can be written as

$$\boxed{y_3 - L_1 - L_3 = \sin\theta\,(L\cos\phi)} \qquad \ldots (6.28.2)$$

Adding the equations (6.28.1) and (6.28.2) on both sides, we get

$$x_3 + [y_3 - L_1 - L_3] = \cos\theta\,(L\cos\phi) + \sin\theta\,(L\cos\phi) \qquad \ldots (6.29)$$

Squaring the equation (6.29) on both sides, we get

$$(x_3)^2 + [y_3 - (L_1 + L_3)]^2 = \cos^2\theta\,(L^2\cos^2\phi) + \sin^2\theta\,(L^2\cos^2\phi)$$

$$x_3^2 + [y_3 - (L_1 + L_3)]^2 = L^2\cos^2\phi\,(\cos^2\theta + \sin^2\theta) \qquad [\because \sin^2\theta + \cos^2\theta = 1]$$

$$x_3^2 + [y_3 - (L_1 + L_3)]^2 = L^2\cos^2\phi \qquad \ldots (6.30)$$

$$L^2 = \frac{x_3^2 + [y_3 - (L_1 + L_3)]^2}{\cos^2\phi}$$

$$\boxed{\begin{aligned} L &= \frac{x_3^2 + [\{y_3 - (L_1 + L_3)\}^2]^{1/2}}{\cos\phi} \\ \tan\theta &= \frac{y_3 - [L_1 + L_3]}{x_3} \\ \sin\phi &= \frac{y_3 - [L_1 + L_3]}{L} \end{aligned}}$$

6.11.1. Representation of Transformation

- ✓ Transformation is defined as making a movement in space.
- ✓ When a frame moves in space relative to fixed reference frame, we can represent this motion in a form similar to a frame representation.
- ✓ This is because a transformation itself is a change in the state of a frame (representing the change in its location and orientation) and thus it can be represented as a frame.
- ✓ A transformation may be in one of the following forms:
  1. Pure translation
  2. Pure rotation about an axis.
  3. A combination of translation and rotation.

Pure Translation

- ✓ If a frame moves in space without any change in its orientation, the transformation is a pure translation.
- ✓ The directional unit vectors remain in the same direction and thus do not change.

- ✓ The new location of the frame relative to the fixed reference frame can be found by adding the vector representing the translation to the vector representing the original location of the origin of the frame.
- ✓ It matrix form, new frame representation may be found by premultiplying the frame with a matrix representing the transformation.

- ✓ Since the directional vectors do not change in a pure translation, the transformation T will simply be,

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

where dx, dy and dz are the three components of a pure translation vectors T relative to the x, y and z axes of the reference frame.

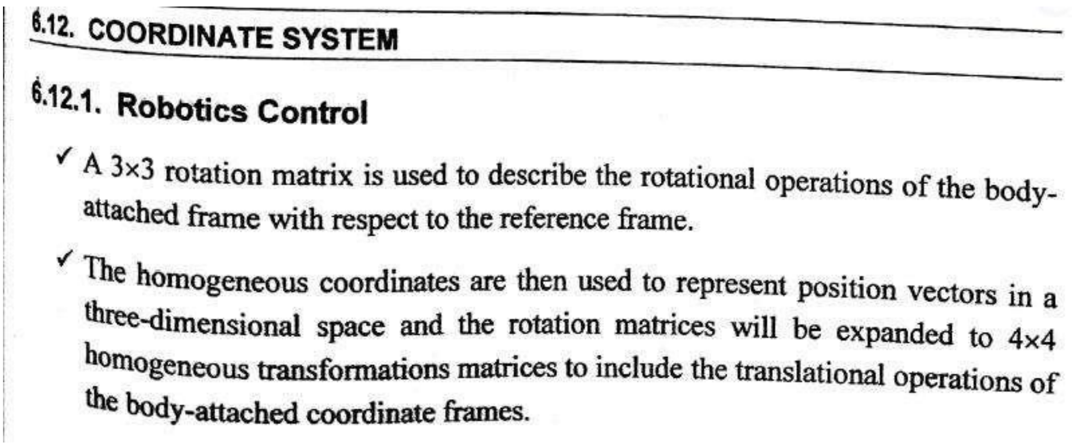
- ✓ First three columns represents no rotational movement (Equivalent to unity), while the last column represents the translation. The new location of the frame will be

$$F_{new} = \begin{bmatrix} 1 & 0 & 0 & dx \\ 0 & 1 & 0 & dy \\ 0 & 0 & 1 & dz \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \ldots (6.43)$$

$$= \begin{bmatrix} n_x & o_x & a_x & p_x + dx \\ n_y & o_y & a_y & p_y + dy \\ n_z & o_z & a_z & p_z + dz \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \ldots (6.44)$$

This equation is written as,

$$F_{new} = \text{Trans}(dx, dy, dz) \times F_{old}$$

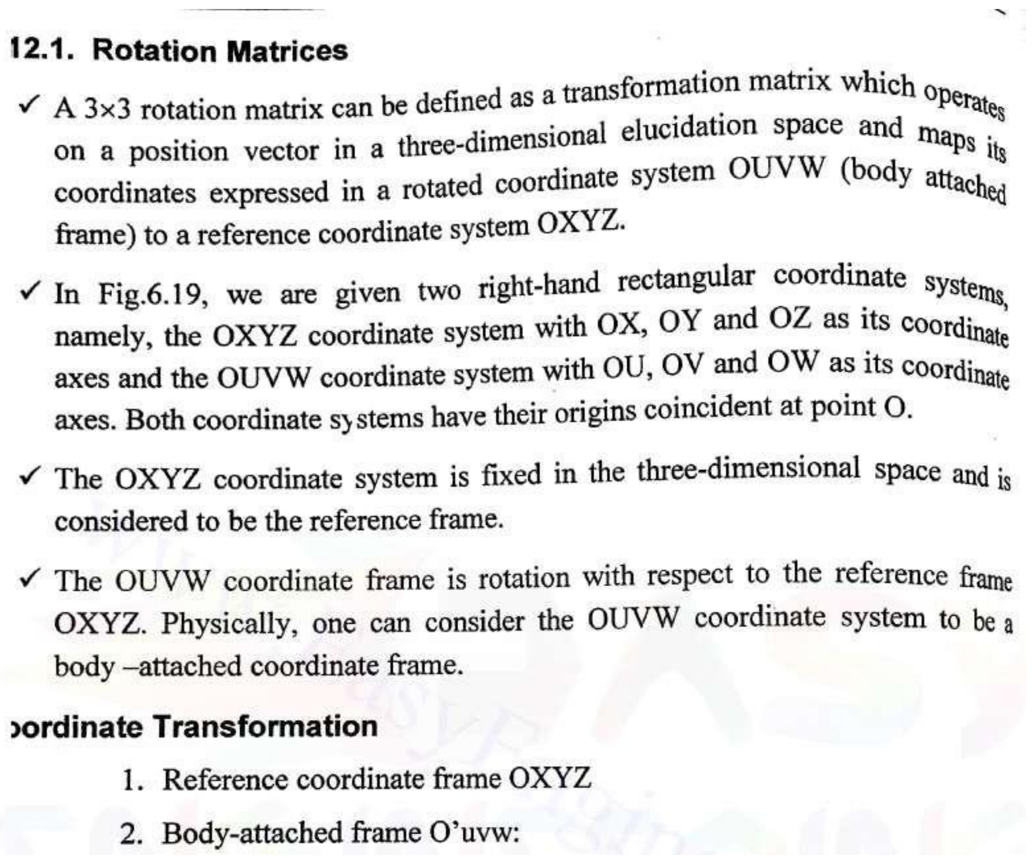


6.12. COORDINATE SYSTEM

6.12.1. Robotics Control

✓ A 3×3 rotation matrix is used to describe the rotational operations of the body-attached frame with respect to the reference frame.

✓ The homogeneous coordinates are then used to represent position vectors in a three-dimensional space and the rotation matrices will be expanded to 4×4 homogeneous transformations matrices to include the translational operations of the body-attached coordinate frames.



12.1. Rotation Matrices

✓ A 3×3 rotation matrix can be defined as a transformation matrix which operates on a position vector in a three-dimensional elucidation space and maps its coordinates expressed in a rotated coordinate system OUVW (body attached frame) to a reference coordinate system OXYZ.

✓ In Fig.6.19, we are given two right-hand rectangular coordinate systems, namely, the OXYZ coordinate system with OX, OY and OZ as its coordinate axes and the OUVW coordinate system with OU, OV and OW as its coordinate axes. Both coordinate systems have their origins coincident at point O.

✓ The OXYZ coordinate system is fixed in the three-dimensional space and is considered to be the reference frame.

✓ The OUVW coordinate frame is rotation with respect to the reference frame OXYZ. Physically, one can consider the OUVW coordinate system to be a body –attached coordinate frame.

ɔordinate Transformation

1. Reference coordinate frame OXYZ
2. Body-attached frame O'uvw:

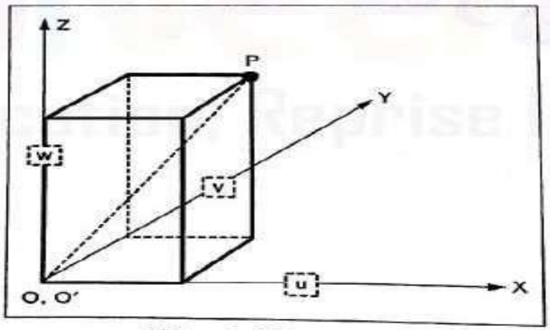
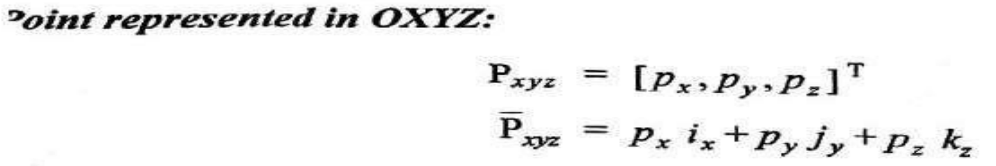


Fig. 6.19.

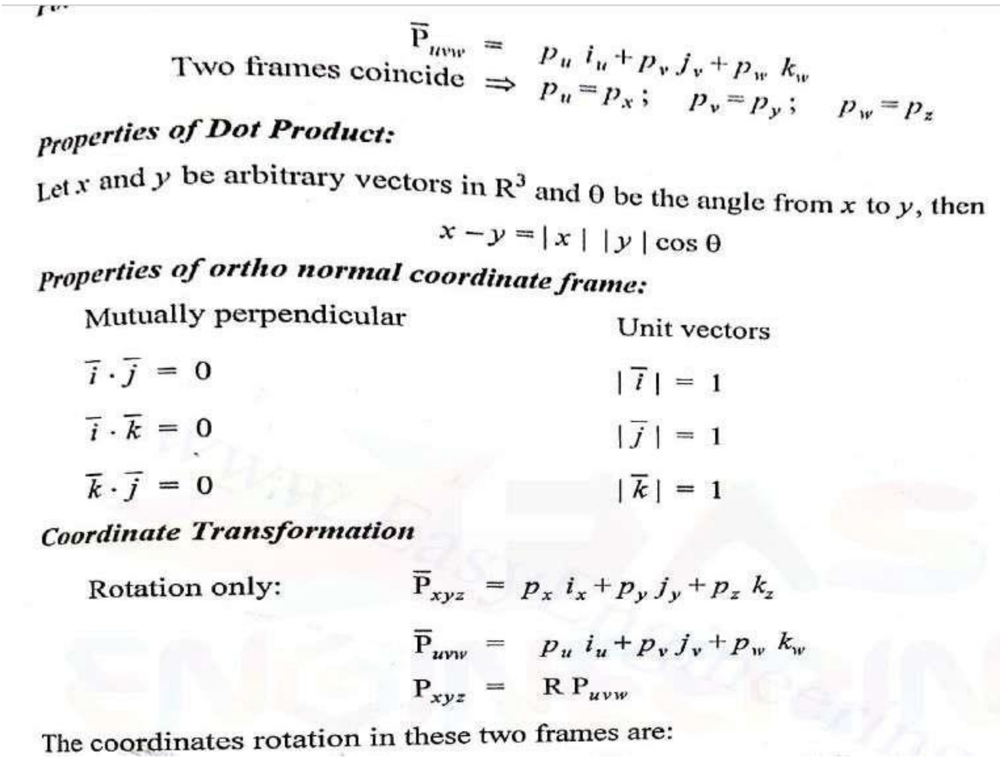


oint represented in OXYZ:

$$\mathbf{P}_{xyz} = [p_x, p_y, p_z]^T$$

$$\overline{\mathbf{P}}_{xyz} = p_x\, i_x + p_y\, j_y + p_z\, k_z$$

Point represented in O’uvw



$$\overline{\mathrm{P}}_{uvw} = p_u\ i_u + p_v\ j_v + p_w\ k_w$$

Two frames coincide $\Rightarrow$ $p_u = p_x;\quad p_v = p_y;\quad p_w = p_z$

Properties of Dot Product:

Let x and y be arbitrary vectors in R^3 and θ be the angle from x to y, then

$$x - y = |\,x\,|\ \ |\,y\,|\cos\theta$$

Properties of ortho normal coordinate frame:

Mutually perpendicular	Unit vectors
$\bar{i}\cdot\bar{j} = 0$	$\lvert\bar{i}\rvert = 1$
$\bar{i}\cdot\bar{k} = 0$	$\lvert\bar{j}\rvert = 1$
$\bar{k}\cdot\bar{j} = 0$	$\lvert\bar{k}\rvert = 1$

Coordinate Transformation

Rotation only: $\overline{\mathrm{P}}_{xyz} = p_x\ i_x + p_y\ j_y + p_z\ k_z$

$$\overline{\mathrm{P}}_{uvw} = p_u\ i_u + p_v\ j_v + p_w\ k_w$$

$$\mathrm{P}_{xyz} = \mathrm{R}\,\mathrm{P}_{uvw}$$

The coordinates rotation in these two frames are:

The coordinates rotation in these two frames are:

p_x, p_y and p_z represent the projections of P onto OX, OY, OZ axes, respectively.

Since
$$P = p_u\, i_u + p_v\, i_v + p_w\, k_w$$
$$p_x = i_x \cdot P = i_x \cdot i_u p_u + i_x \cdot j_v p_v + i_x \cdot k_w p_w$$
$$p_y = j_y \cdot P = j_y \cdot i_u p_u + j_y \cdot j_v p_v + j_y \cdot k_w p_w$$
$$p_z = k_z \cdot P = k_z \cdot i_u p_u + k_z \cdot j_v p_v + k_z \cdot k_w p_w$$

Expressed in matrix form
$$\begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = \begin{bmatrix} i_x \cdot i_u & i_x \cdot j_v & i_x \cdot k_w \\ j_y \cdot i_u & j_y \cdot j_v & j_y \cdot k_w \\ k_z \cdot i_u & k_z \cdot j_v & k_z \cdot k_w \end{bmatrix} \begin{bmatrix} p_u \\ p_v \\ p_w \end{bmatrix}$$

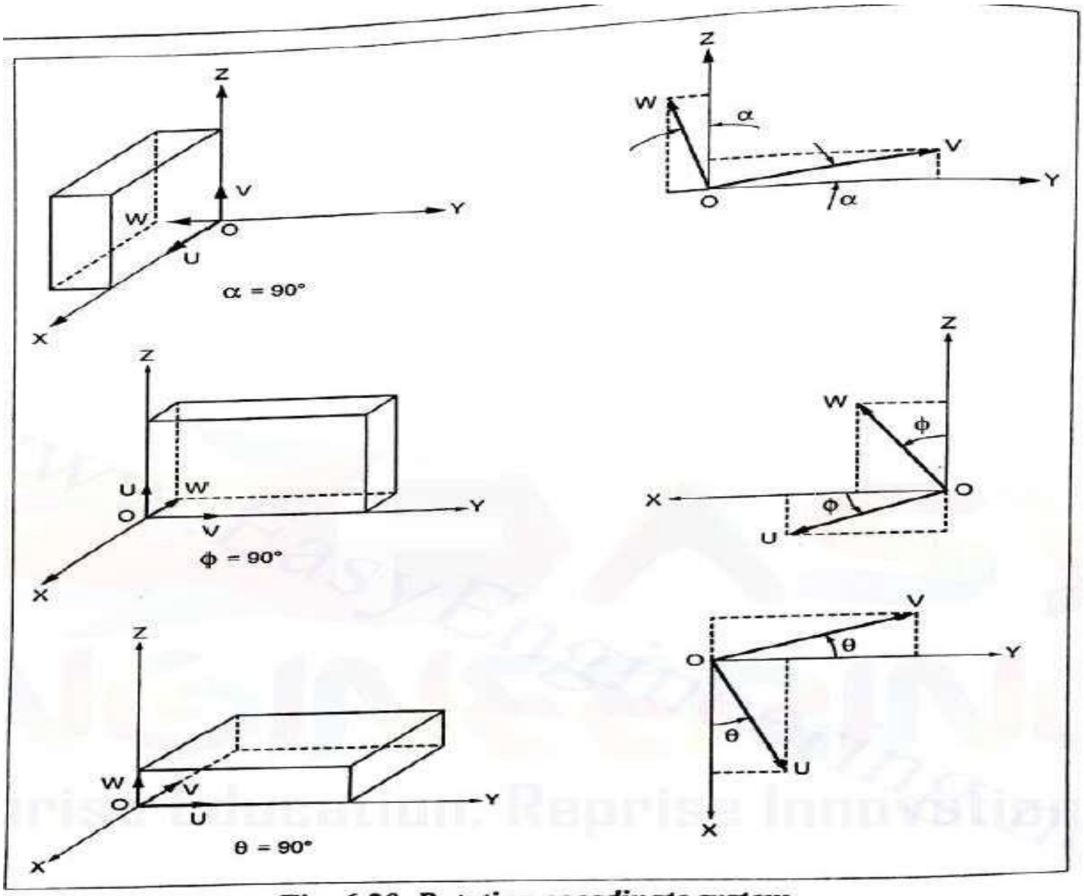


Fig. 6.20. Rotating coordinate system

Rotation about x axis with θ:

$$\begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} p_u \\ p_v \\ p_w \end{bmatrix}$$

$$p_x = p_u$$

$$p_y = p_v \cos\theta - p_w \sin\theta$$

$$p_z = p_v \sin\theta + p_w \cos\theta$$

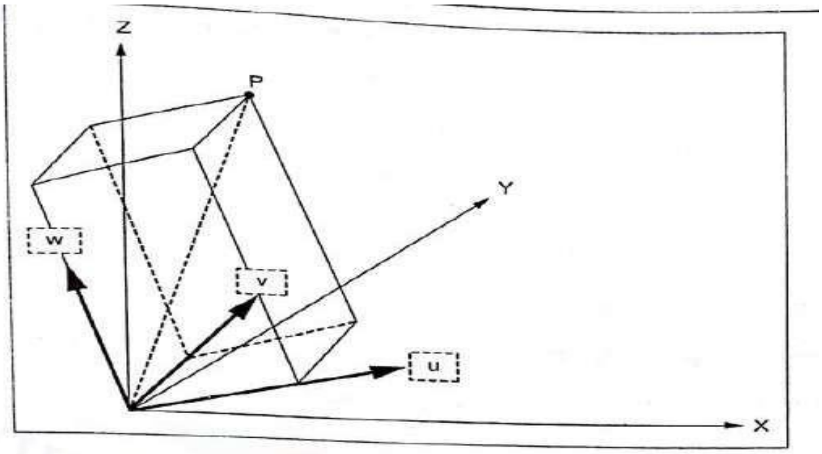


Fig. 6.21.

Rotation about x-axis with θ:

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

Rotation about y-axis with θ:

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

Rotation about z-axis with θ:

$$P_{xyz} = RP_{uvw}$$

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

Basic Rotation Matrix:

$$\mathrm{R} = \begin{bmatrix} i_x \cdot i_u & i_x \cdot j_v & i_x \cdot k_w \\ j_y \cdot i_u & j_y \cdot j_v & j_y \cdot k_w \\ k_z \cdot i_u & k_z \cdot j_v & k_z \cdot k_w \end{bmatrix}; \quad \mathrm{P}_{xyz} = \mathrm{RP}_{uvw}$$

Obtain the coordinate of P_{uvw} from the coordinate of P_{xyz}. Dot products are commutative.

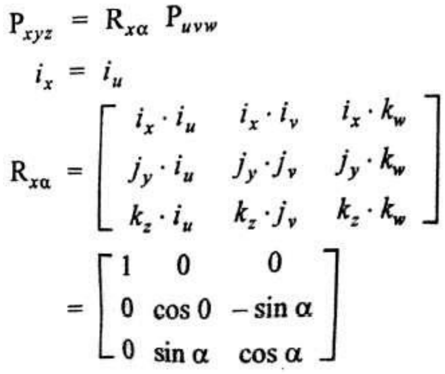
$$\begin{bmatrix} p_u \\ p_v \\ p_w \end{bmatrix} = \begin{bmatrix} i_x \cdot i_u & i_x \cdot j_y & i_u \cdot k_z \\ j_v \cdot i_x & j_v \cdot j_y & j_v \cdot k_z \\ k_w \cdot i_x & k_w \cdot j_y & k_w \cdot k_z \end{bmatrix} \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix};$$

$$\mathrm{P}_{uvw} = \mathrm{QP}_{xyz}$$

$$\mathrm{Q} = \mathrm{R}^{-1} = \mathrm{R}^{\mathrm{T}}$$

$$\mathrm{QR} = \mathrm{R}^{\mathrm{T}}\mathrm{R} = \mathrm{R}^{-1}\mathrm{R} = \mathrm{I}_3 \quad \Leftarrow 3 \times 3 \text{ identify matrix}$$

- ✓ The transformation $\mathrm{P}_{uvw} = \mathrm{QP}_{xyz}$ is called orthogonal transformation and since the vectors in the dot products are all unit vectors, it is also called an orthonormal transformation.
- ✓ The primary interest in developing the above transformation matrix is to find the rotation matrices that represent rotation of the OUVW coordinate system about each of the three principle axes of the reference coordinate system.
- ✓ If the OUVW coordinate system is rotated, an angle α about the OX axis to arrive at a new location in the space, then the point P_{uvw} having coordinates $(p_u, p_v, p_w)^{\mathrm{T}}$ with respect to the OUVW system will have different coordinates $(p_x, p_y, p_z)^{\mathrm{T}}$ with respect to the reference system OXYZ.
- ✓ The necessary transformation matrix $\mathrm{R}_{x,\alpha}$ is called the rotation matrix about the OX axis with α angle.
- ✓ $\mathrm{R}_{x\alpha}$ can be derived from the above transformation matrix concept, that is



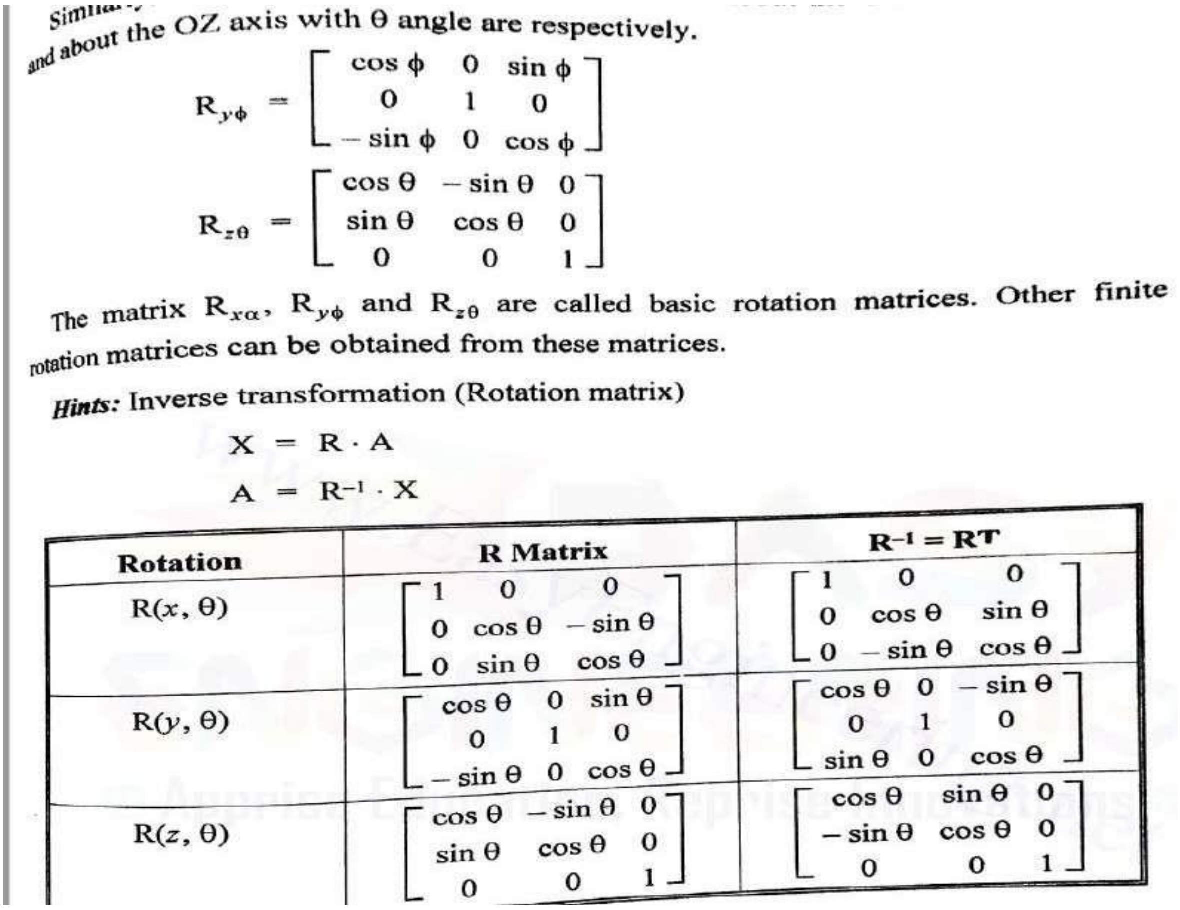
$$P_{xyz} = R_{x\alpha}\ P_{uvw}$$

$$i_x = i_u$$

$$R_{x\alpha} = \begin{bmatrix} i_x \cdot i_u & i_x \cdot i_v & i_x \cdot k_w \\ j_y \cdot i_u & j_y \cdot j_v & j_y \cdot k_w \\ k_z \cdot i_u & k_z \cdot j_v & k_z \cdot k_w \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos 0 & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix}$$

Similarly, the 3 x 3 rotation matrices for rotation about the OY axis with ø angle



Simila

and about the OZ axis with θ angle are respectively.

$$R_{y\phi} = \begin{bmatrix} \cos\phi & 0 & \sin\phi \\ 0 & 1 & 0 \\ -\sin\phi & 0 & \cos\phi \end{bmatrix}$$

$$R_{z\theta} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

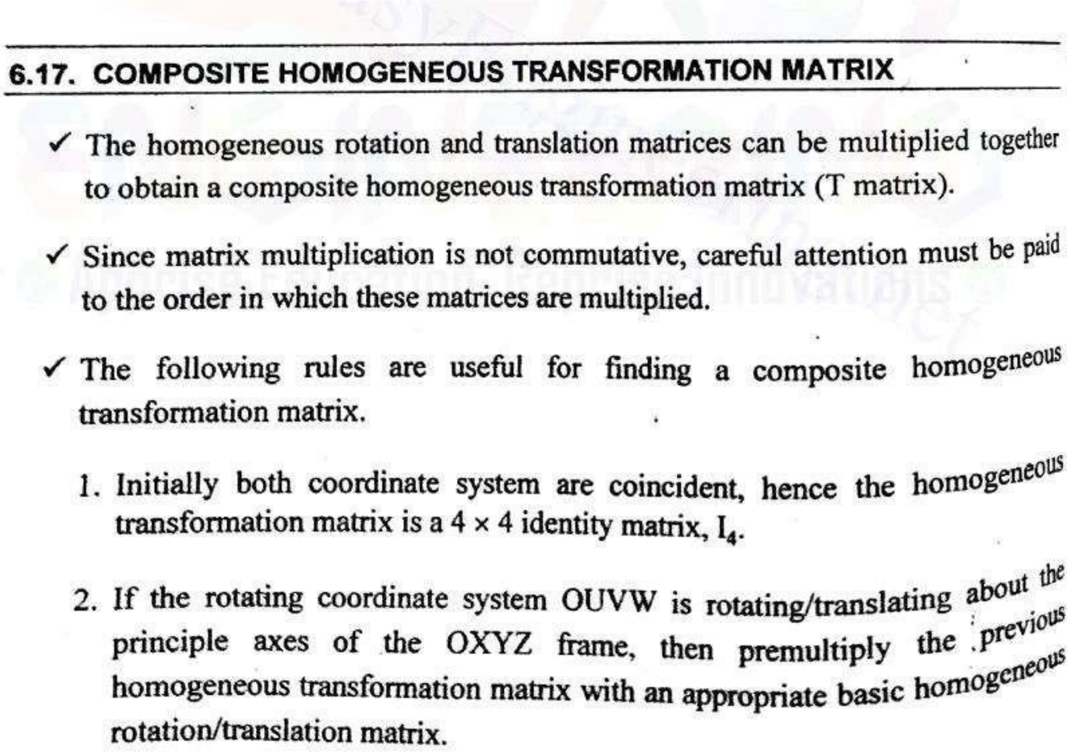
The matrix $R_{x\alpha}$, $R_{y\phi}$ and $R_{z\theta}$ are called basic rotation matrices. Other finite rotation matrices can be obtained from these matrices.

Hints: Inverse transformation (Rotation matrix)

$$X = R \cdot A$$

$$A = R^{-1} \cdot X$$

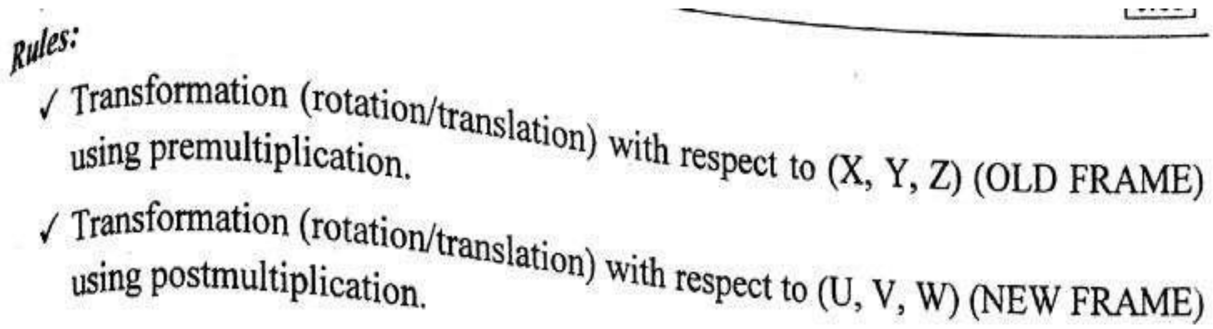
Rotation	**R Matrix**	**R^{-1} = RT**
$R(x, \theta)$	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}$	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix}$
$R(y, \theta)$	$\begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$	$\begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix}$
$R(z, \theta)$	$\begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$\begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$



6.17. COMPOSITE HOMOGENEOUS TRANSFORMATION MATRIX

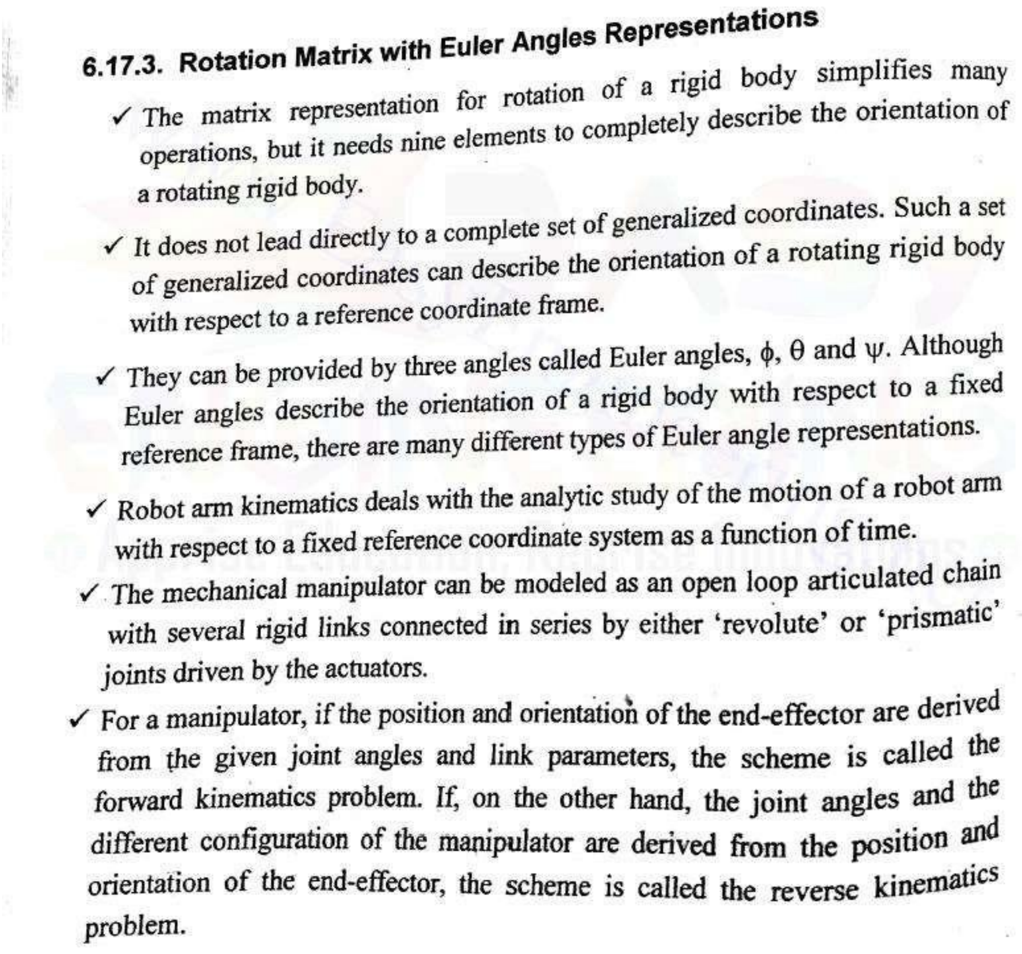
- ✓ The homogeneous rotation and translation matrices can be multiplied together to obtain a composite homogeneous transformation matrix (T matrix).
- ✓ Since matrix multiplication is not commutative, careful attention must be paid to the order in which these matrices are multiplied.
- ✓ The following rules are useful for finding a composite homogeneous transformation matrix.

1. Initially both coordinate system are coincident, hence the homogeneous transformation matrix is a 4 × 4 identity matrix, I_4.
2. If the rotating coordinate system OUVW is rotating/translating about the principle axes of the OXYZ frame, then premultiply the previous homogeneous transformation matrix with an appropriate basic homogeneous rotation/translation matrix.



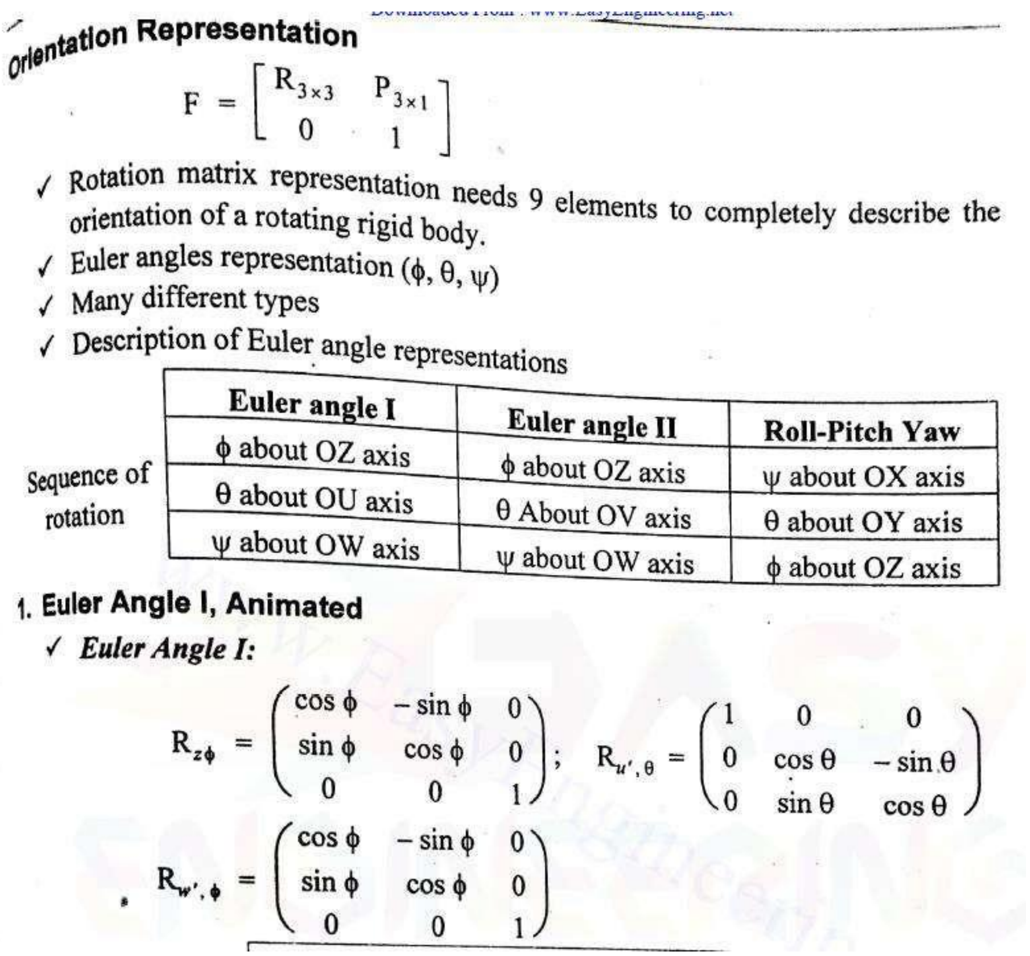
Rules:

- ✓ Transformation (rotation/translation) with respect to (X, Y, Z) (OLD FRAME) using premultiplication.
- ✓ Transformation (rotation/translation) with respect to (U, V, W) (NEW FRAME) using postmultiplication.



6.17.3. Rotation Matrix with Euler Angles Representations

- ✓ The matrix representation for rotation of a rigid body simplifies many operations, but it needs nine elements to completely describe the orientation of a rotating rigid body.
- ✓ It does not lead directly to a complete set of generalized coordinates. Such a set of generalized coordinates can describe the orientation of a rotating rigid body with respect to a reference coordinate frame.
- ✓ They can be provided by three angles called Euler angles, ϕ, θ and ψ. Although Euler angles describe the orientation of a rigid body with respect to a fixed reference frame, there are many different types of Euler angle representations.
- ✓ Robot arm kinematics deals with the analytic study of the motion of a robot arm with respect to a fixed reference coordinate system as a function of time.
- ✓ The mechanical manipulator can be modeled as an open loop articulated chain with several rigid links connected in series by either 'revolute' or 'prismatic' joints driven by the actuators.
- ✓ For a manipulator, if the position and orientation of the end-effector are derived from the given joint angles and link parameters, the scheme is called the forward kinematics problem. If, on the other hand, the joint angles and the different configuration of the manipulator are derived from the position and orientation of the end-effector, the scheme is called the reverse kinematics problem.



Orientation Representation

$$F = \begin{bmatrix} R_{3\times3} & P_{3\times1} \\ 0 & 1 \end{bmatrix}$$

- ✓ Rotation matrix representation needs 9 elements to completely describe the orientation of a rotating rigid body.
- ✓ Euler angles representation (ϕ, θ, ψ)
- ✓ Many different types
- ✓ Description of Euler angle representations

	Euler angle I	Euler angle II	Roll-Pitch Yaw
Sequence of rotation	ϕ about OZ axis	ϕ about OZ axis	ψ about OX axis
	θ about OU axis	θ About OV axis	θ about OY axis
	ψ about OW axis	ψ about OW axis	ϕ about OZ axis

1. Euler Angle I, Animated

✓ ***Euler Angle I:***

$$R_{z\phi} = \begin{pmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{pmatrix}; \quad R_{u',\theta} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix}$$

$$R_{w',\phi} = \begin{pmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

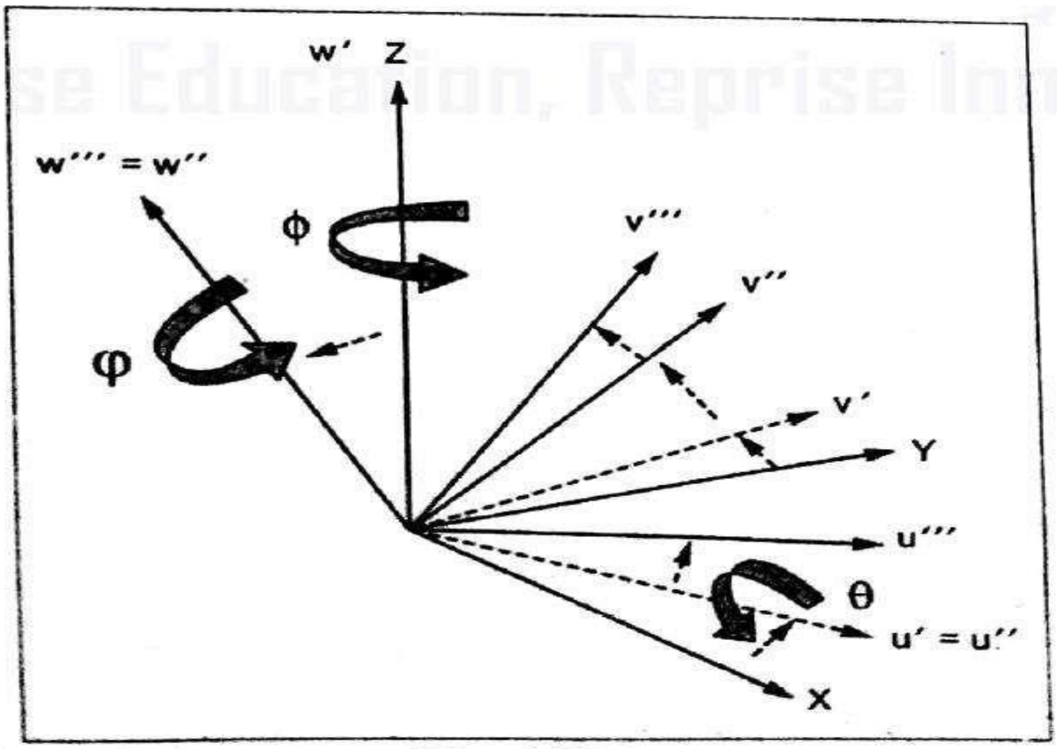


Fig. 6.23.

Resultant Eulerian rotation matrix:

$$R = R_{z\phi}\ R_{u',\theta}\ R_{w',\phi}$$

$$\begin{pmatrix} \cos\phi\cos\varphi-\sin\phi\sin\varphi\cos\theta & -\cos\phi\sin\varphi-\sin\phi\cos\varphi\cos\theta & \sin\varphi\sin\theta \\ \sin\phi\cos\varphi+\cos\phi\sin\varphi\cos\theta & -\sin\phi\sin\varphi+\cos\phi\cos\varphi\cos\theta & -\cos\phi\sin\theta \\ \sin\varphi\sin\theta & \cos\varphi\sin\theta & \cos\theta \end{pmatrix}$$

2. Euler Angle II, Animated

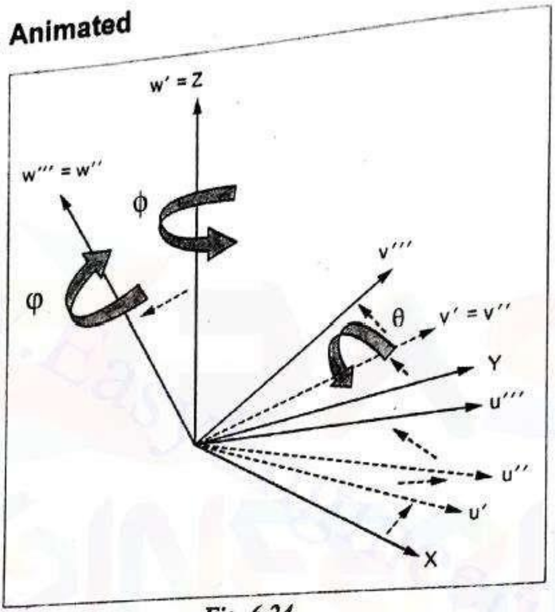


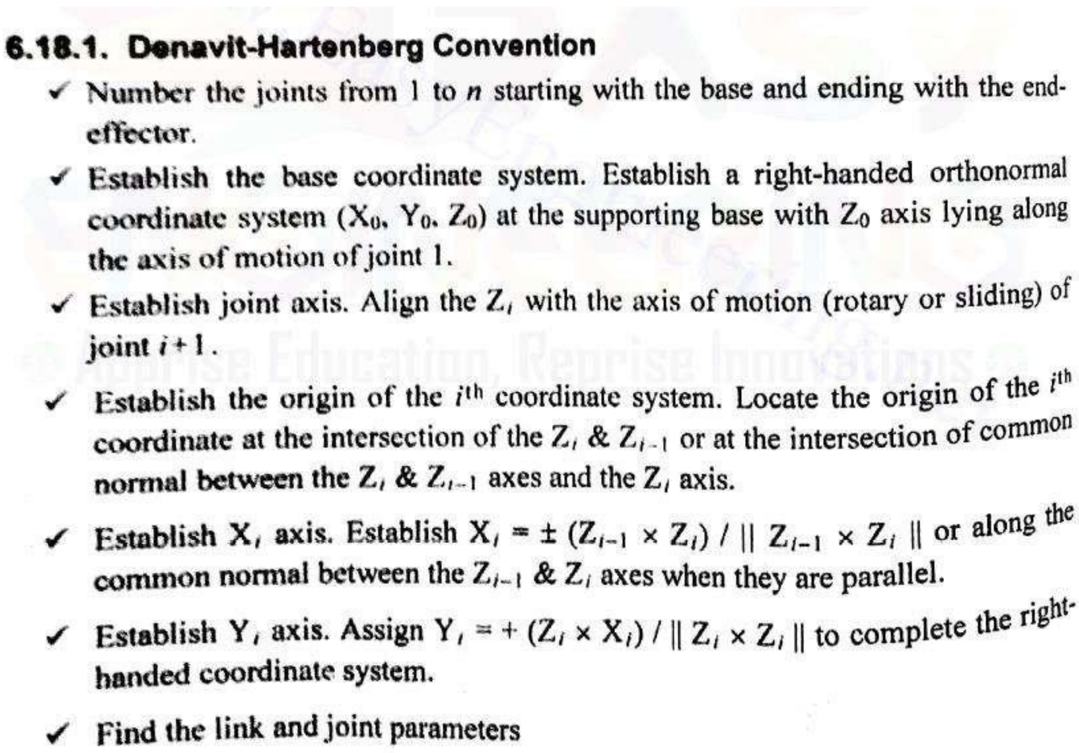
Fig. 6.24.

Note the opposite (clockwise) sense of the third rotation, ϕ.

Orientation Representation

Matrix with Euler Angle II:

$$\begin{pmatrix} \sin\phi\sin\varphi+\cos\phi\sin\varphi\cos\theta & -\sin\phi\cos\varphi-\sin\phi\cos\varphi\cos\theta & \cos\phi\sin\theta \\ \cos\phi\sin\varphi+\sin\phi\cos\varphi\cos\theta & \cos\phi\cos\varphi-\sin\phi\cos\varphi\cos\theta & \sin\varphi\sin\theta \\ -\cos\varphi\sin\theta & \sin\varphi\sin\theta & \cos\theta \end{pmatrix}$$



6.18.1. Denavit-Hartenberg Convention

- ✓ Number the joints from 1 to *n* starting with the base and ending with the end-effector.
- ✓ Establish the base coordinate system. Establish a right-handed orthonormal coordinate system (X_0, Y_0, Z_0) at the supporting base with Z_0 axis lying along the axis of motion of joint 1.
- ✓ Establish joint axis. Align the Z_i with the axis of motion (rotary or sliding) of joint $i+1$.
- ✓ Establish the origin of the i^{th} coordinate system. Locate the origin of the i^{th} coordinate at the intersection of the Z_i & Z_{i-1} or at the intersection of common normal between the Z_i & Z_{i-1} axes and the Z_i axis.
- ✓ Establish X_i axis. Establish $X_i = \pm (Z_{i-1} \times Z_i) / \| Z_{i-1} \times Z_i \|$ or along the common normal between the Z_{i-1} & Z_i axes when they are parallel.
- ✓ Establish Y_i axis. Assign $Y_i = + (Z_i \times X_i) / \| Z_i \times Z_i \|$ to complete the right-handed coordinate system.
- ✓ Find the link and joint parameters

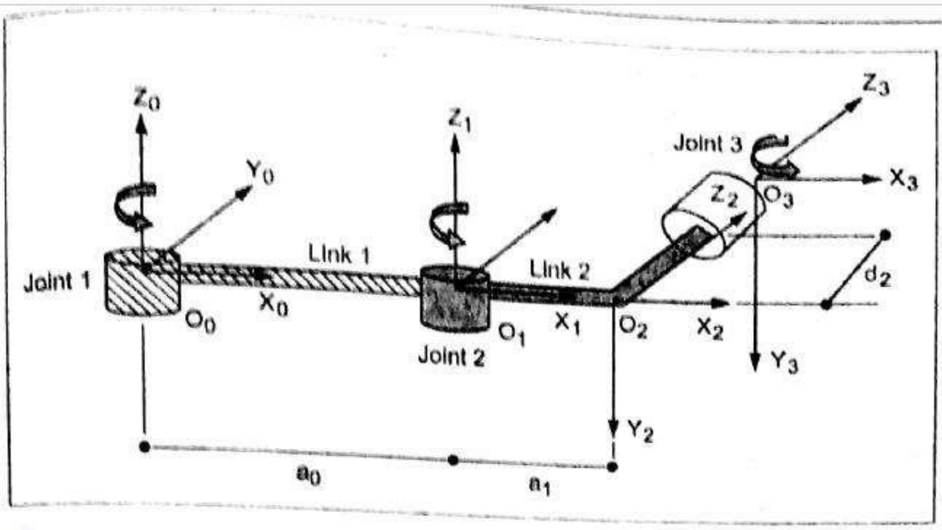


Fig. 6.25. Revolute Joints

LINK COORDINATE FRAMES

(1) Assign Link Coordinate Frames

- ✓ To describe the geometry of robot motion, we assign a Cartesian coordinate frame (O_i, X_i, Y_i, Z_i) to each link, as follows:
- ✓ Establish a right-handed orthonormal coordinate frame O_0 at the supporting base with Z_0 lying along joint 1 motion axis.
- ✓ The Z_i axis is directed along the axis of motion of joint $(i+1)$, that is, $(i+1)$ rotates about or translates along Z_i.

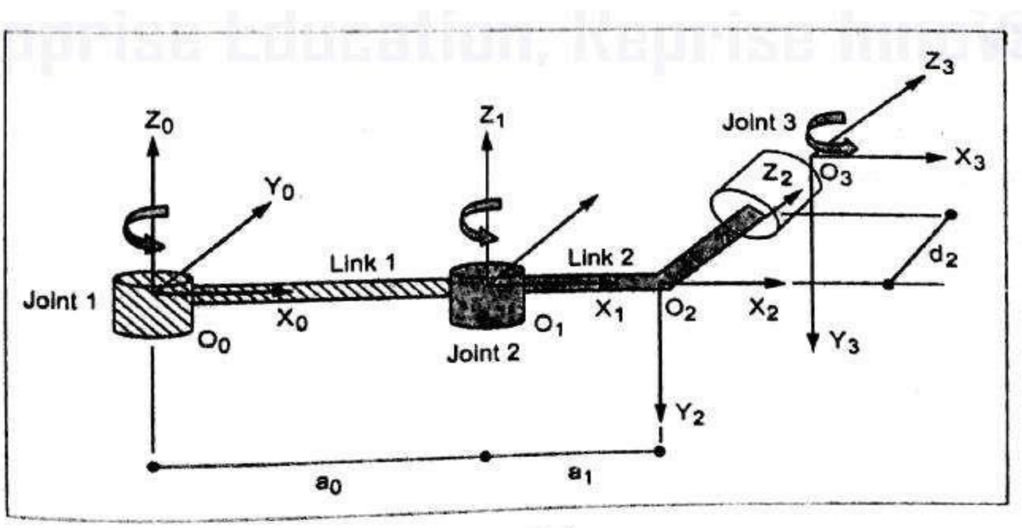


Fig. 6.26.

6.78

2) Link Coordinate Frames

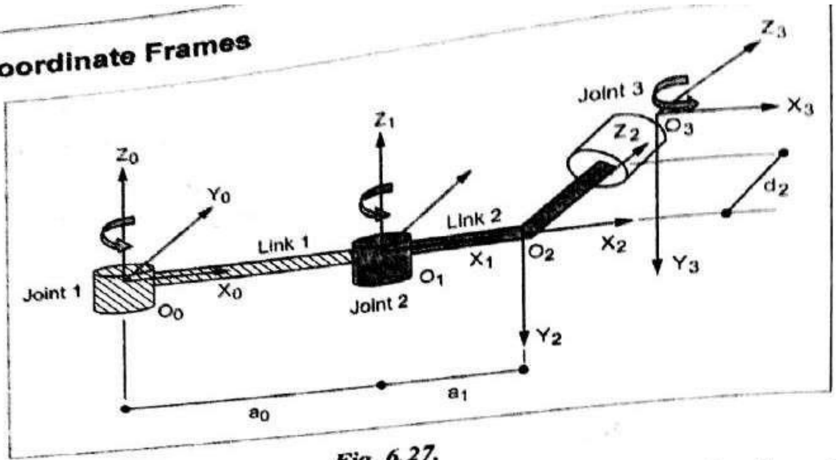


Fig. 6.27.

- Locate the origin of the i^{th} coordinate at the intersection of the Z_i and Z_{i-1} or at the intersection of common normal between the Z_i and Z_{i-1} axes and the Z_i axis.
- The X_i axis lies along the common normal from the Z_{i-1} axis to the Z_i axis $X_i = \pm (Z_{i-1} \times Z_i) / \| Z_{i-1} \times Z_i \|$, (if Z_{i-1} is parallel to Z_i, then X_i is specified arbitrarily, subject only to X_i being perpendicular to Z_i).
- Assign $Y_i = + (Z_i \times X_i) / \| Z_i \times X_i \|$ to complete the right-handed coordinate system.

metry of the end-effector.

system.

The hand coordinate frame is specified by the geometry of the end-effector. Normally, establish Z_n along the direction of Z_{n-1} axis and pointing away from the robot. Establish X_n such that it is normal to both Z_{n-1} and Z_n axes. Assign Y_n to complete the right-handed coordinate system.

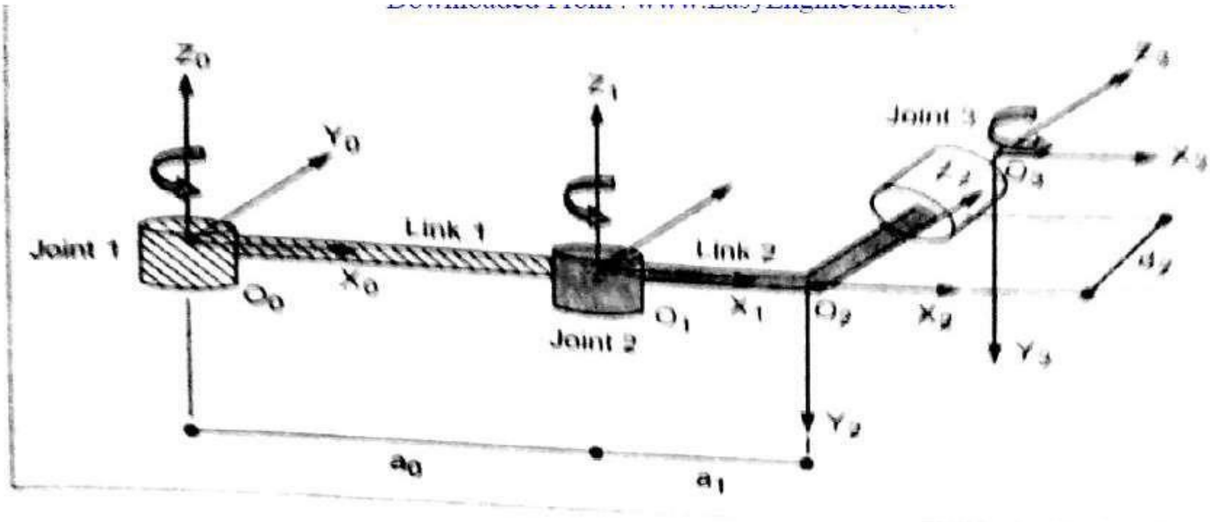


Fig. 6.28.

3) Link and Joint Parameters

- ✓ Joint angle θ; the angle of rotation from the X_{i-1} axis to the X_i axis about the Z_{i-1} axis. It is the joint variable if joint *i* is rotary.

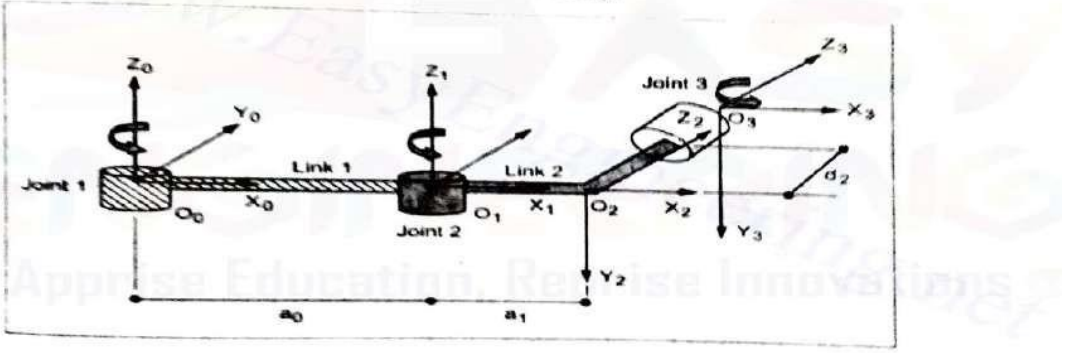
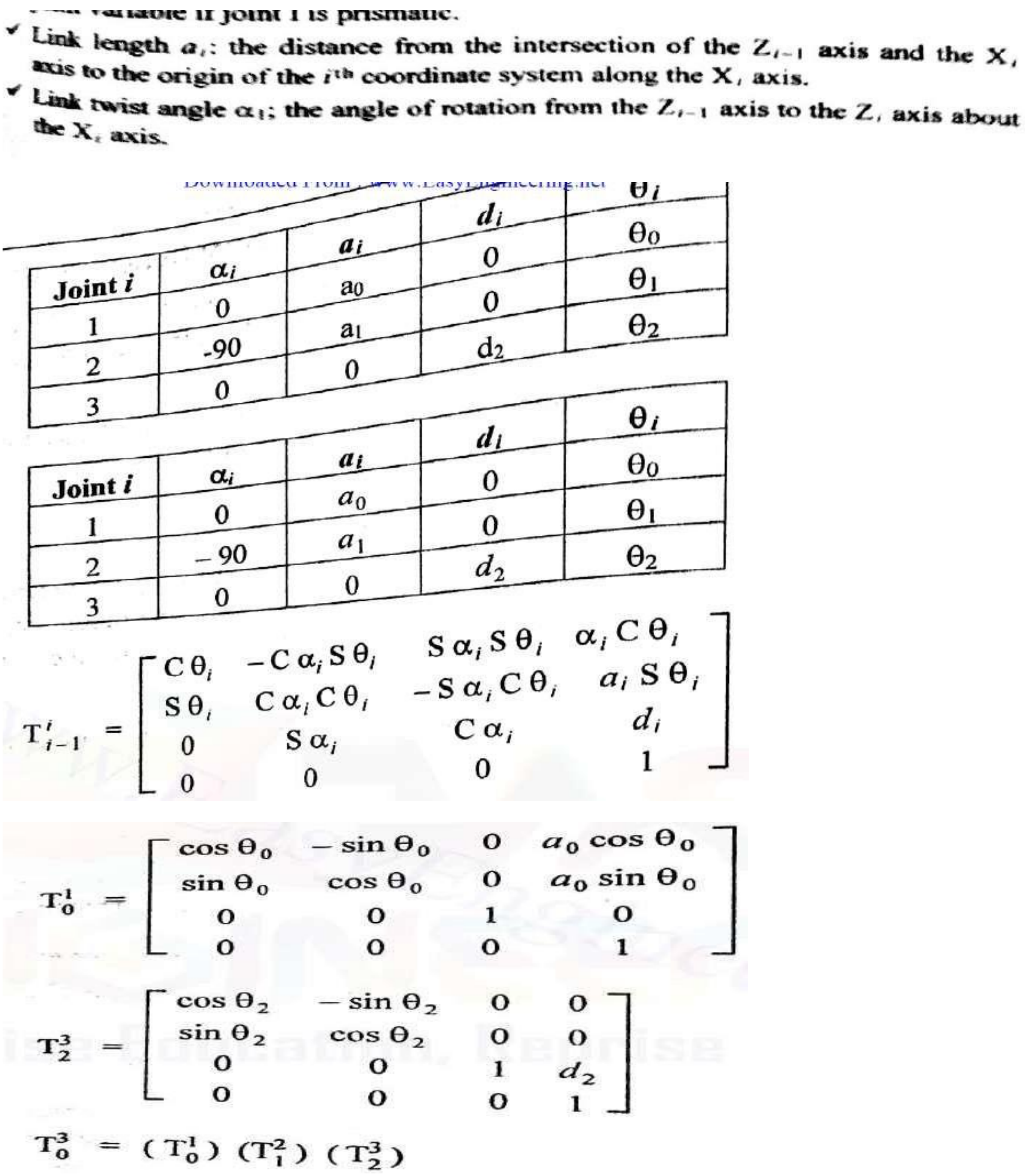


Fig. 6.29.

- ✓ Joint distances d_i: The distance from the origin of the (i-1) coordinate system to the intersection of the Z_{i-1} axis and the X_i axis along the Z_{i-1} axis. It is the joint variable if joint I is prismatic.



variable if joint i is prismatic.

- ✓ Link length a_i: the distance from the intersection of the Z_{i-1} axis and the X_i axis to the origin of the i^{th} coordinate system along the X_i axis.
- ✓ Link twist angle α_i: the angle of rotation from the Z_{i-1} axis to the Z_i axis about the X_i axis.

Joint i	α_i	a_i	d_i	θ_i
1	0	a_0	0	θ_0
2	-90	a_1	0	θ_1
3	0	0	d_2	θ_2

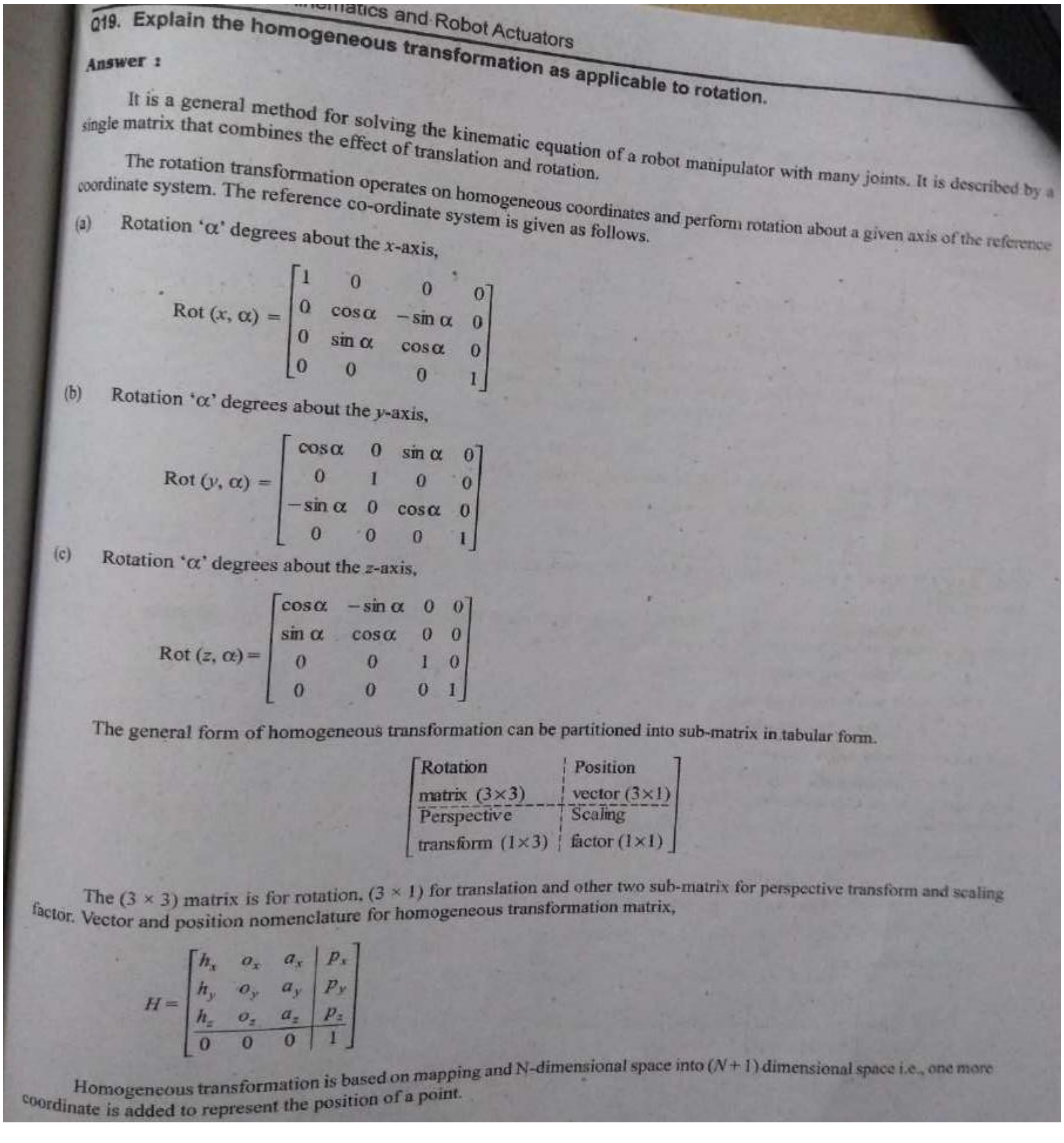
Joint i	α_i	a_i	d_i	θ_i
1	0	a_0	0	θ_0
2	– 90	a_1	0	θ_1
3	0	0	d_2	θ_2

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

$$T_0^1 = \begin{bmatrix} \cos\theta_0 & -\sin\theta_0 & 0 & a_0\cos\theta_0 \\ \sin\theta_0 & \cos\theta_0 & 0 & a_0\sin\theta_0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_2^3 = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & 0 \\ \sin\theta_2 & \cos\theta_2 & 0 & 0 \\ 0 & 0 & 1 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_0^3 = (T_0^1)\,(T_1^2)\,(T_2^3)$$



Q19. Explain the homogeneous transformation as applicable to rotation.

Answer :

It is a general method for solving the kinematic equation of a robot manipulator with many joints. It is described by a single matrix that combines the effect of translation and rotation.

The rotation transformation operates on homogeneous coordinates and perform rotation about a given axis of the reference coordinate system. The reference co-ordinate system is given as follows.

(a) Rotation 'α' degrees about the x-axis,

$$\text{Rot}(x, \alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha & 0 \\ 0 & \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(b) Rotation 'α' degrees about the y-axis,

$$\text{Rot}(y, \alpha) = \begin{bmatrix} \cos\alpha & 0 & \sin\alpha & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\alpha & 0 & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(c) Rotation 'α' degrees about the z-axis,

$$\text{Rot}(z, \alpha) = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 & 0 \\ \sin\alpha & \cos\alpha & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

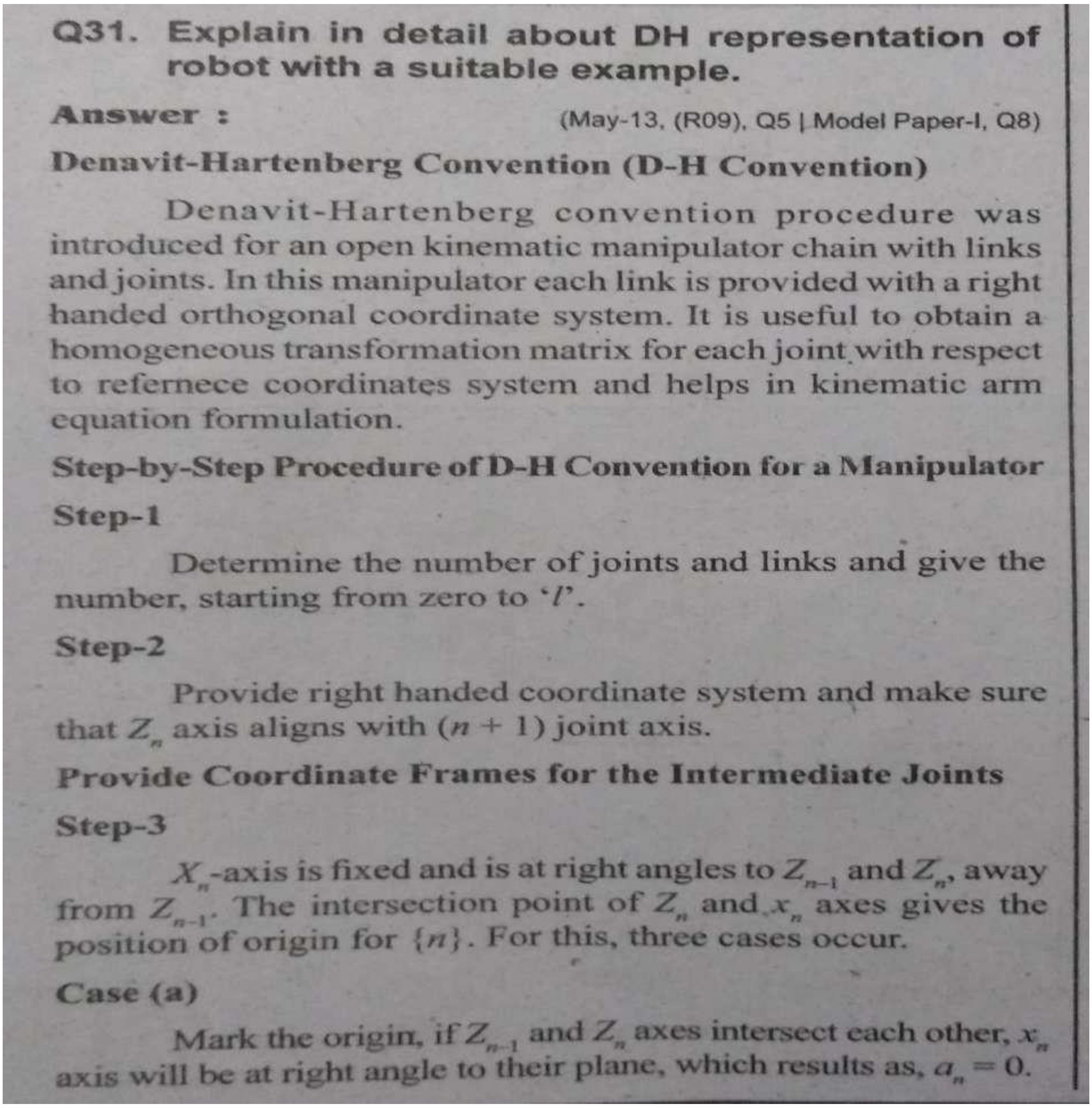
The general form of homogeneous transformation can be partitioned into sub-matrix in tabular form.

$$\left[\begin{array}{l|l} \text{Rotation} & \text{Position} \\ \text{matrix } (3\times3) & \text{vector } (3\times1) \\ \hline \text{Perspective} & \text{Scaling} \\ \text{transform } (1\times3) & \text{factor } (1\times1) \end{array}\right]$$

The (3 × 3) matrix is for rotation, (3 × 1) for translation and other two sub-matrix for perspective transform and scaling factor. Vector and position nomenclature for homogeneous transformation matrix,

$$H = \left[\begin{array}{ccc|c} h_x & o_x & a_x & p_x \\ h_y & o_y & a_y & p_y \\ h_z & o_z & a_z & p_z \\ \hline 0 & 0 & 0 & 1 \end{array}\right]$$

Homogeneous transformation is based on mapping and N-dimensional space into $(N+1)$ dimensional space i.e., one more coordinate is added to represent the position of a point.



Q31. Explain in detail about DH representation of robot with a suitable example.

Answer : (May-13, (R09), Q5 | Model Paper-I, Q8)

Denavit-Hartenberg Convention (D-H Convention)

Denavit-Hartenberg convention procedure was introduced for an open kinematic manipulator chain with links and joints. In this manipulator each link is provided with a right handed orthogonal coordinate system. It is useful to obtain a homogeneous transformation matrix for each joint with respect to refernece coordinates system and helps in kinematic arm equation formulation.

Step-by-Step Procedure of D-H Convention for a Manipulator

Step-1

Determine the number of joints and links and give the number, starting from zero to '*l*'.

Step-2

Provide right handed coordinate system and make sure that Z_n axis aligns with $(n + 1)$ joint axis.

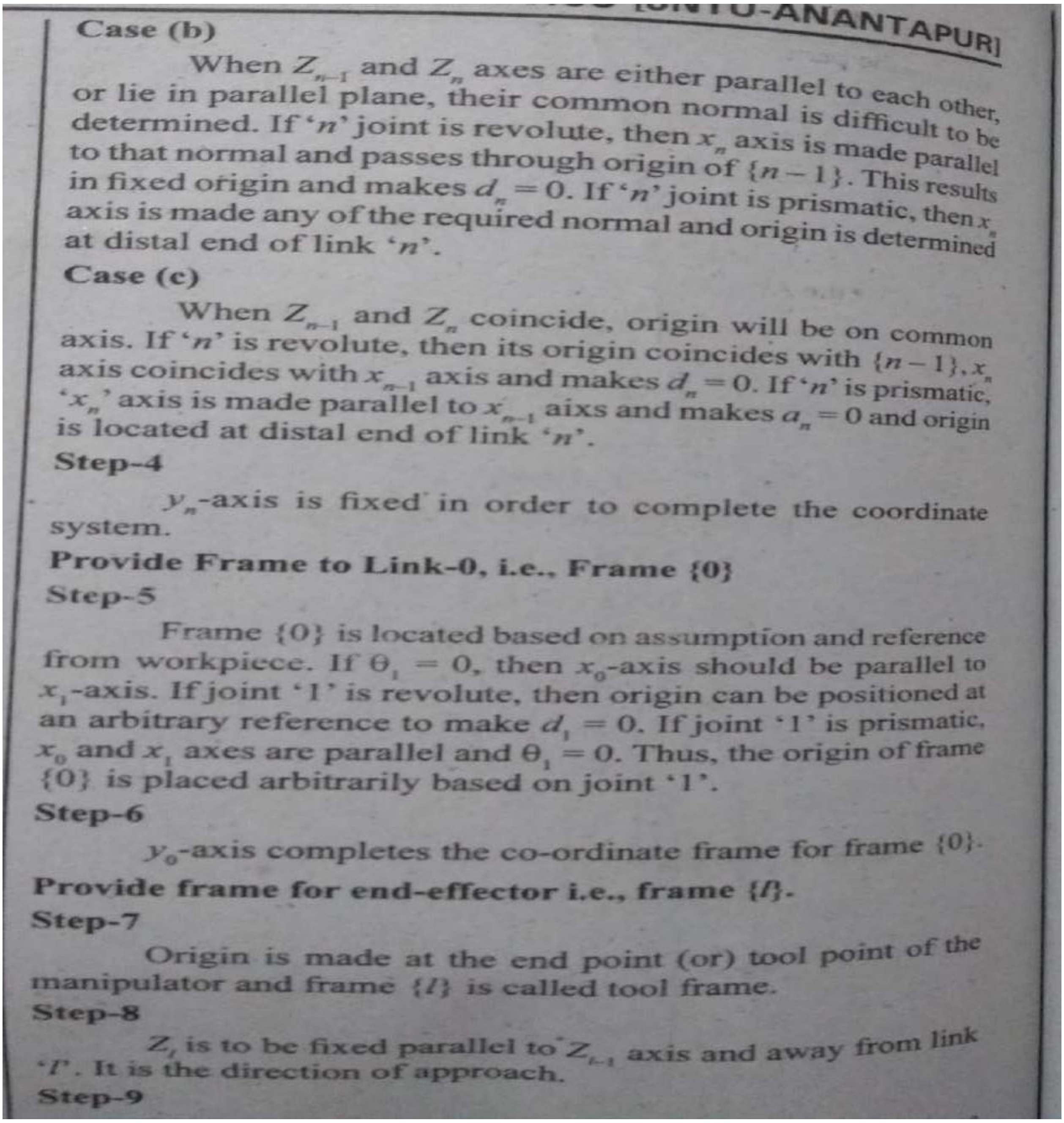
Provide Coordinate Frames for the Intermediate Joints

Step-3

X_n-axis is fixed and is at right angles to Z_{n-1} and Z_n, away from Z_{n-1}. The intersection point of Z_n and x_n axes gives the position of origin for $\{n\}$. For this, three cases occur.

Case (a)

Mark the origin, if Z_{n-1} and Z_n axes intersect each other, x_n axis will be at right angle to their plane, which results as, $a_n = 0$.



Case (b)

When Z_{n-1} and Z_n axes are either parallel to each other, or lie in parallel plane, their common normal is difficult to be determined. If 'n' joint is revolute, then x_n axis is made parallel to that normal and passes through origin of $\{n-1\}$. This results in fixed origin and makes $d_n = 0$. If 'n' joint is prismatic, then x_n axis is made any of the required normal and origin is determined at distal end of link 'n'.

Case (c)

When Z_{n-1} and Z_n coincide, origin will be on common axis. If 'n' is revolute, then its origin coincides with $\{n-1\}$, x_n axis coincides with x_{n-1} axis and makes $d_n = 0$. If 'n' is prismatic, 'x_n' axis is made parallel to x_{n-1} aixs and makes $a_n = 0$ and origin is located at distal end of link 'n'.

Step-4

y_n-axis is fixed in order to complete the coordinate system.

Provide Frame to Link-0, i.e., Frame {0}

Step-5

Frame $\{0\}$ is located based on assumption and reference from workpiece. If $\theta_1 = 0$, then x_0-axis should be parallel to x_1-axis. If joint '1' is revolute, then origin can be positioned at an arbitrary reference to make $d_1 = 0$. If joint '1' is prismatic, x_0 and x_1 axes are parallel and $\theta_1 = 0$. Thus, the origin of frame $\{0\}$ is placed arbitrarily based on joint '1'.

Step-6

y_0-axis completes the co-ordinate frame for frame $\{0\}$.

Provide frame for end-effector i.e., frame {*l*}.

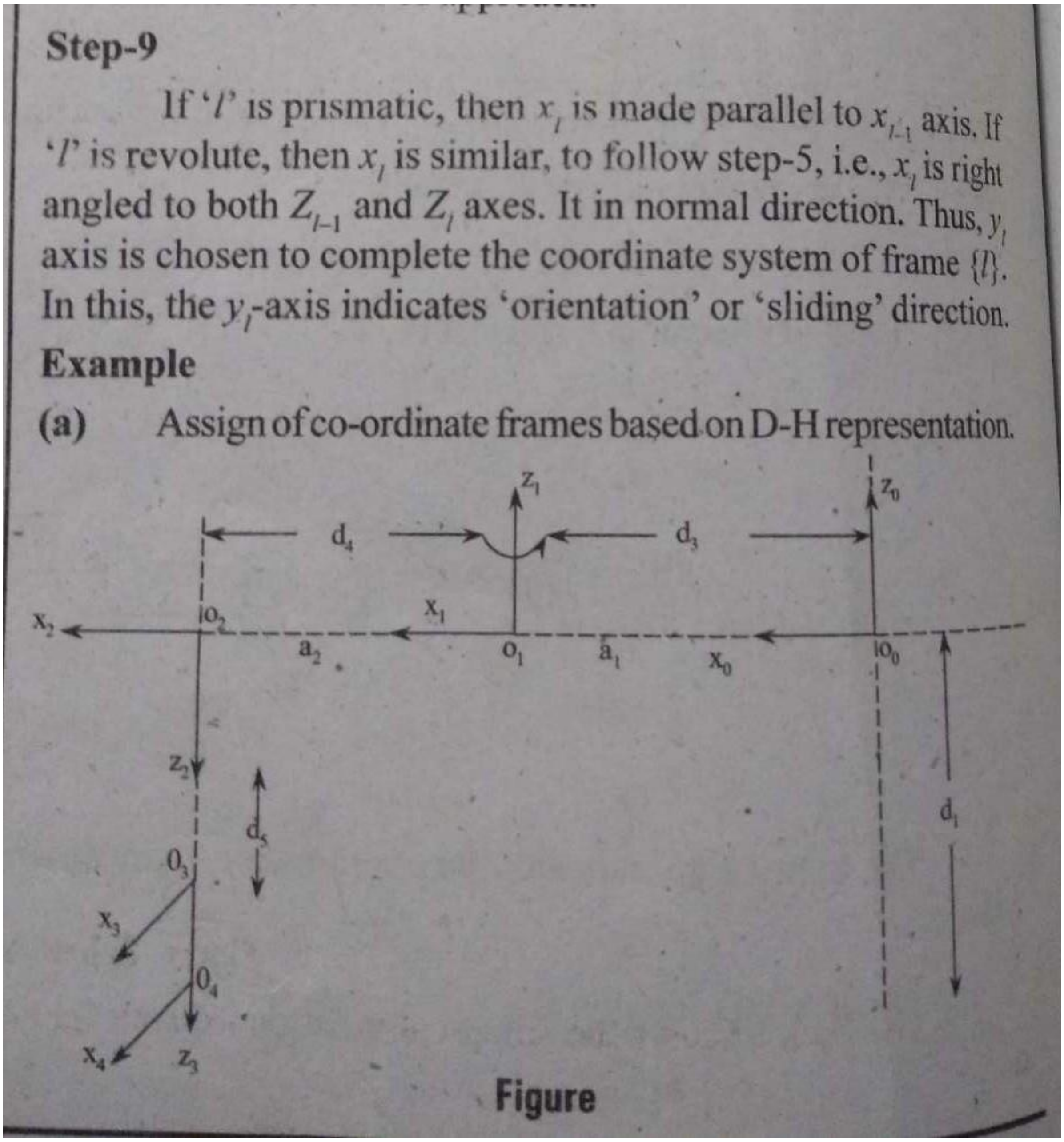
Step-7

Origin is made at the end point (or) tool point of the manipulator and frame $\{l\}$ is called tool frame.

Step-8

Z_l is to be fixed parallel to Z_{l-1} axis and away from link 'l'. It is the direction of approach.

Step-9



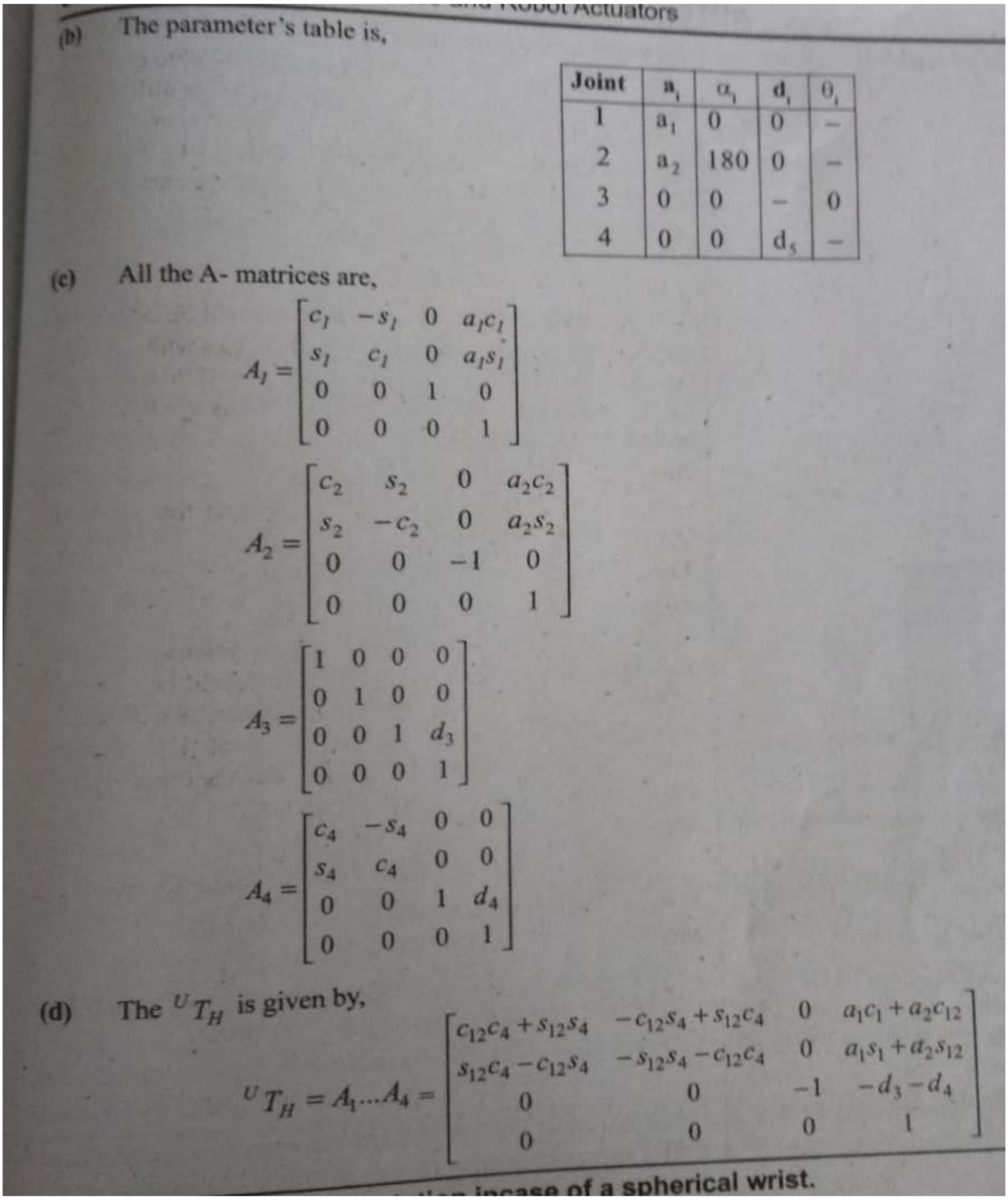
Step-9

If 'l' is prismatic, then x_l is made parallel to x_{l-1} axis. If 'l' is revolute, then x_l is similar, to follow step-5, i.e., x_l is right angled to both Z_{l-1} and Z_l axes. It in normal direction. Thus, y_l axis is chosen to complete the coordinate system of frame $\{l\}$. In this, the y_l-axis indicates 'orientation' or 'sliding' direction.

Example

(a) Assign of co-ordinate frames based on D-H representation.

Figure



(b) The parameter's table is,

Joint	a_i	α_i	d_i	θ_i
1	a_1	0	0	–
2	a_2	180	0	–
3	0	0	–	0
4	0	0	d_5	–

(c) All the A- matrices are,

$$A_1 = \begin{bmatrix} c_1 & -s_1 & 0 & a_1c_1 \\ s_1 & c_1 & 0 & a_1s_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_2 = \begin{bmatrix} c_2 & s_2 & 0 & a_2c_2 \\ s_2 & -c_2 & 0 & a_2s_2 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

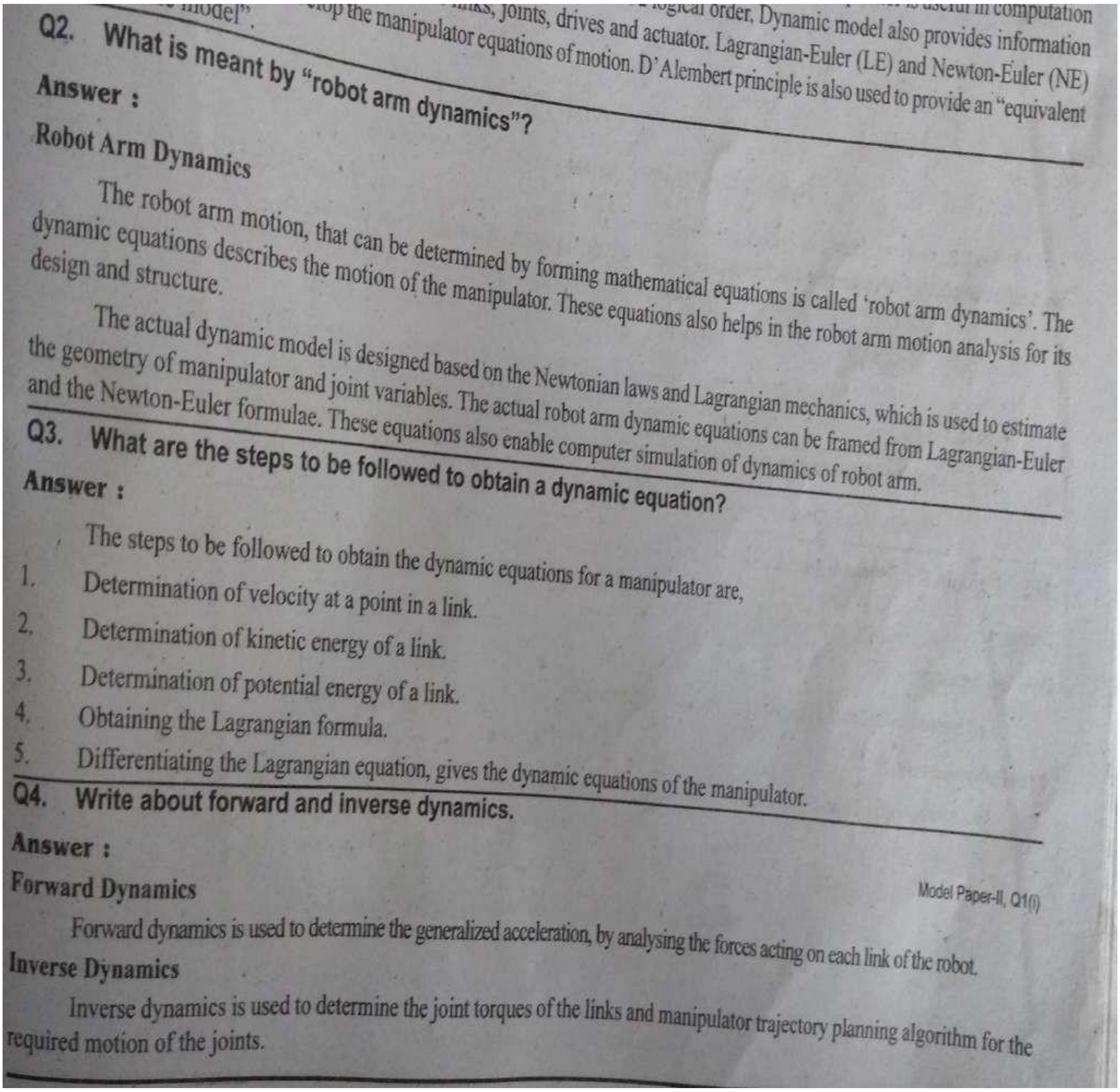
$$A_3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_4 = \begin{bmatrix} c_4 & -s_4 & 0 & 0 \\ s_4 & c_4 & 0 & 0 \\ 0 & 0 & 1 & d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(d) The ${}^{U}T_H$ is given by,

$${}^{U}T_H = A_1 \ldots A_4 = \begin{bmatrix} c_{12}c_4 + s_{12}s_4 & -c_{12}s_4 + s_{12}c_4 & 0 & a_1c_1 + a_2c_{12} \\ s_{12}c_4 - c_{12}s_4 & -s_{12}s_4 - c_{12}c_4 & 0 & a_1s_1 + a_2s_{12} \\ 0 & 0 & -1 & -d_3 - d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

incase of a spherical wrist.



useful in computation
logical order. Dynamic model also provides information
ks, joints, drives and actuator. Lagrangian-Euler (LE) and Newton-Euler (NE)
op the manipulator equations of motion. D'Alembert principle is also used to provide an "equivalent
model".

Q2. What is meant by "robot arm dynamics"?

Answer :

Robot Arm Dynamics

The robot arm motion, that can be determined by forming mathematical equations is called 'robot arm dynamics'. The dynamic equations describes the motion of the manipulator. These equations also helps in the robot arm motion analysis for its design and structure.

The actual dynamic model is designed based on the Newtonian laws and Lagrangian mechanics, which is used to estimate the geometry of manipulator and joint variables. The actual robot arm dynamic equations can be framed from Lagrangian-Euler and the Newton-Euler formulae. These equations also enable computer simulation of dynamics of robot arm.

Q3. What are the steps to be followed to obtain a dynamic equation?

Answer :

The steps to be followed to obtain the dynamic equations for a manipulator are,

1. Determination of velocity at a point in a link.
2. Determination of kinetic energy of a link.
3. Determination of potential energy of a link.
4. Obtaining the Lagrangian formula.
5. Differentiating the Lagrangian equation, gives the dynamic equations of the manipulator.

Q4. Write about forward and inverse dynamics.

Answer :

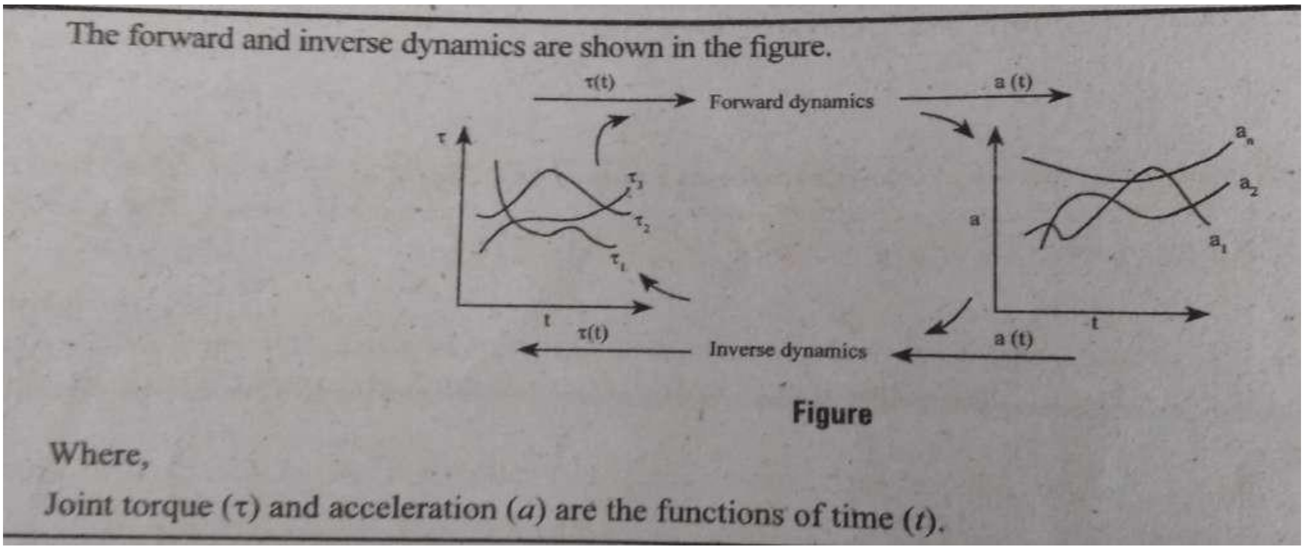
Model Paper-II, Q1(i)

Forward Dynamics

Forward dynamics is used to determine the generalized acceleration, by analysing the forces acting on each link of the robot.

Inverse Dynamics

Inverse dynamics is used to determine the joint torques of the links and manipulator trajectory planning algorithm for the required motion of the joints.

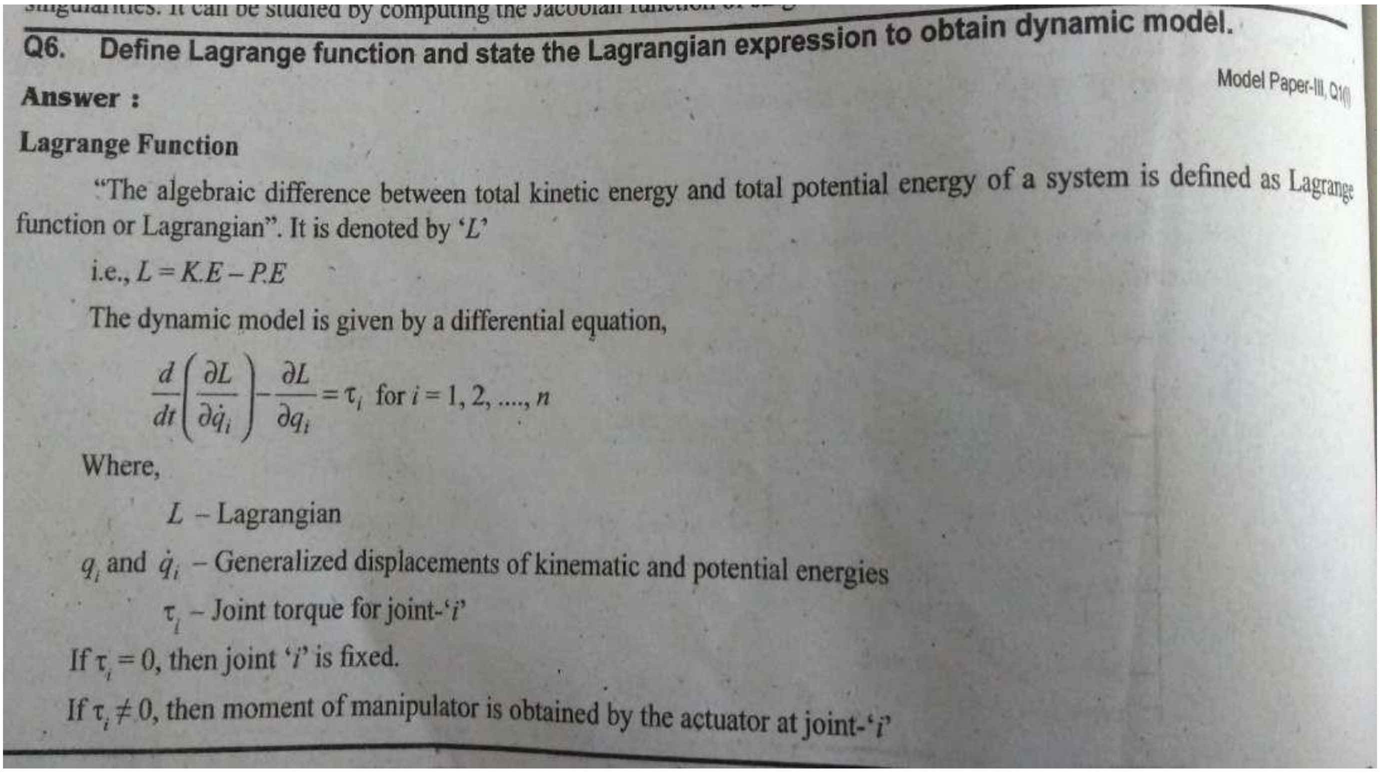


The forward and inverse dynamics are shown in the figure.

Figure

Where,

Joint torque (τ) and acceleration (*a*) are the functions of time (*t*).



singularities. It can be studied by computing the Jacobian function of

Q6. Define Lagrange function and state the Lagrangian expression to obtain dynamic model.

Model Paper-III, Q1(

Answer :

Lagrange Function

"The algebraic difference between total kinetic energy and total potential energy of a system is defined as Lagrange function or Lagrangian". It is denoted by '*L*'

i.e., $L = K.E - P.E$

The dynamic model is given by a differential equation,

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = \tau_i \text{ for } i = 1, 2, ..., n$$

Where,

L – Lagrangian

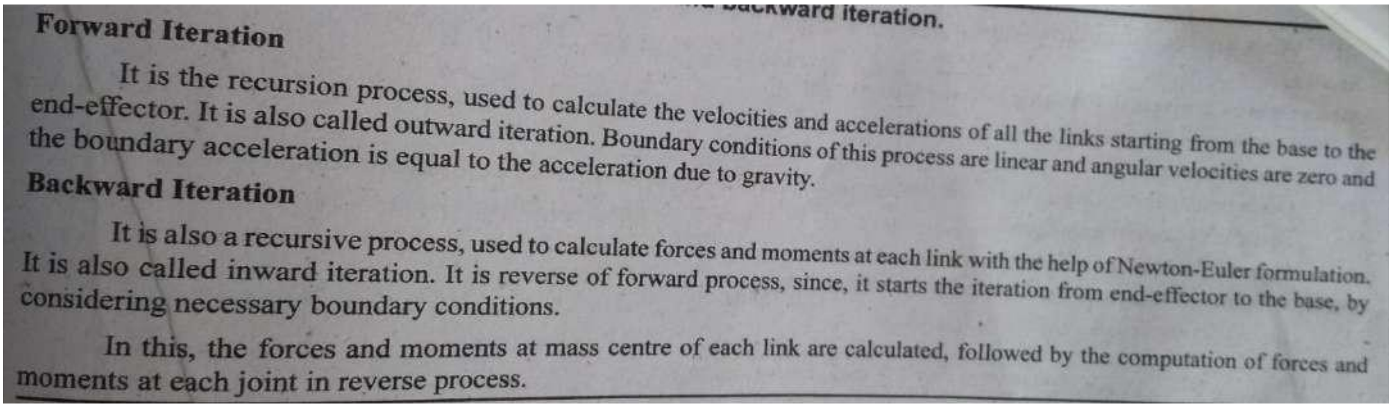
q_i and $\dot{q}_i$ – Generalized displacements of kinematic and potential energies

τ_i – Joint torque for joint-'*i*'

If $\tau_i = 0$, then joint '*i*' is fixed.

If $\tau_i \neq 0$, then moment of manipulator is obtained by the actuator at joint-'*i*'

Q) Write a short note on forward and backward iteration?



backward iteration.

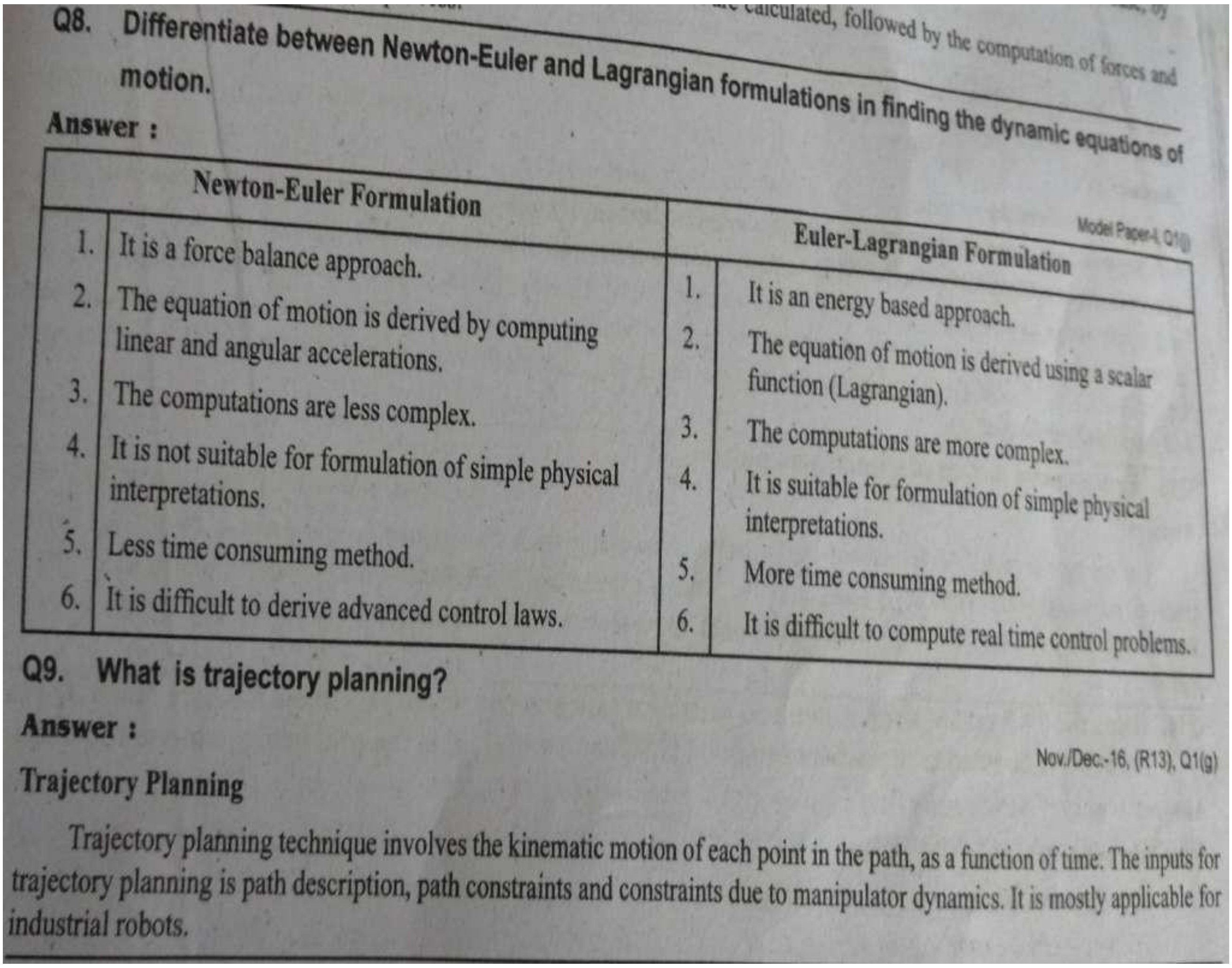
Forward Iteration

It is the recursion process, used to calculate the velocities and accelerations of all the links starting from the base to the end-effector. It is also called outward iteration. Boundary conditions of this process are linear and angular velocities are zero and the boundary acceleration is equal to the acceleration due to gravity.

Backward Iteration

It is also a recursive process, used to calculate forces and moments at each link with the help of Newton-Euler formulation. It is also called inward iteration. It is reverse of forward process, since, it starts the iteration from end-effector to the base, by considering necessary boundary conditions.

In this, the forces and moments at mass centre of each link are calculated, followed by the computation of forces and moments at each joint in reverse process.



calculated, followed by the computation of forces and

Q8. Differentiate between Newton-Euler and Lagrangian formulations in finding the dynamic equations of motion.

Answer :

Model Paper-I, Q1(j)

	Newton-Euler Formulation		Euler-Lagrangian Formulation
1.	It is a force balance approach.	1.	It is an energy based approach.
2.	The equation of motion is derived by computing linear and angular accelerations.	2.	The equation of motion is derived using a scalar function (Lagrangian).
3.	The computations are less complex.	3.	The computations are more complex.
4.	It is not suitable for formulation of simple physical interpretations.	4.	It is suitable for formulation of simple physical interpretations.
5.	Less time consuming method.	5.	More time consuming method.
6.	It is difficult to derive advanced control laws.	6.	It is difficult to compute real time control problems.

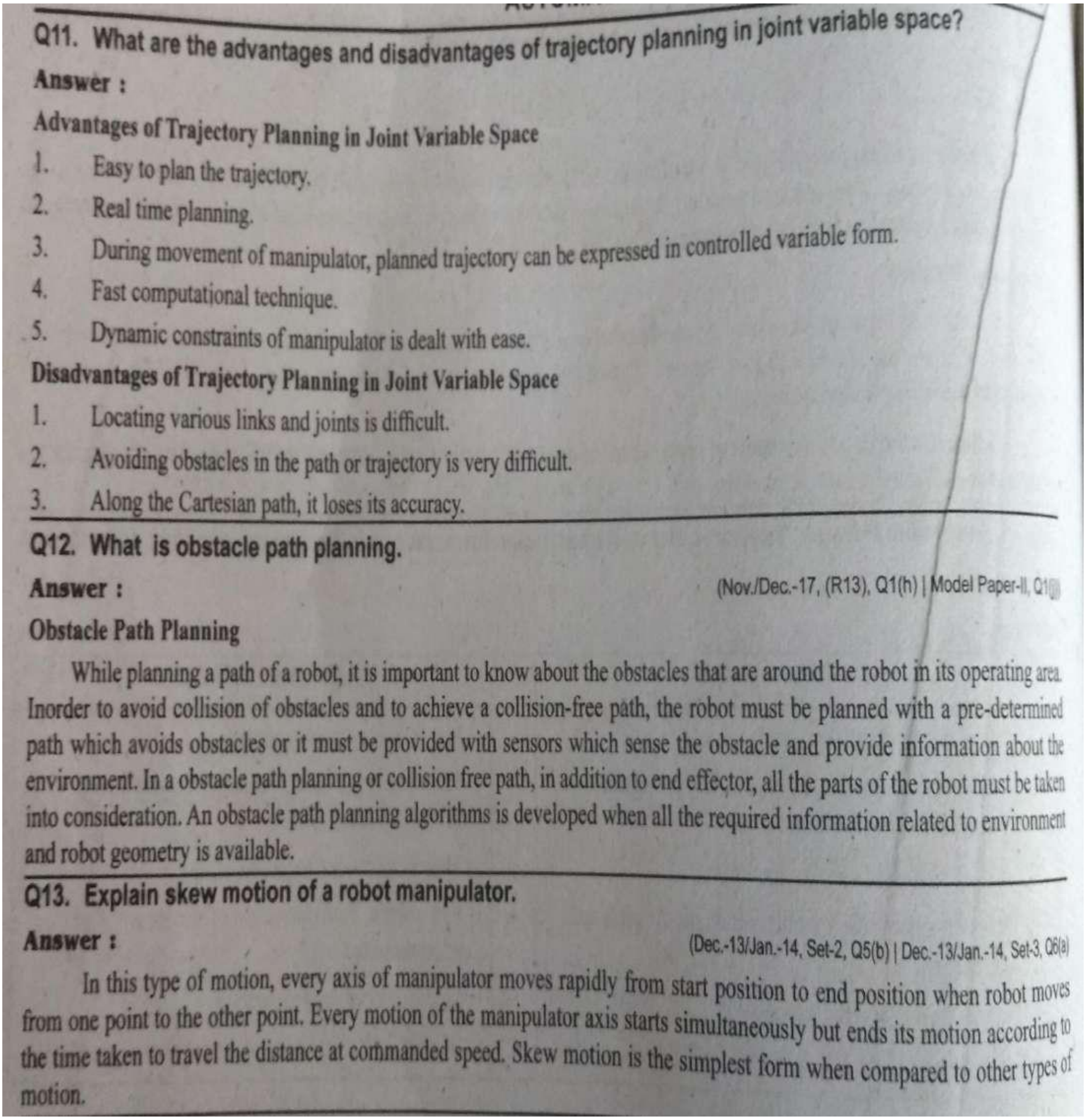
Q9. What is trajectory planning?

Answer :

Nov./Dec.-16, (R13), Q1(g)

Trajectory Planning

Trajectory planning technique involves the kinematic motion of each point in the path, as a function of time. The inputs for trajectory planning is path description, path constraints and constraints due to manipulator dynamics. It is mostly applicable for industrial robots.



Q11. What are the advantages and disadvantages of trajectory planning in joint variable space?

Answer :

Advantages of Trajectory Planning in Joint Variable Space

1. Easy to plan the trajectory.
2. Real time planning.
3. During movement of manipulator, planned trajectory can be expressed in controlled variable form.
4. Fast computational technique.
5. Dynamic constraints of manipulator is dealt with ease.

Disadvantages of Trajectory Planning in Joint Variable Space

1. Locating various links and joints is difficult.
2. Avoiding obstacles in the path or trajectory is very difficult.
3. Along the Cartesian path, it loses its accuracy.

Q12. What is obstacle path planning.

Answer : (Nov./Dec.-17, (R13), Q1(h) | Model Paper-II, Q1

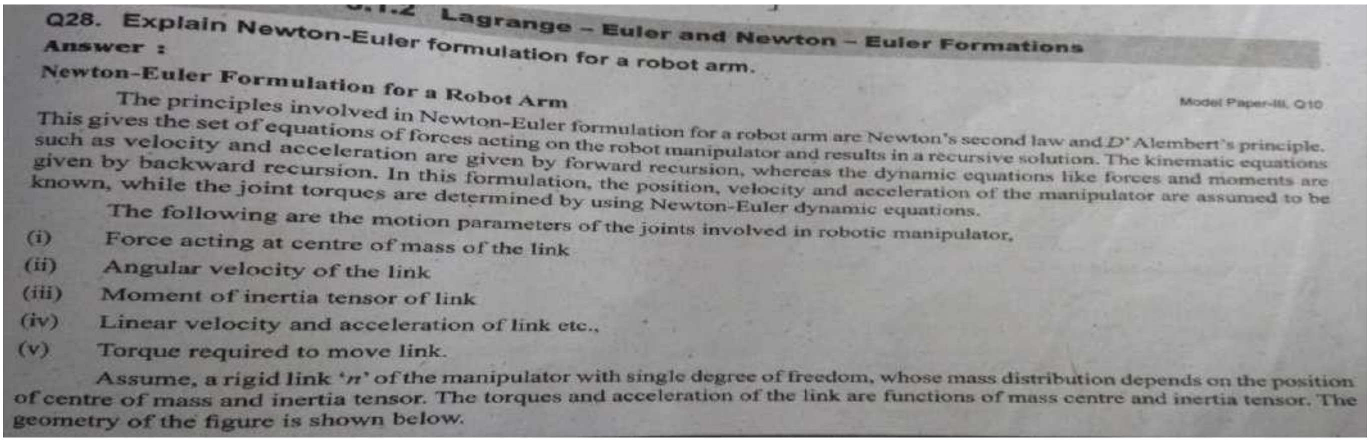
Obstacle Path Planning

While planning a path of a robot, it is important to know about the obstacles that are around the robot in its operating area. Inorder to avoid collision of obstacles and to achieve a collision-free path, the robot must be planned with a pre-determined path which avoids obstacles or it must be provided with sensors which sense the obstacle and provide information about the environment. In a obstacle path planning or collision free path, in addition to end effector, all the parts of the robot must be taken into consideration. An obstacle path planning algorithms is developed when all the required information related to environment and robot geometry is available.

Q13. Explain skew motion of a robot manipulator.

Answer : (Dec.-13/Jan.-14, Set-2, Q5(b) | Dec.-13/Jan.-14, Set-3, Q6(a)

In this type of motion, every axis of manipulator moves rapidly from start position to end position when robot moves from one point to the other point. Every motion of the manipulator axis starts simultaneously but ends its motion according to the time taken to travel the distance at commanded speed. Skew motion is the simplest form when compared to other types of motion.



Lagrange – Euler and Newton – Euler Formations

Q28. Explain Newton-Euler formulation for a robot arm.

Answer :

Model Paper-III, Q10

Newton-Euler Formulation for a Robot Arm

The principles involved in Newton-Euler formulation for a robot arm are Newton's second law and *D'* Alembert's principle. This gives the set of equations of forces acting on the robot manipulator and results in a recursive solution. The kinematic equations such as velocity and acceleration are given by forward recursion, whereas the dynamic equations like forces and moments are given by backward recursion. In this formulation, the position, velocity and acceleration of the manipulator are assumed to be known, while the joint torques are determined by using Newton-Euler dynamic equations.

The following are the motion parameters of the joints involved in robotic manipulator,

(i) Force acting at centre of mass of the link
(ii) Angular velocity of the link
(iii) Moment of inertia tensor of link
(iv) Linear velocity and acceleration of link etc.,
(v) Torque required to move link.

Assume, a rigid link 'n' of the manipulator with single degree of freedom, whose mass distribution depends on the position of centre of mass and inertia tensor. The torques and acceleration of the link are functions of mass centre and inertia tensor. The geometry of the figure is shown below.

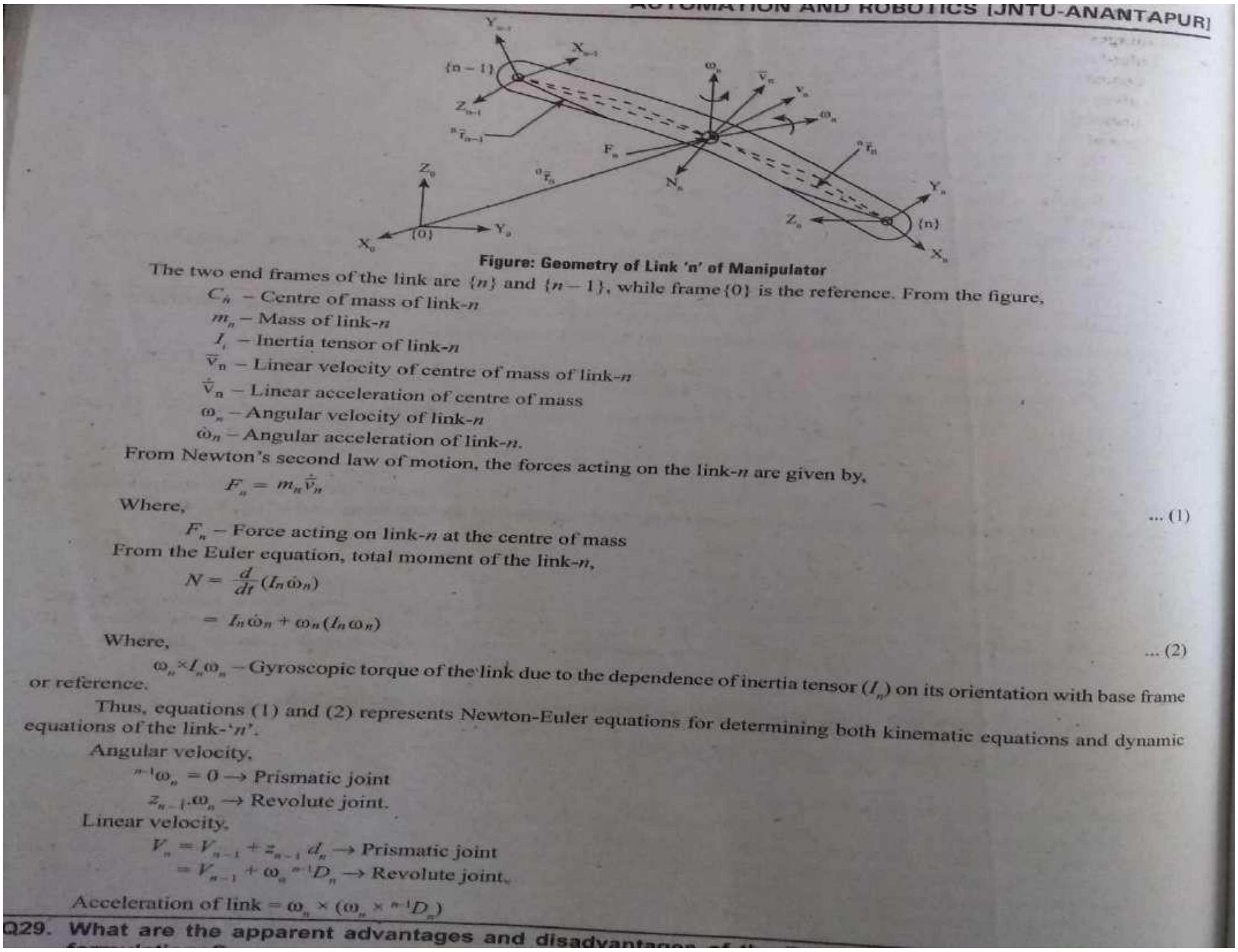


Figure: Geometry of Link 'n' of Manipulator

The two end frames of the link are $\{n\}$ and $\{n-1\}$, while frame $\{0\}$ is the reference. From the figure,

C_n – Centre of mass of link-n
m_n – Mass of link-n
I_i – Inertia tensor of link-n
$\bar{v}_n$ – Linear velocity of centre of mass of link-n
$\dot{\bar{v}}_n$ – Linear acceleration of centre of mass
ω_n – Angular velocity of link-n
$\dot{\omega}_n$ – Angular acceleration of link-n.

From Newton's second law of motion, the forces acting on the link-n are given by,

$$F_n = m_n \dot{\bar{v}}_n \qquad \ldots (1)$$

Where,

F_n – Force acting on link-n at the centre of mass

From the Euler equation, total moment of the link-n,

$$N = \frac{d}{dt}(I_n \dot{\omega}_n)$$

$$= I_n \dot{\omega}_n + \omega_n (I_n \omega_n) \qquad \ldots (2)$$

Where,

$\omega_n \times I_n \omega_n$ – Gyroscopic torque of the link due to the dependence of inertia tensor (I_n) on its orientation with base frame or reference.

Thus, equations (1) and (2) represents Newton-Euler equations for determining both kinematic equations and dynamic equations of the link-'n'.

Angular velocity,

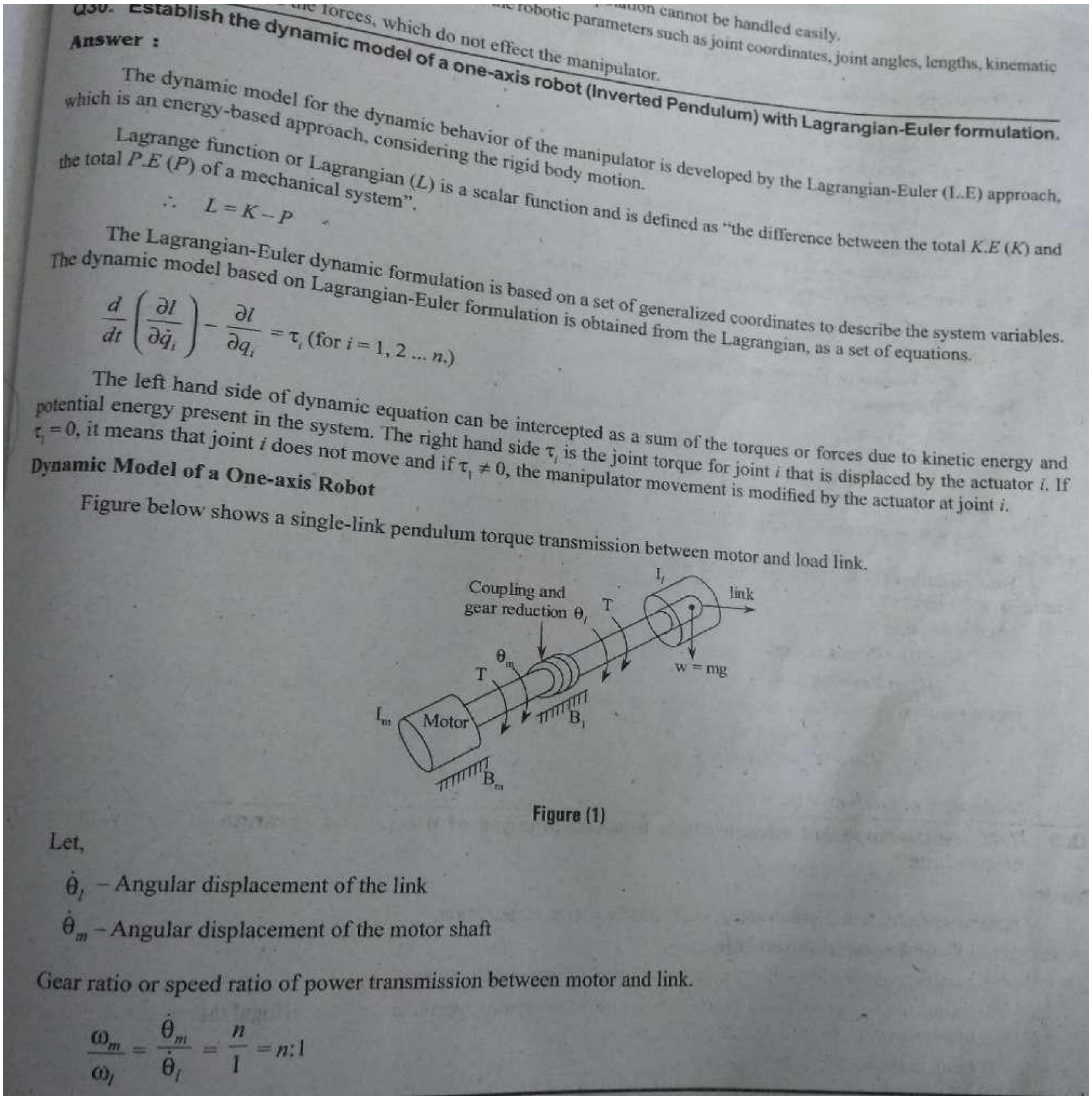
$^{n-1}\omega_n = 0 \rightarrow$ Prismatic joint
$z_{n-1} . \omega_n \rightarrow$ Revolute joint.

Linear velocity,

$V_n = V_{n-1} + z_{n-1}\, d_n \rightarrow$ Prismatic joint
$= V_{n-1} + \omega_n\, {}^{n-1}D_n \rightarrow$ Revolute joint.

Acceleration of link $= \omega_n \times (\omega_n \times {}^{n-1}D_n)$

Q29. What are the apparent advantages and disadvan



ation cannot be handled easily.

robotic parameters such as joint coordinates, joint angles, lengths, kinematic

forces, which do not effect the manipulator.

Q30. Establish the dynamic model of a one-axis robot (Inverted Pendulum) with Lagrangian-Euler formulation.

Answer :

The dynamic model for the dynamic behavior of the manipulator is developed by the Lagrangian-Euler (L.E) approach, which is an energy-based approach, considering the rigid body motion.

Lagrange function or Lagrangian (L) is a scalar function and is defined as "the difference between the total $K.E$ (K) and the total $P.E$ (P) of a mechanical system".

$$\therefore \quad L = K - P$$

The Lagrangian-Euler dynamic formulation is based on a set of generalized coordinates to describe the system variables. The dynamic model based on Lagrangian-Euler formulation is obtained from the Lagrangian, as a set of equations.

$$\frac{d}{dt}\left(\frac{\partial l}{\partial \dot{q}_i}\right) - \frac{\partial l}{\partial q_i} = \tau_i \text{ (for } i = 1, 2 \ldots n.)$$

The left hand side of dynamic equation can be intercepted as a sum of the torques or forces due to kinetic energy and potential energy present in the system. The right hand side τ_i is the joint torque for joint i that is displaced by the actuator i. If $\tau_1 = 0$, it means that joint i does not move and if $\tau_1 \neq 0$, the manipulator movement is modified by the actuator at joint i.

Dynamic Model of a One-axis Robot

Figure below shows a single-link pendulum torque transmission between motor and load link.

Figure (1)

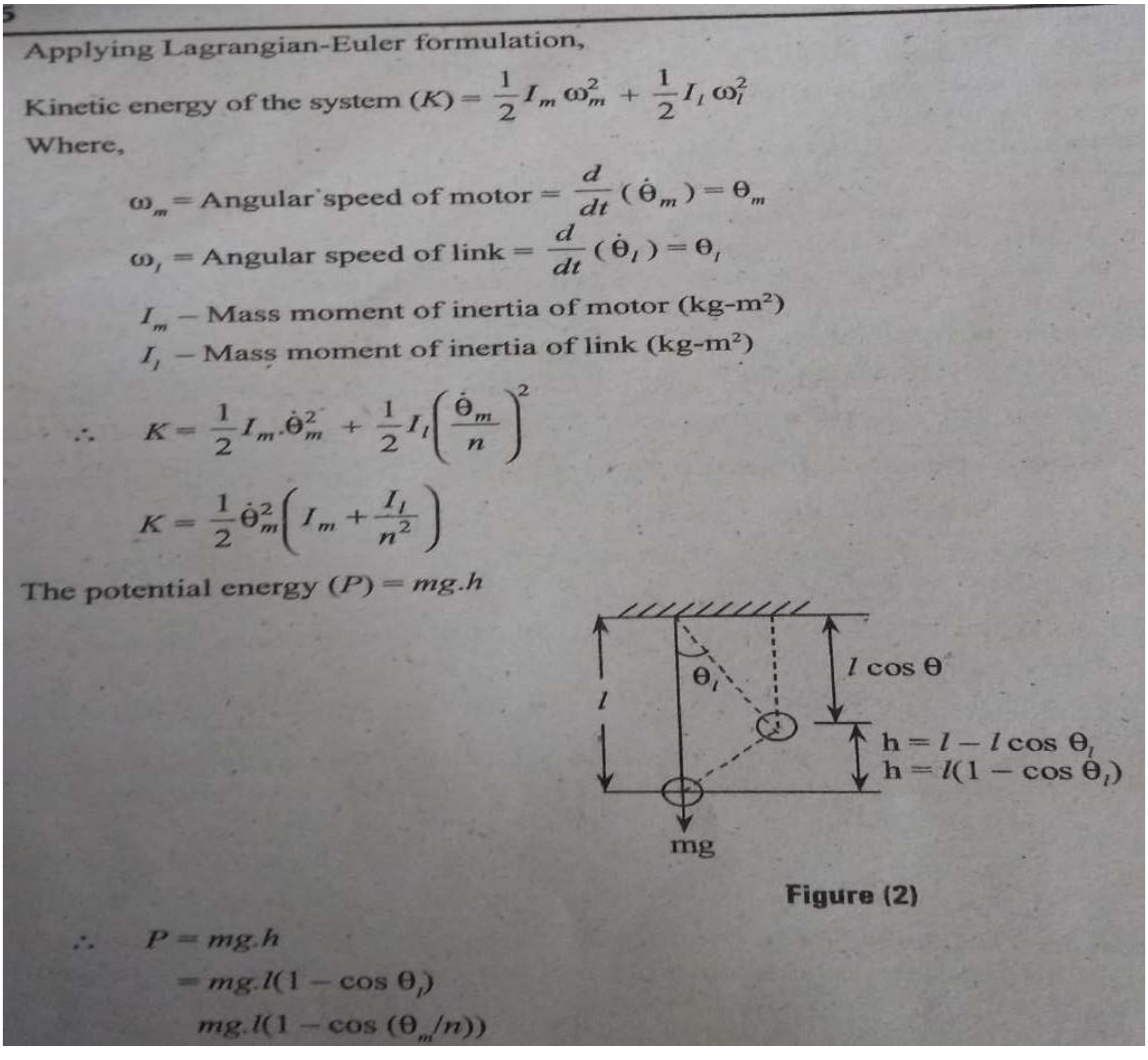
Let,

$\dot{\theta}_l$ – Angular displacement of the link

$\dot{\theta}_m$ – Angular displacement of the motor shaft

Gear ratio or speed ratio of power transmission between motor and link.

$$\frac{\omega_m}{\omega_l} = \frac{\dot{\theta}_m}{\dot{\theta}_l} = \frac{n}{1} = n:1$$



Applying Lagrangian-Euler formulation,

Kinetic energy of the system $(K) = \frac{1}{2} I_m \omega_m^2 + \frac{1}{2} I_l \omega_l^2$

Where,

ω_m = Angular speed of motor = $\frac{d}{dt}(\dot{\theta}_m) = \theta_m$

ω_l = Angular speed of link = $\frac{d}{dt}(\dot{\theta}_l) = \theta_l$

I_m – Mass moment of inertia of motor (kg-m^2)

I_l – Mass moment of inertia of link (kg-m^2)

$$\therefore \quad K = \frac{1}{2} I_m . \dot{\theta}_m^2 + \frac{1}{2} I_l \left(\frac{\dot{\theta}_m}{n} \right)^2$$

$$K = \frac{1}{2} \dot{\theta}_m^2 \left(I_m + \frac{I_l}{n^2} \right)$$

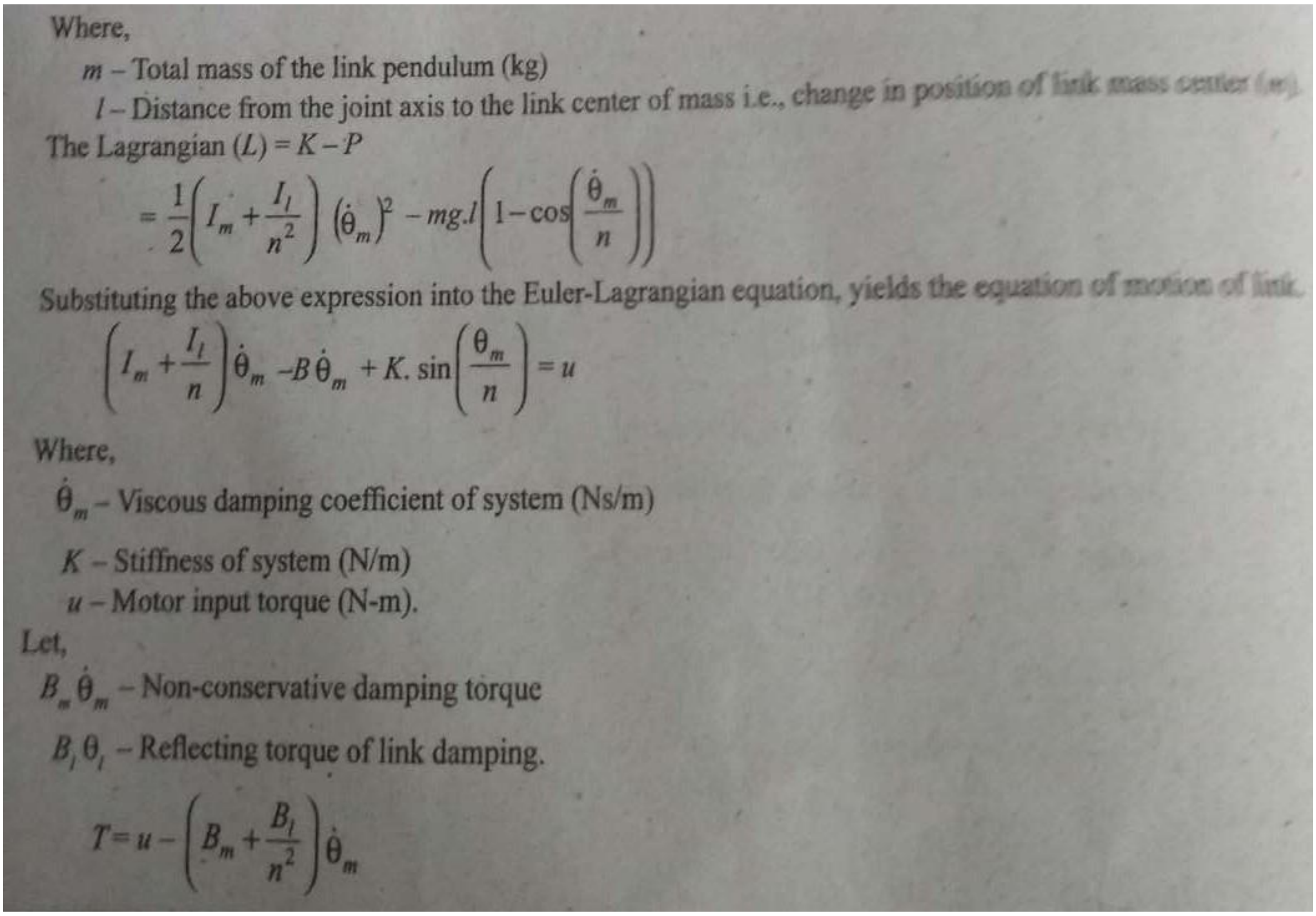
The potential energy $(P) = mg.h$

Figure (2)

$$\therefore \quad P = mg.h$$

$$= mg.l(1 - \cos \theta_l)$$

$$mg.l(1 - \cos (\theta_m / n))$$



Where,

m – Total mass of the link pendulum (kg)

l – Distance from the joint axis to the link center of mass i.e., change in position of link mass center (m)

The Lagrangian $(L) = K - P$

$$= \frac{1}{2}\left(I_m + \frac{I_l}{n^2}\right)\left(\dot{\theta}_m\right)^2 - mg.l\left(1 - \cos\left(\frac{\dot{\theta}_m}{n}\right)\right)$$

Substituting the above expression into the Euler-Lagrangian equation, yields the equation of motion of link.

$$\left(I_m + \frac{I_l}{n}\right)\dot{\theta}_m - B\dot{\theta}_m + K.\sin\left(\frac{\theta_m}{n}\right) = u$$

Where,

$\dot{\theta}_m$ – Viscous damping coefficient of system (Ns/m)

K – Stiffness of system (N/m)

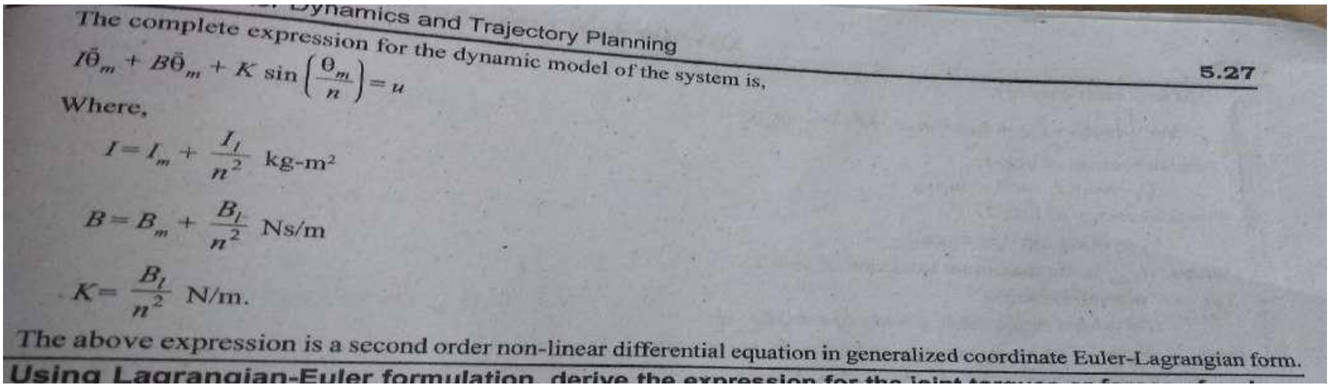
u – Motor input torque (N-m).

Let,

$B_m\dot{\theta}_m$ – Non-conservative damping torque

$B_l\theta_l$ – Reflecting torque of link damping.

$$T = u - \left(B_m + \frac{B_l}{n^2}\right)\dot{\theta}_m$$



Dynamics and Trajectory Planning 5.27

The complete expression for the dynamic model of the system is,

$$I\ddot{\theta}_m + B\dot{\theta}_m + K\sin\left(\frac{\theta_m}{n}\right) = u$$

Where,

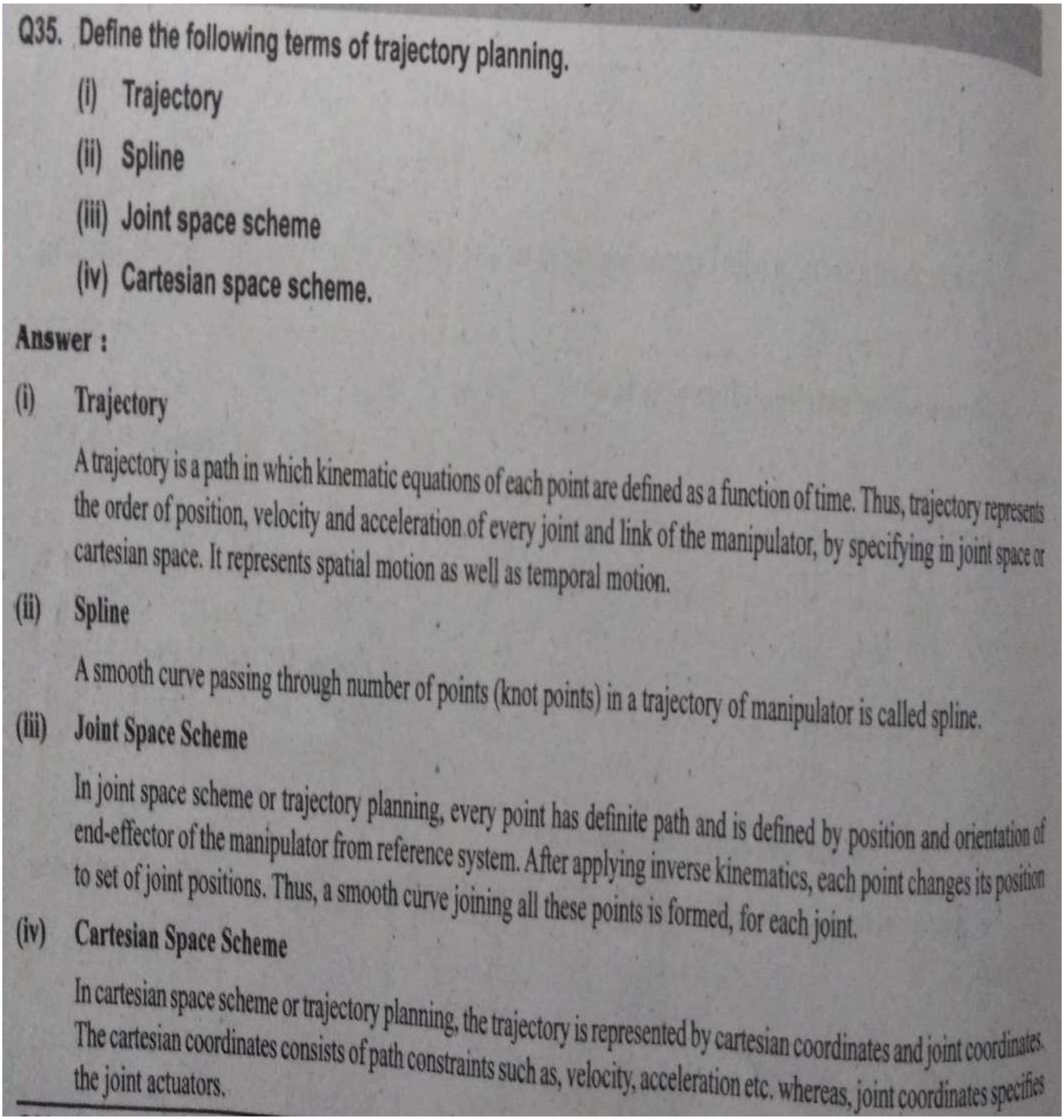
$$I = I_m + \frac{I_l}{n^2} \text{ kg-m}^2$$

$$B = B_m + \frac{B_l}{n^2} \text{ Ns/m}$$

$$K = \frac{B_l}{n^2} \text{ N/m.}$$

The above expression is a second order non-linear differential equation in generalized coordinate Euler-Lagrangian form.

Using Lagrangian-Euler formulation, derive the expression



Q35. Define the following terms of trajectory planning.

(i) Trajectory

(ii) Spline

(iii) Joint space scheme

(iv) Cartesian space scheme.

Answer :

(i) Trajectory

A trajectory is a path in which kinematic equations of each point are defined as a function of time. Thus, trajectory represents the order of position, velocity and acceleration of every joint and link of the manipulator, by specifying in joint space or cartesian space. It represents spatial motion as well as temporal motion.

(ii) Spline

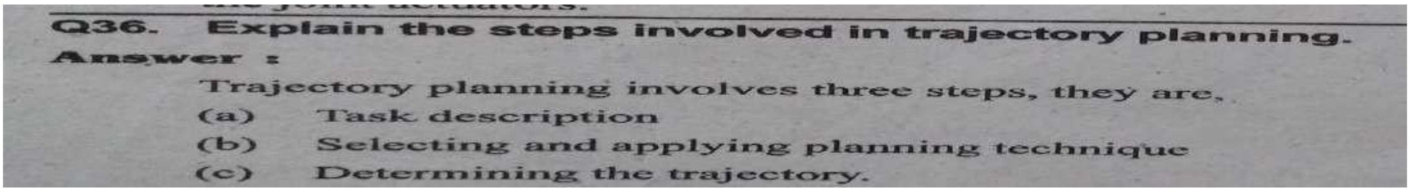
A smooth curve passing through number of points (knot points) in a trajectory of manipulator is called spline.

(iii) Joint Space Scheme

In joint space scheme or trajectory planning, every point has definite path and is defined by position and orientation of end-effector of the manipulator from reference system. After applying inverse kinematics, each point changes its position to set of joint positions. Thus, a smooth curve joining all these points is formed, for each joint.

(iv) Cartesian Space Scheme

In cartesian space scheme or trajectory planning, the trajectory is represented by cartesian coordinates and joint coordinates. The cartesian coordinates consists of path constraints such as, velocity, acceleration etc. whereas, joint coordinates specifies the joint actuators.



Q36. Explain the steps involved in trajectory planning.

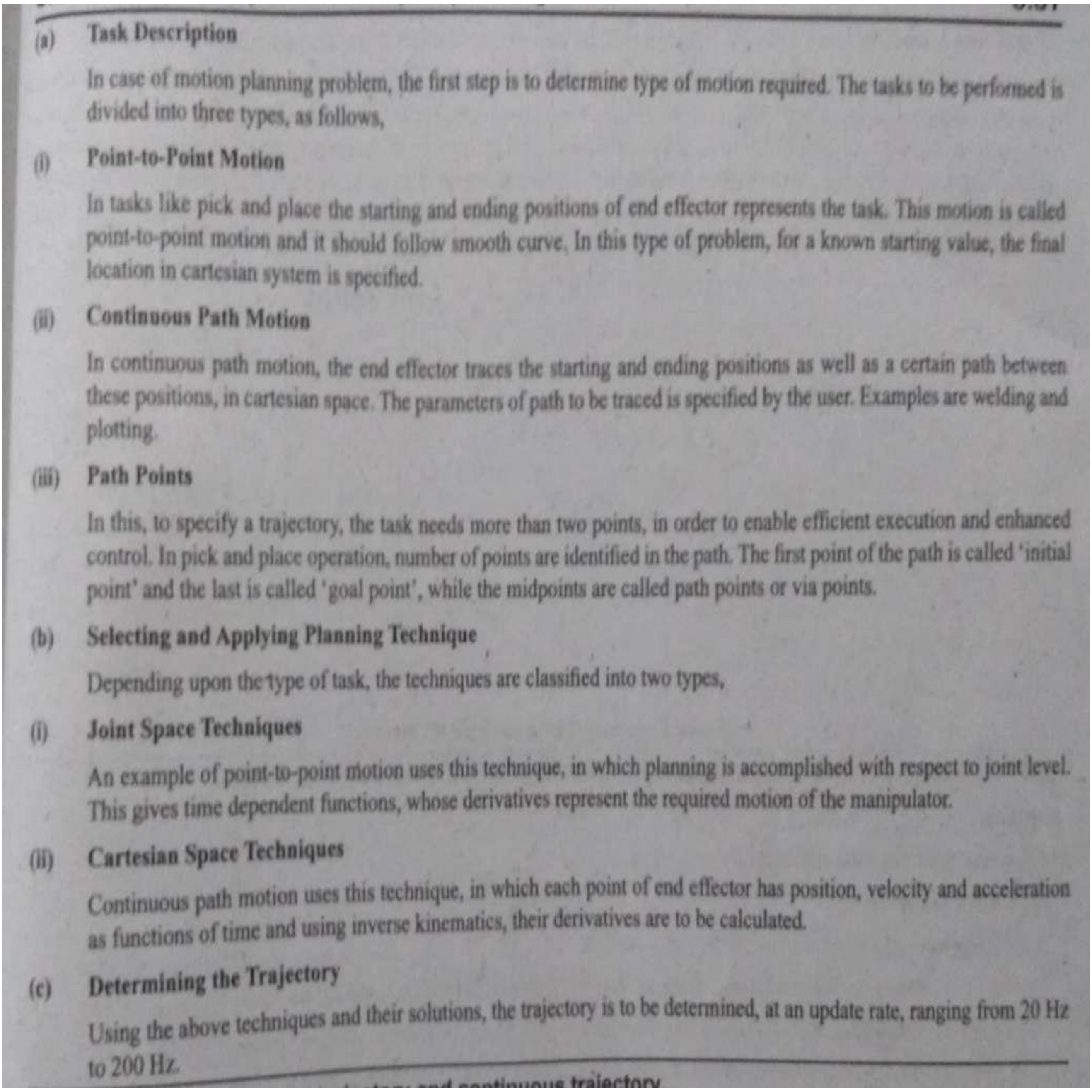
Answer :

Trajectory planning involves three steps, they are,

(a) Task description

(b) Selecting and applying planning technique

(c) Determining the trajectory.



(a) Task Description

In case of motion planning problem, the first step is to determine type of motion required. The tasks to be performed is divided into three types, as follows,

(i) Point-to-Point Motion

In tasks like pick and place the starting and ending positions of end effector represents the task. This motion is called point-to-point motion and it should follow smooth curve. In this type of problem, for a known starting value, the final location in cartesian system is specified.

(ii) Continuous Path Motion

In continuous path motion, the end effector traces the starting and ending positions as well as a certain path between these positions, in cartesian space. The parameters of path to be traced is specified by the user. Examples are welding and plotting.

(iii) Path Points

In this, to specify a trajectory, the task needs more than two points, in order to enable efficient execution and enhanced control. In pick and place operation, number of points are identified in the path. The first point of the path is called 'initial point' and the last is called 'goal point', while the midpoints are called path points or via points.

(b) Selecting and Applying Planning Technique

Depending upon the type of task, the techniques are classified into two types,

(i) Joint Space Techniques

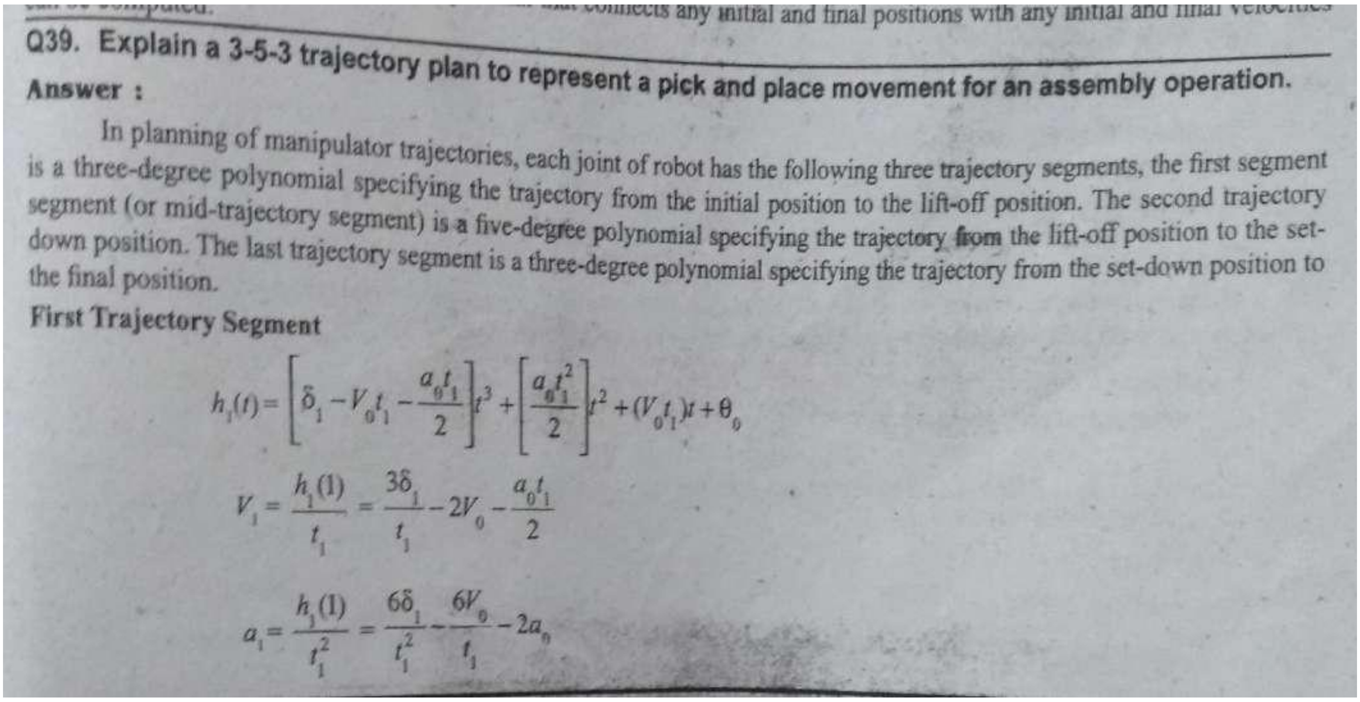
An example of point-to-point motion uses this technique, in which planning is accomplished with respect to joint level. This gives time dependent functions, whose derivatives represent the required motion of the manipulator.

(ii) Cartesian Space Techniques

Continuous path motion uses this technique, in which each point of end effector has position, velocity and acceleration as functions of time and using inverse kinematics, their derivatives are to be calculated.

(c) Determining the Trajectory

Using the above techniques and their solutions, the trajectory is to be determined, at an update rate, ranging from 20 Hz to 200 Hz.



connects any initial and final positions with any initial and final velocities

Q39. Explain a 3-5-3 trajectory plan to represent a pick and place movement for an assembly operation.

Answer :

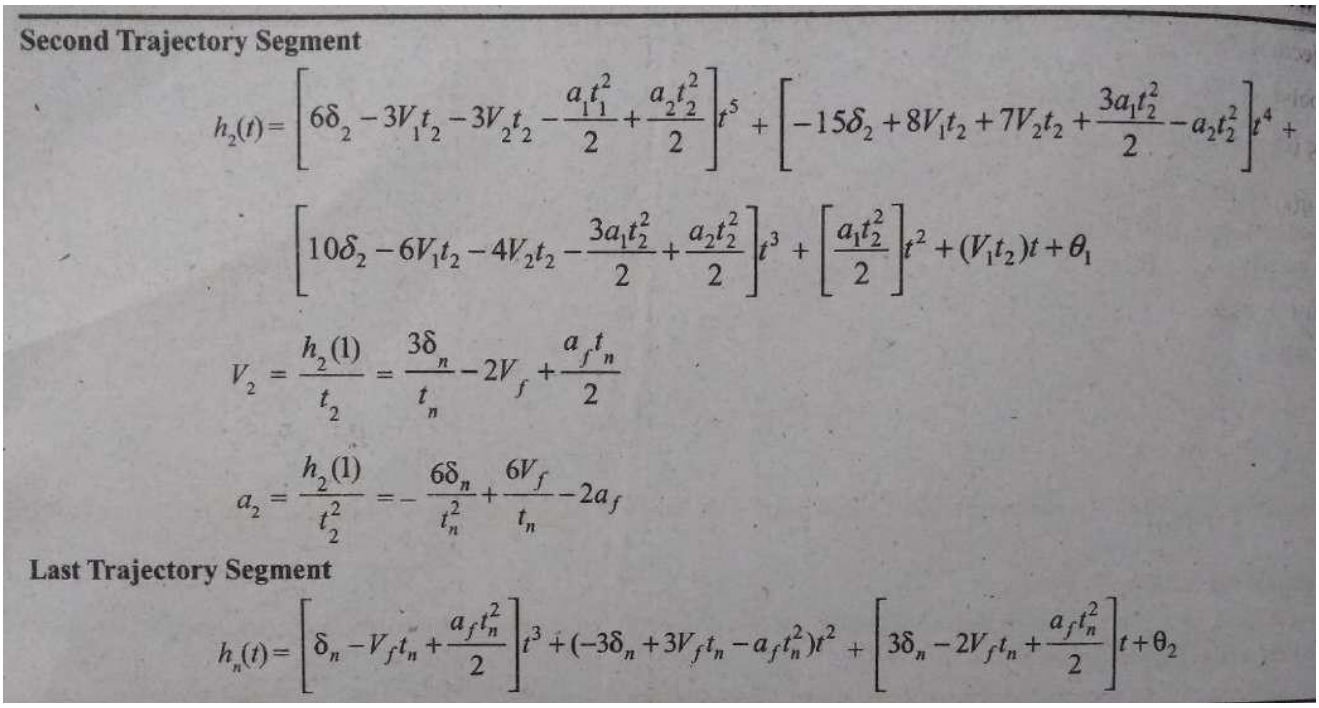
In planning of manipulator trajectories, each joint of robot has the following three trajectory segments, the first segment is a three-degree polynomial specifying the trajectory from the initial position to the lift-off position. The second trajectory segment (or mid-trajectory segment) is a five-degree polynomial specifying the trajectory from the lift-off position to the set-down position. The last trajectory segment is a three-degree polynomial specifying the trajectory from the set-down position to the final position.

First Trajectory Segment

$$h_1(t) = \left[\delta_1 - V_0 t_1 - \frac{a_0 t_1}{2}\right] t^3 + \left[\frac{a_0 t_1^2}{2}\right] t^2 + (V_0 t_1) t + \theta_0$$

$$V_1 = \frac{h_1(1)}{t_1} = \frac{3\delta_1}{t_1} - 2V_0 - \frac{a_0 t_1}{2}$$

$$a_1 = \frac{h_1(1)}{t_1^2} = \frac{6\delta_1}{t_1^2} - \frac{6V_0}{t_1} - 2a_0$$



Second Trajectory Segment

$$h_2(t) = \left[6\delta_2 - 3V_1 t_2 - 3V_2 t_2 - \frac{a_1 t_1^2}{2} + \frac{a_2 t_2^2}{2}\right] t^5 + \left[-15\delta_2 + 8V_1 t_2 + 7V_2 t_2 + \frac{3a_1 t_2^2}{2} - a_2 t_2^2\right] t^4 +$$

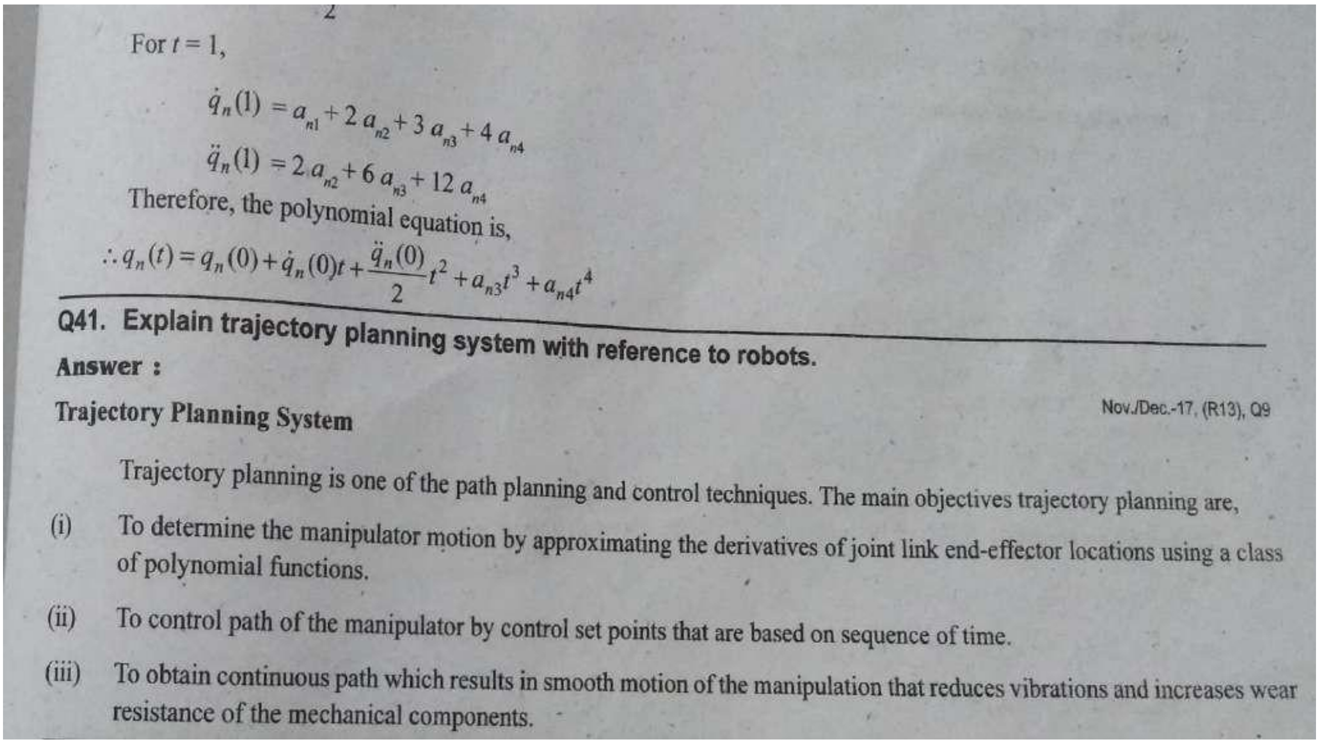
$$\left[10\delta_2 - 6V_1 t_2 - 4V_2 t_2 - \frac{3a_1 t_2^2}{2} + \frac{a_2 t_2^2}{2}\right] t^3 + \left[\frac{a_1 t_2^2}{2}\right] t^2 + (V_1 t_2) t + \theta_1$$

$$V_2 = \frac{h_2(1)}{t_2} = \frac{3\delta_n}{t_n} - 2V_f + \frac{a_f t_n}{2}$$

$$a_2 = \frac{h_2(1)}{t_2^2} = -\frac{6\delta_n}{t_n^2} + \frac{6V_f}{t_n} - 2a_f$$

Last Trajectory Segment

$$h_n(t) = \left[\delta_n - V_f t_n + \frac{a_f t_n^2}{2}\right] t^3 + (-3\delta_n + 3V_f t_n - a_f t_n^2) t^2 + \left[3\delta_n - 2V_f t_n + \frac{a_f t_n^2}{2}\right] t + \theta_2$$



For $t = 1$,

$$\dot{q}_n(1) = a_{n1} + 2\,a_{n2} + 3\,a_{n3} + 4\,a_{n4}$$

$$\ddot{q}_n(1) = 2\,a_{n2} + 6\,a_{n3} + 12\,a_{n4}$$

Therefore, the polynomial equation is,

$$\therefore q_n(t) = q_n(0) + \dot{q}_n(0)t + \frac{\ddot{q}_n(0)}{2}t^2 + a_{n3}t^3 + a_{n4}t^4$$

Q41. Explain trajectory planning system with reference to robots.

Answer :

Nov./Dec.-17, (R13), Q9

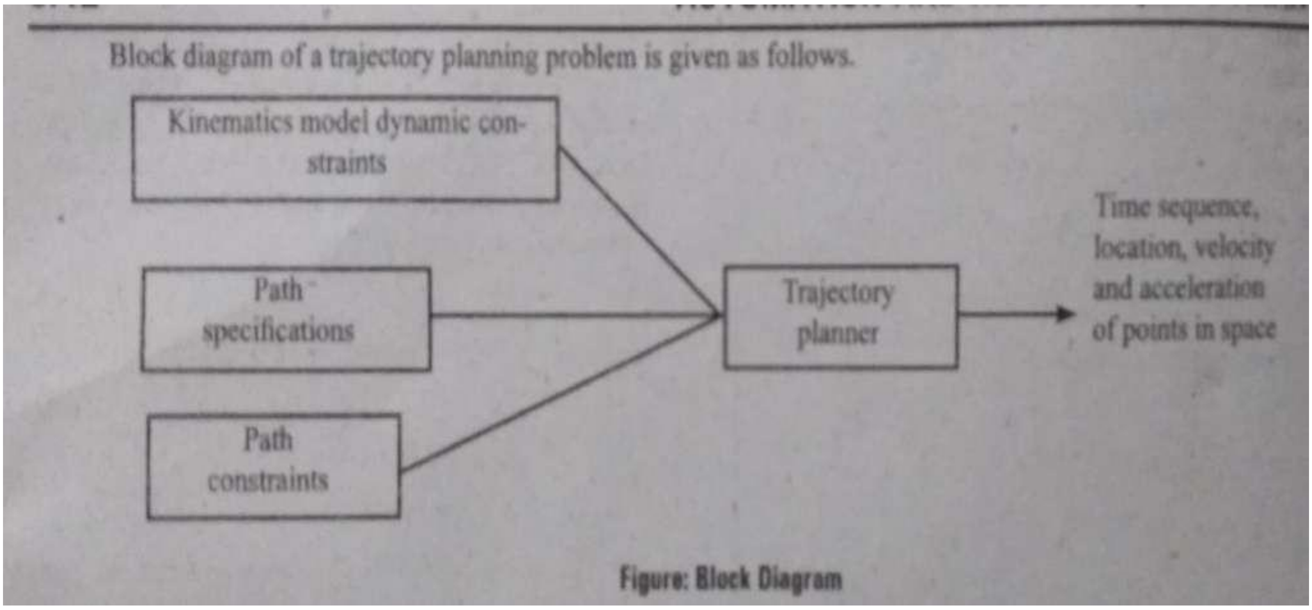
Trajectory Planning System

Trajectory planning is one of the path planning and control techniques. The main objectives trajectory planning are,

(i) To determine the manipulator motion by approximating the derivatives of joint link end-effector locations using a class of polynomial functions.

(ii) To control path of the manipulator by control set points that are based on sequence of time.

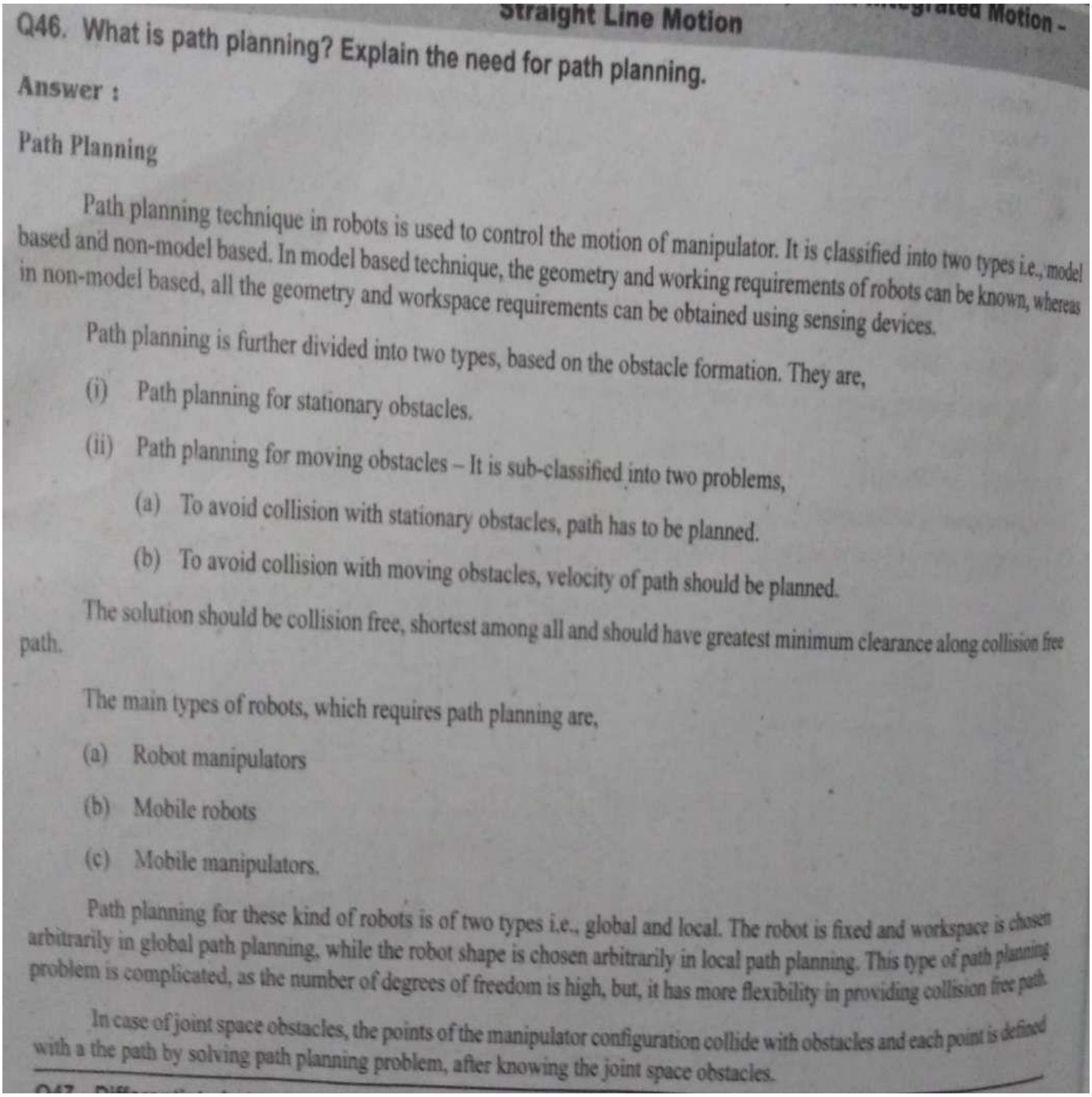
(iii) To obtain continuous path which results in smooth motion of the manipulation that reduces vibrations and increases wear resistance of the mechanical components.



Block diagram of a trajectory planning problem is given as follows.

Figure: Block Diagram

Also explain steps involved in trajectory planning refer question 36



Q46. What is path planning? Explain the need for path planning.

Answer :

Path Planning

Path planning technique in robots is used to control the motion of manipulator. It is classified into two types i.e., model based and non-model based. In model based technique, the geometry and working requirements of robots can be known, whereas in non-model based, all the geometry and workspace requirements can be obtained using sensing devices.

Path planning is further divided into two types, based on the obstacle formation. They are,

(i) Path planning for stationary obstacles.

(ii) Path planning for moving obstacles – It is sub-classified into two problems,

  (a) To avoid collision with stationary obstacles, path has to be planned.

  (b) To avoid collision with moving obstacles, velocity of path should be planned.

The solution should be collision free, shortest among all and should have greatest minimum clearance along collision free path.

The main types of robots, which requires path planning are,

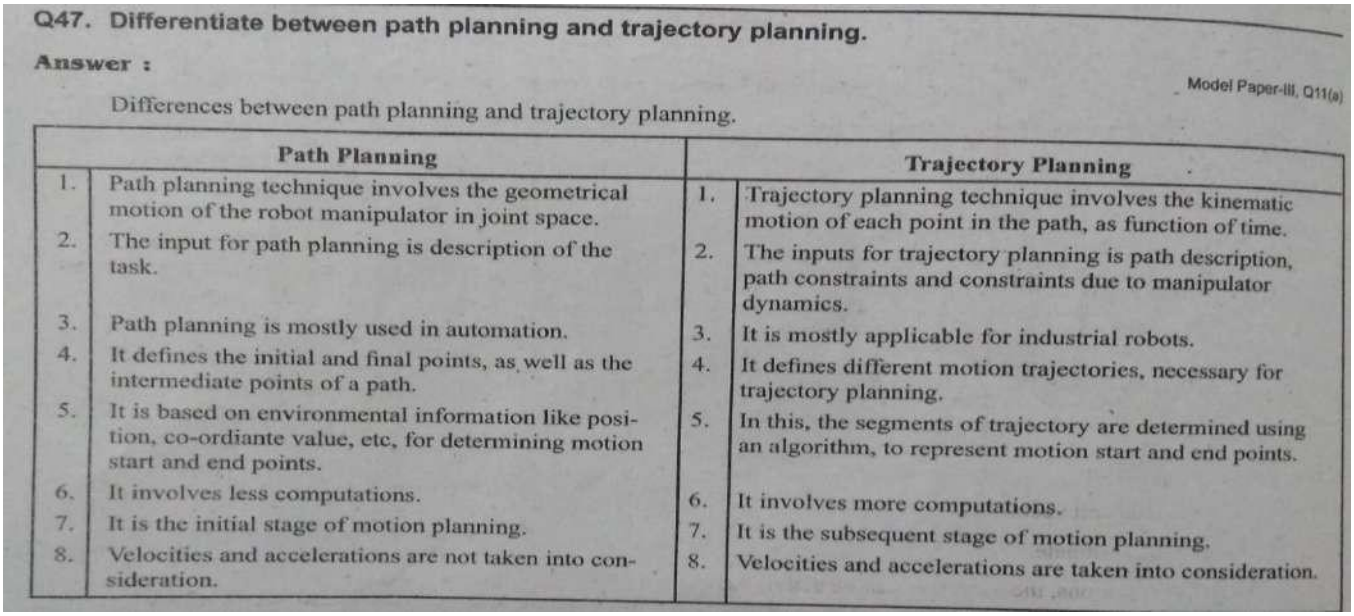
(a) Robot manipulators

(b) Mobile robots

(c) Mobile manipulators.

Path planning for these kind of robots is of two types i.e., global and local. The robot is fixed and workspace is chosen arbitrarily in global path planning, while the robot shape is chosen arbitrarily in local path planning. This type of path planning problem is complicated, as the number of degrees of freedom is high, but, it has more flexibility in providing collision free path.

In case of joint space obstacles, the points of the manipulator configuration collide with obstacles and each point is defined with a the path by solving path planning problem, after knowing the joint space obstacles.



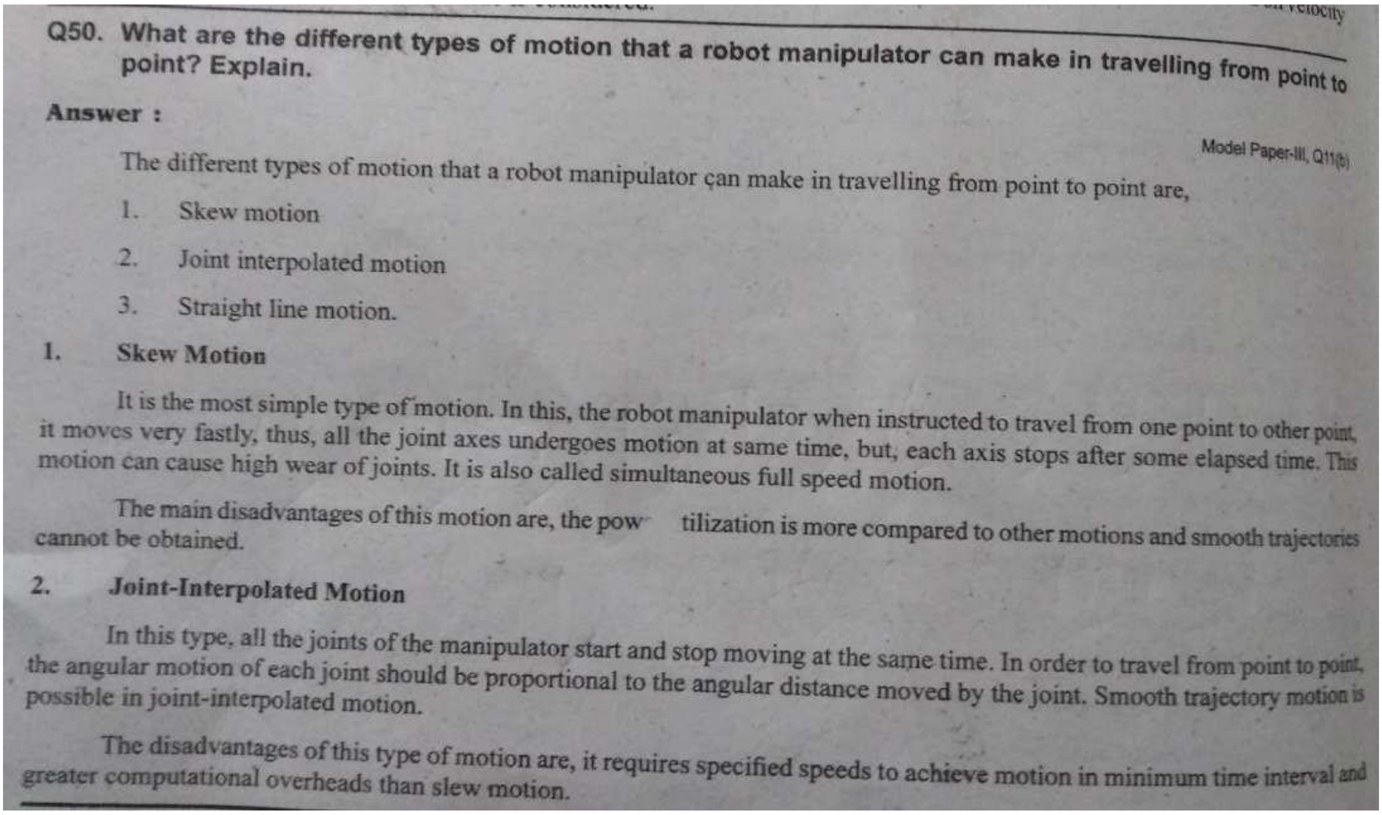
Q47. Differentiate between path planning and trajectory planning.

Answer :

Model Paper-III, Q11(a)

Differences between path planning and trajectory planning.

	Path Planning		Trajectory Planning
1.	Path planning technique involves the geometrical motion of the robot manipulator in joint space.	1.	Trajectory planning technique involves the kinematic motion of each point in the path, as function of time.
2.	The input for path planning is description of the task.	2.	The inputs for trajectory planning is path description, path constraints and constraints due to manipulator dynamics.
3.	Path planning is mostly used in automation.	3.	It is mostly applicable for industrial robots.
4.	It defines the initial and final points, as well as the intermediate points of a path.	4.	It defines different motion trajectories, necessary for trajectory planning.
5.	It is based on environmental information like position, co-ordiante value, etc, for determining motion start and end points.	5.	In this, the segments of trajectory are determined using an algorithm, to represent motion start and end points.
6.	It involves less computations.	6.	It involves more computations.
7.	It is the initial stage of motion planning.	7.	It is the subsequent stage of motion planning.
8.	Velocities and accelerations are not taken into consideration.	8.	Velocities and accelerations are taken into consideration.



Q50. What are the different types of motion that a robot manipulator can make in travelling from point to point? Explain.

Answer :

Model Paper-III, Q11(b)

The different types of motion that a robot manipulator can make in travelling from point to point are,

1. Skew motion
2. Joint interpolated motion
3. Straight line motion.

1. Skew Motion

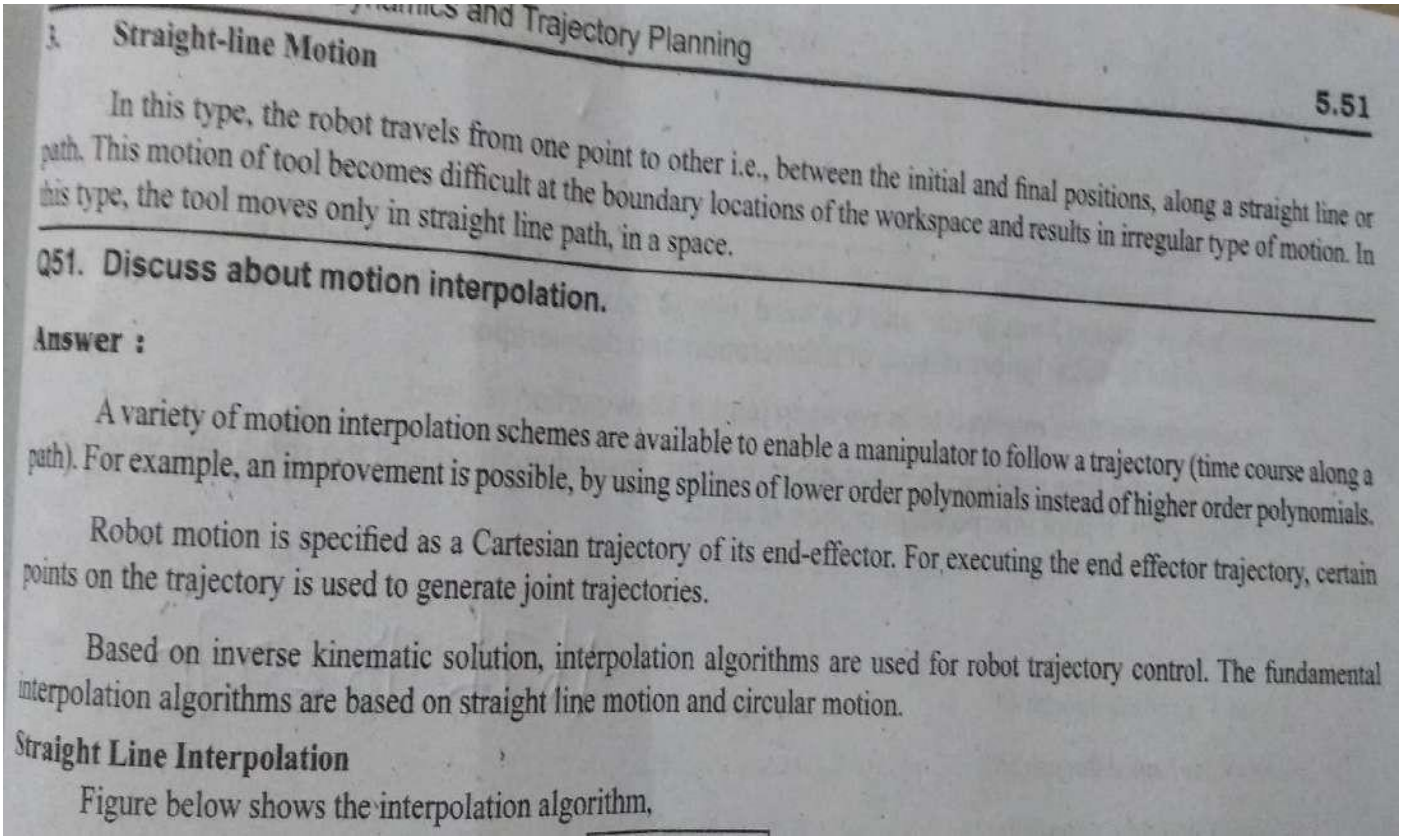
It is the most simple type of motion. In this, the robot manipulator when instructed to travel from one point to other point, it moves very fastly, thus, all the joint axes undergoes motion at same time, but, each axis stops after some elapsed time. This motion can cause high wear of joints. It is also called simultaneous full speed motion.

The main disadvantages of this motion are, the pow tilization is more compared to other motions and smooth trajectories cannot be obtained.

2. Joint-Interpolated Motion

In this type, all the joints of the manipulator start and stop moving at the same time. In order to travel from point to point, the angular motion of each joint should be proportional to the angular distance moved by the joint. Smooth trajectory motion is possible in joint-interpolated motion.

The disadvantages of this type of motion are, it requires specified speeds to achieve motion in minimum time interval and greater computational overheads than slew motion.



3. **Straight-line Motion**

In this type, the robot travels from one point to other i.e., between the initial and final positions, along a straight line or path. This motion of tool becomes difficult at the boundary locations of the workspace and results in irregular type of motion. In this type, the tool moves only in straight line path, in a space.

Q51. Discuss about motion interpolation.

Answer :

A variety of motion interpolation schemes are available to enable a manipulator to follow a trajectory (time course along a path). For example, an improvement is possible, by using splines of lower order polynomials instead of higher order polynomials.

Robot motion is specified as a Cartesian trajectory of its end-effector. For executing the end effector trajectory, certain points on the trajectory is used to generate joint trajectories.

Based on inverse kinematic solution, interpolation algorithms are used for robot trajectory control. The fundamental interpolation algorithms are based on straight line motion and circular motion.

Straight Line Interpolation

Figure below shows the interpolation algorithm,

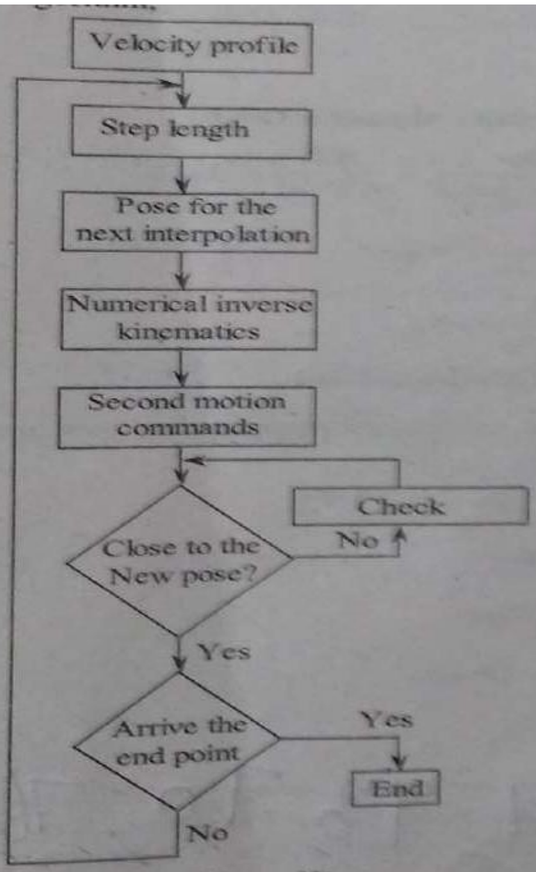


Figure (1)

The representation of interpolation and command points is,

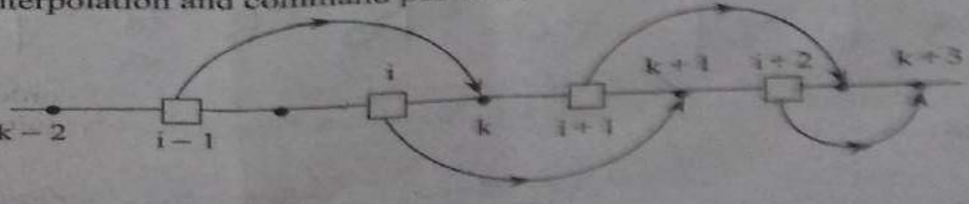
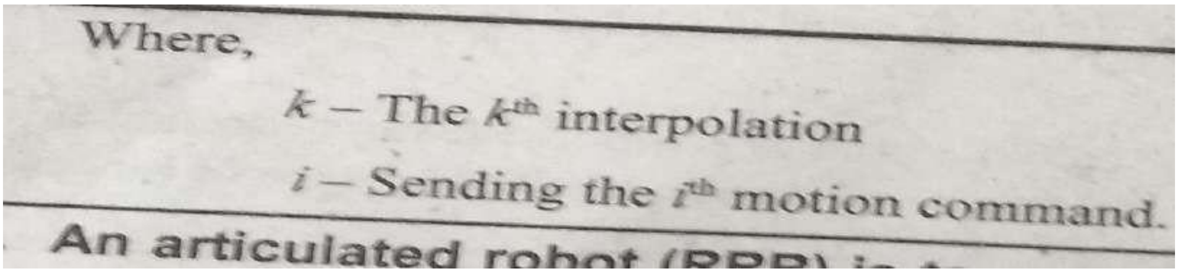


Figure (2)



Where,

k – The k^{th} interpolation

i – Sending the i^{th} motion command.

An articulated robot (RRR) is

UNIT – 5: ROBOT PROGRAMMING AND APPLICATION

Transducers: It is a device which converts one form of physical variable (pressure or force or temperature) / energy into another form (usually electrical signal).

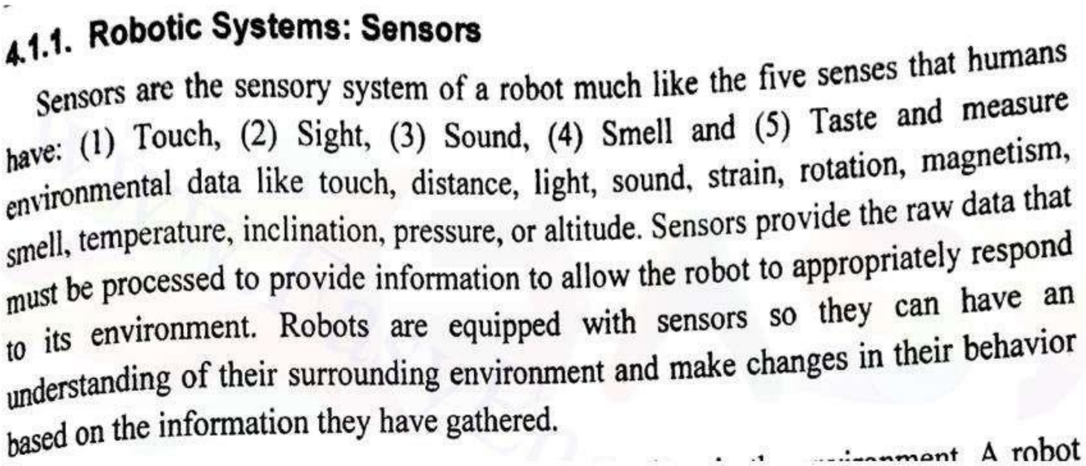
Sensor is a device which measure the physical quantity or variable and convert it into an electrical signal.

Actuator: it is a device which converts the electrical signal into a physical variable or quantity.

Sensors used in robotics:

- **Tactile sensors:** Used to determine whether contact is made between the sensor and another object. Tactile sensors can be divided into two types in robot applications: (1) **touch sensors** and (2) **force sensors**, Touch sensors are those that indicate simply that contact has been made with the object. Force sensors are used to indicate the magnitude of the force with the object. This might be useful in a gripper to measure and control the force being applied to grasp an object.
- **Proximity sensors.** Indicate when an object is close to the sensor, When this type of sensor is used to indicate the actual distance of the object, it is called a **range sensor**.
- **Optical sensors:** Photocells and other photometric devices can be utilized to detect the presence or absence of objects and are often used for proximity detection.
- **Machine vision.** Used in robotics for inspection, parts identification, guidance, and other uses.
- **Other sensors.** This miscellaneous category includes other types of sensors that might be used in robotics, including devices for measuring temperature, fluid pressure, fluid flow, electrical voltage, current, and various other physical properties.

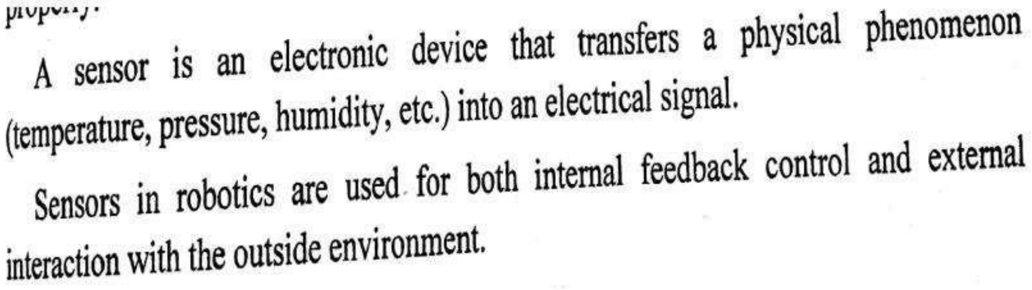
Introduction to sensors



4.1.1. Robotic Systems: Sensors

Sensors are the sensory system of a robot much like the five senses that humans have: (1) Touch, (2) Sight, (3) Sound, (4) Smell and (5) Taste and measure environmental data like touch, distance, light, sound, strain, rotation, magnetism, smell, temperature, inclination, pressure, or altitude. Sensors provide the raw data that must be processed to provide information to allow the robot to appropriately respond to its environment. Robots are equipped with sensors so they can have an understanding of their surrounding environment and make changes in their behavior based on the information they have gathered.

Sensor



A sensor is an electronic device that transfers a physical phenomenon (temperature, pressure, humidity, etc.) into an electrical signal.

Sensors in robotics are used for both internal feedback control and external interaction with the outside environment.

Range sensors

Range sensor which senses the range of the object.

A range sensor measures the distance from a reference point (usually on the sensor itself) to objects in the field of operation of the sensor.

- ✓ Humans estimate distance by means of stereo visual processing, as discussed in previously while other animals, such as bats, utilize the "time of flight" concept in which distance estimates are based on the time elapsed between the transmission and return of a sonic pulse.
- ✓ Range sensors are used for robot navigation and obstacle avoidance where interest lies in estimating the distance to the closest objects, to more detailed applications in which the location and general shape characteristics of objects in the work space of a robot are desired. In this section we discuss several range sensing techniques that address these problems.

Range Sensing Techniques

1. Triangular technique
2. Structured lighting approach
3. Time of flight range finder

Range Sensing Techniques

1. Triangular technique
2. Structured lighting approach
3. Time of flight range finder

(i) Triangulation principle

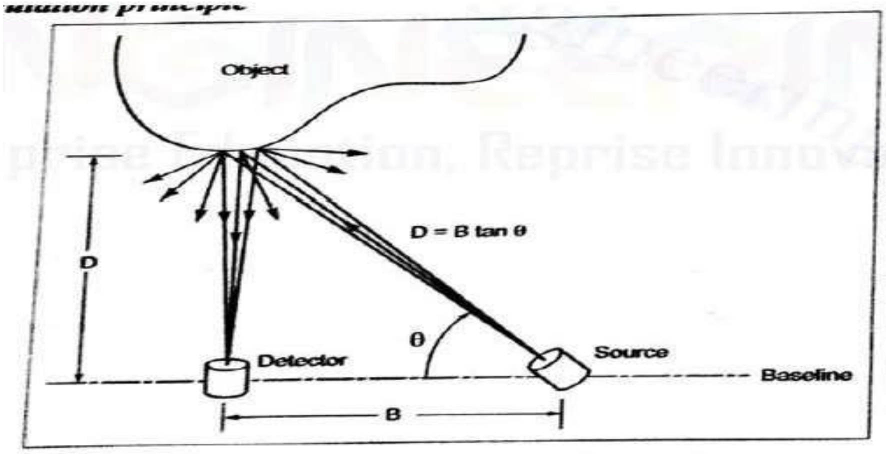


Fig. 4.11. Range sensing by triangulation

- ✓ One of the simplest methods for measuring range is through triangulation techniques.
- ✓ This approach can be easily explained with the aid of Fig.4.11.
- ✓ An object is illuminated by a narrow beam of light which is swept over the surface. The sweeping motion is in the plane defined by the line from the object to the detector and the line from the detector to the source. If the detector is focused on a small portion of the surface then, when the detector sees the light spot, its distance D to the illuminated portion of the surface can be calculated from the geometry of Fig.4.11 since the angle of the source with the baseline and the distance B between the source and detector are known.
- ✓ The above approach yields a point measurement. If the source-detector arrangement is moved in a fixed plane (up and down and sideways on a plane perpendicular to the paper and containing the baseline in Fig.4.11), then it is possible to obtain a set of points whose distances from the detector are known.
- ✓ These distances are easily transformed to three-dimensional coordinates by keeping track of the location and orientation of the detector as the objects are scanned. An example is shown in Fig.4.12(*a*) and Fig.4.12(*b*) shows an arrangement of objects scanned in the manner just explained.
- ✓ Figure 4.12(b) shows the results in terms of an image whose intensity (darker is closer) is proportional to the range measured from the plane of motion of the source-detector pair.

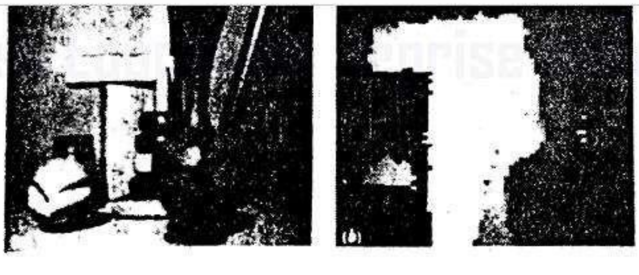


Fig. 4.12. (a) An arrangement of objects scanned by a triangulation ranging device. (b) Corresponding image with intensities proportional to range.

(ii) Structured Lighting Approach

- ✓ This approach consists of projecting a light pattern onto a set of objects and using the distortion of the pattern to calculate the range. One of the most popular light patterns in use today is a sheet of light generated through a cylindrical lens or a narrow slit.

- ✓ As illustrated in Fig.4.13. the intersection of the sheet with objects in the work space yields a light stripe which is viewed through a television camera displaced a distance B from the light source. The stripe pattern is easily analyzed by a computer to obtain range information.
- ✓ For example, an inflection indicates a change of surface, and a break corresponds to a gap between surfaces.

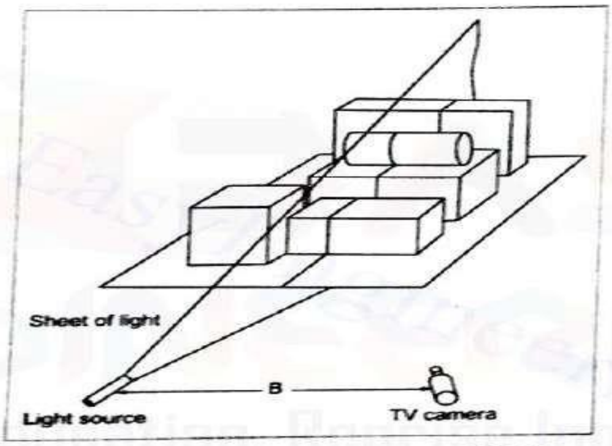
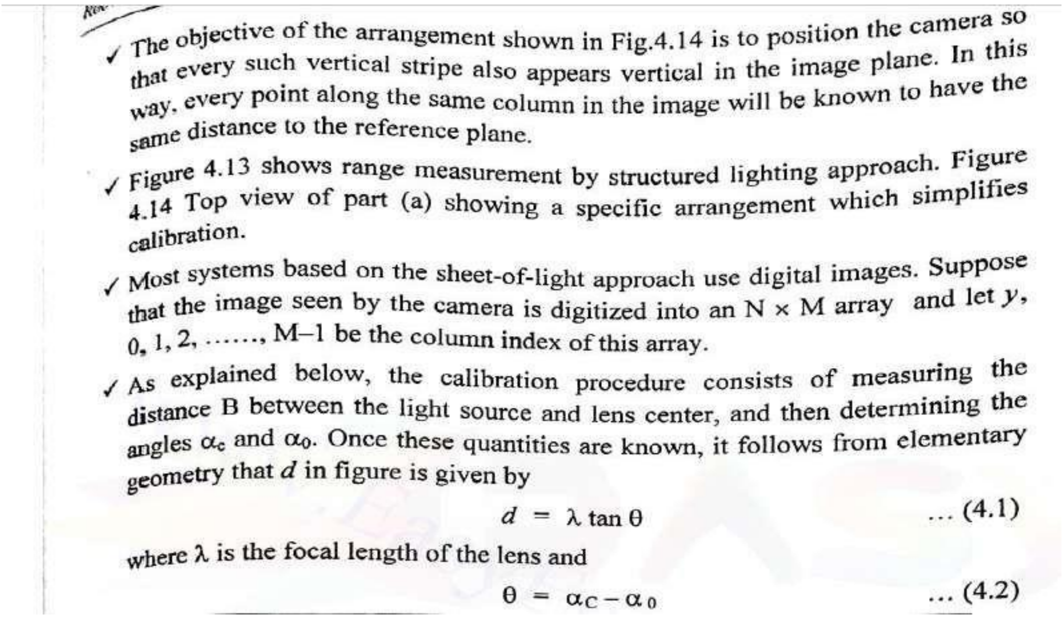


Fig. 4.13. Range measurement by structured lighting approach

Fig. 4.13. Range measurement by structured lighting

- ✓ Specific range values are computed by first calibrating the system. One of the simplest arrangements is shown in Fig.4.14, which represents a top view of Fig.4.13. In this arrangement, the light source and camera are placed at the same height, and the sheet of light is perpendicular to the line joining the origin of the light sheet and the center of the camera lens.
- ✓ We call the vertical plane containing this line the reference plane. Clearly, the reference plane is perpendicular to the sheet of light, and any vertical flat surface that intersects the sheet will produce a vertical stripe of light (see Fig.4.13) in which every point will have the same perpendicular distance to the reference plane.



- ✓ The objective of the arrangement shown in Fig.4.14 is to position the camera so that every such vertical stripe also appears vertical in the image plane. In this way, every point along the same column in the image will be known to have the same distance to the reference plane.
- ✓ Figure 4.13 shows range measurement by structured lighting approach. Figure 4.14 Top view of part (a) showing a specific arrangement which simplifies calibration.
- ✓ Most systems based on the sheet-of-light approach use digital images. Suppose that the image seen by the camera is digitized into an N × M array and let y, 0, 1, 2, ……, M–1 be the column index of this array.
- ✓ As explained below, the calibration procedure consists of measuring the distance B between the light source and lens center, and then determining the angles α_c and α_0. Once these quantities are known, it follows from elementary geometry that d in figure is given by

$$d = \lambda \tan \theta \qquad \dots (4.1)$$

where λ is the focal length of the lens and

$$\theta = \alpha_C - \alpha_0 \qquad \dots (4.2)$$

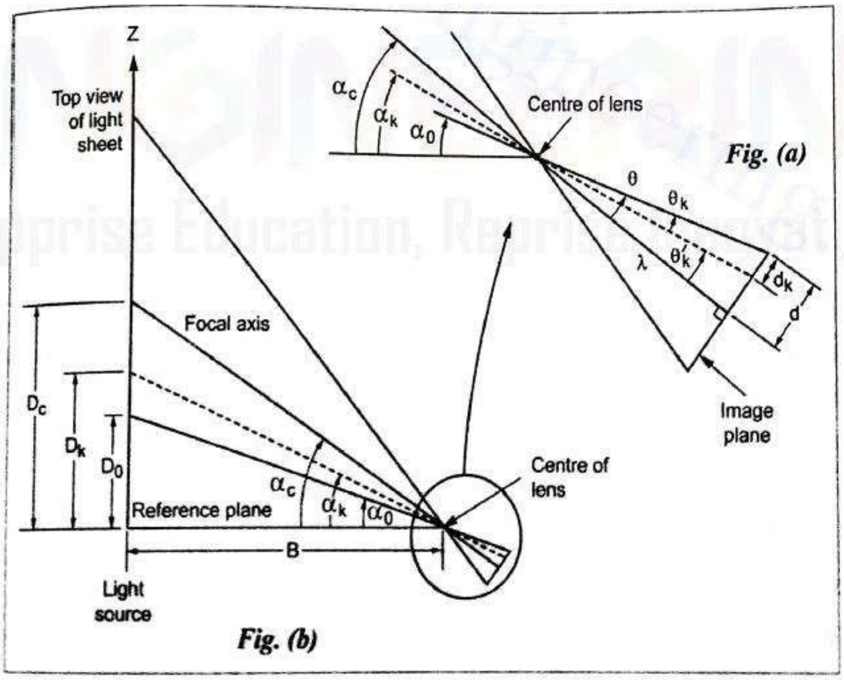


Fig. 4.14. (a) showing a specific arrangement which simplifies calibration.

For an M-column digital image, the distance increment d_k between columns is given by

$$d_k = k \frac{d}{M/2} = \frac{2kd}{M} \qquad \dots (4.3)$$

For $0 \le k \le M/2$, (in an image viewed on a monitor, $k = 0$ would correspond to the leftmost column and $k = M/2$ to the center column). The angle α_k made by the projection of an arbitrary stripe is easily obtained by noting that

$$\alpha_k = \alpha_c - \theta'_k \qquad \dots (4.4)$$

where, $$\tan \theta'_k = \frac{d - d_k}{\lambda} \qquad \dots (4.5)$$

or, using equation $$\theta'_k = \tan^{-1}\left[\frac{d\,(M - 2\,k)}{M\,\lambda}\right] \qquad \dots (4.6)$$

where $0 \le k \le M/2$. For the remaining values of k (*i.e.*, on the other side of the optical axis), we have

$$\alpha_k = \alpha_C + \theta''_k \qquad \dots (4.7)$$

where, $$\theta''_k = \tan^{-1}\left[\frac{d(2\,k - M)}{M\,\lambda}\right] \qquad \dots (4.8)$$

for $M/2 < k \le (M - 1)$.

By comparing Equations (4.6) and (4.8) we note that $\theta''_k = -\theta'_k$. So Equations (4.4) and (4.7) are identical for the *entire* range $0 \le k \le M - 1$. It then follows from Fig.4.14 shows that the perpendicular distance D_k between an arbitrary light stripe and the reference plane is given by

$$D_k = B \tan \theta_k \qquad \dots (4.9)$$

For $0 \le k \le M - 1$, where α_k is given either by equations (4.4) & (4.7).

- ✓ It is important to note that once B, α_0, α_c, M, and λ are known, the column number in the digital image completely determines the distance between the reference plane and all points in the stripe imaged on that column.
- ✓ Since M and λ are fixed parameters, the calibration procedure consists simply of measuring B and determining α_c and α_0, as indicated above.
- ✓ To determine α_c. we place a flat vertical surface so that its intersection with the sheet of light is imaged on the center of the image plane (*i.e.*, at $y = M/2$).
- ✓ We then physically measure the perpendicular distance D_c between the surface and the reference plane. From the geometry of Fig.4.14, it follows that

$$\alpha_c = \tan^{-1}\left(\frac{D_c}{B}\right) \qquad \dots (4.10)$$

In order to determine α_0, we move the surface closer to the reference plane until its light stripe is imaged at $y = 0$ on the image plane. We then measure D_0 and, from Fig.4.10.

$$\alpha_0 = \tan^{-1}\left(\frac{D_0}{B}\right)$$

- ✓ This completes the calibration procedure.
- ✓ The principal advantage of the arrangement just discussed is that it results in a relatively simple range measuring technique.
- ✓ Once calibration is completed, the distance associated with every column in the image is computed using Equation (4.9) with $k = 0, 1, 2, \ldots, M - 1$ and the results are stored in memory.
- ✓ Then, during normal operation, the distance of any imaged point is obtained simply by determining its column number in the image and addressing the corresponding location in memory.
- ✓ We point out that it is possible to use the concepts discussed in previously to solve a more general problem in which the light source and camera are placed arbitrarily with respect to each other.
- ✓ The resulting expressions, however, would be considerably more complicated and difficult to handle from a computational point of view.

4.12. LASER RANGE FINDER

- ✓ This sensors uses a laser beam in order to determine the distance to a reflective object.
- ✓ The most common form of laser rangefinder operates on the time of flight principle by sending a laser pulse in a narrow beam towards the object and measuring the time taken by the pulse to be reflected off the target and returned to the sender.
- ✓ Due to the high speed of light, this technique is not appropriate for high precision sub-millimeter measurements, where triangulation and other techniques are often used.

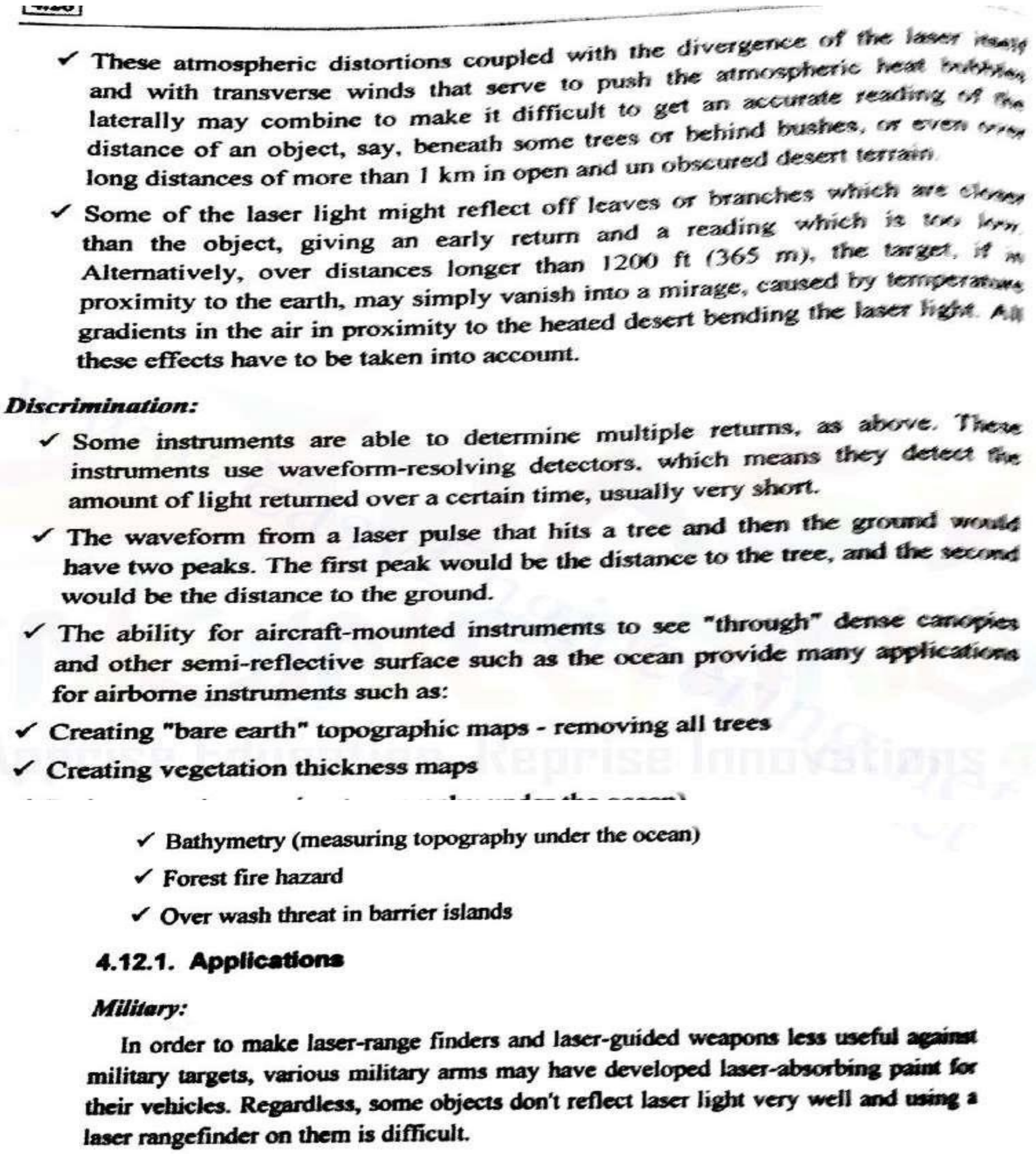
Operation:

Pulse:

- ✓ The pulse may be coded in order to reduce the chance that the rangefinder can be jammed. It is possible to use Doppler effect techniques to judge whether the object is moving towards or away from the rangefinder, and if so how fast.
- ✓ The accuracy of the instrument is determined by the brevity of the laser pulse and the speed of the receiver. One that uses very short, sharp laser pulses and has a very fast detector can range an object to within a few centimeters.

Range:

- ✓ Despite the beam being narrow, it eventually spreads over long distances due to the divergence of the laser beam, as well as to scintillation and beam wander effects, caused by the presence of air bubbles in the air acting as lenses ranging in size from microscopic to roughly half the height of the laser beam's path above the earth.



- ✓ These atmospheric distortions coupled with the divergence of the laser itself and with transverse winds that serve to push the atmospheric heat bubbles laterally may combine to make it difficult to get an accurate reading of the distance of an object, say, beneath some trees or behind bushes, or even over long distances of more than 1 km in open and un obscured desert terrain.
- ✓ Some of the laser light might reflect off leaves or branches which are closer than the object, giving an early return and a reading which is too low. Alternatively, over distances longer than 1200 ft (365 m), the target, if in proximity to the earth, may simply vanish into a mirage, caused by temperature gradients in the air in proximity to the heated desert bending the laser light. All these effects have to be taken into account.

Discrimination:

- ✓ Some instruments are able to determine multiple returns, as above. These instruments use waveform-resolving detectors, which means they detect the amount of light returned over a certain time, usually very short.
- ✓ The waveform from a laser pulse that hits a tree and then the ground would have two peaks. The first peak would be the distance to the tree, and the second would be the distance to the ground.
- ✓ The ability for aircraft-mounted instruments to see "through" dense canopies and other semi-reflective surface such as the ocean provide many applications for airborne instruments such as:
- ✓ Creating "bare earth" topographic maps - removing all trees
- ✓ Creating vegetation thickness maps
- ✓ Bathymetry (measuring topography under the ocean)
- ✓ Forest fire hazard
- ✓ Over wash threat in barrier islands

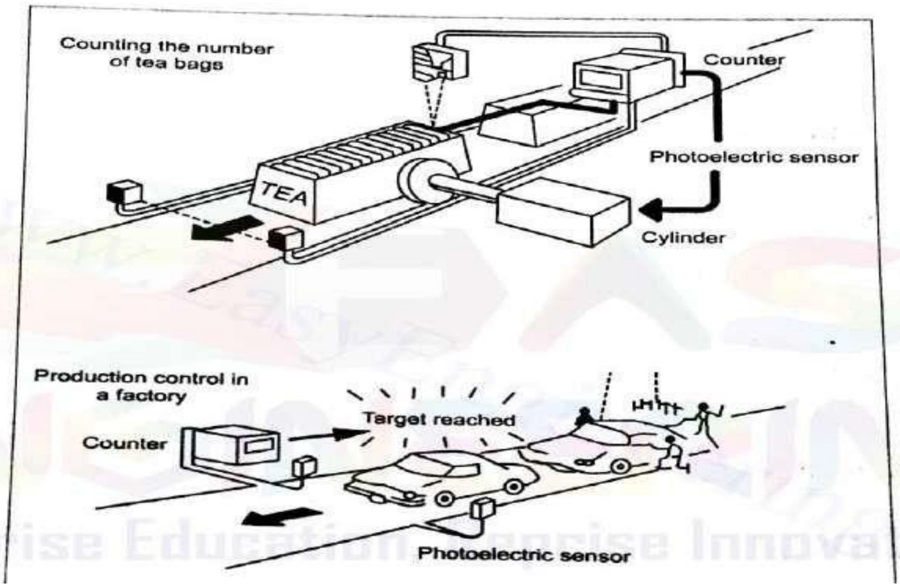
4.12.1. Applications

Military:

In order to make laser-range finders and laser-guided weapons less useful against military targets, various military arms may have developed laser-absorbing paint for their vehicles. Regardless, some objects don't reflect laser light very well and using a laser rangefinder on them is difficult.

Proximity sensors

- ✓ ***Proximity sensor*** is a sensor, which senses the presence or absence of the object without having physical contact between the objects.
- ✓ Proximity sensors are used in robotics for the near field work in connection with object grasping (or) avoidance.



4.13.1. The Classifications of a Proximity Sensor

The Classifications of a Proximity Sensor are:

- ✓ Inductive Sensor
- ✓ Capacitive Sensor
- ✓ Ultrasonic Sensor
- ✓ Magnetic Sensor

4.13.2. Proximity Sensing

- ✓ The range sensors discussed in the previous section yield an estimate of the distance between a sensor and a reflecting object.
- ✓ Proximity sensors, on the other hand, generally have a binary output which indicates the presence of an object within a specified distance interval.
- ✓ Proximity sensors are used in robotics for near-field work in connection with object grasping or avoidance. In this section we consider several fundamental approaches to proximity sensing and discuss the basic operational characteristics of these sensors.

Inductive Proximity sensors

- ✓ Sensors based on a change of inductance due to the presence of a metallic object are among the most widely used industrial proximity sensors.
- ✓ The principle of operation of these sensors can be explained with the aid of Figs.4.17 and 4.18. Figure 4.17 shows a schematic diagram of an inductive sensor which basically consists of a wound coil located next to a permanent magnet packaged in a simple, rugged housing.
- ✓ The effect of bringing the sensor in close proximity to a ferromagnetic material causes a change in the position of the flux lines of the permanent magnet, as shown in Fig.4.17(*b*) and (*c*).

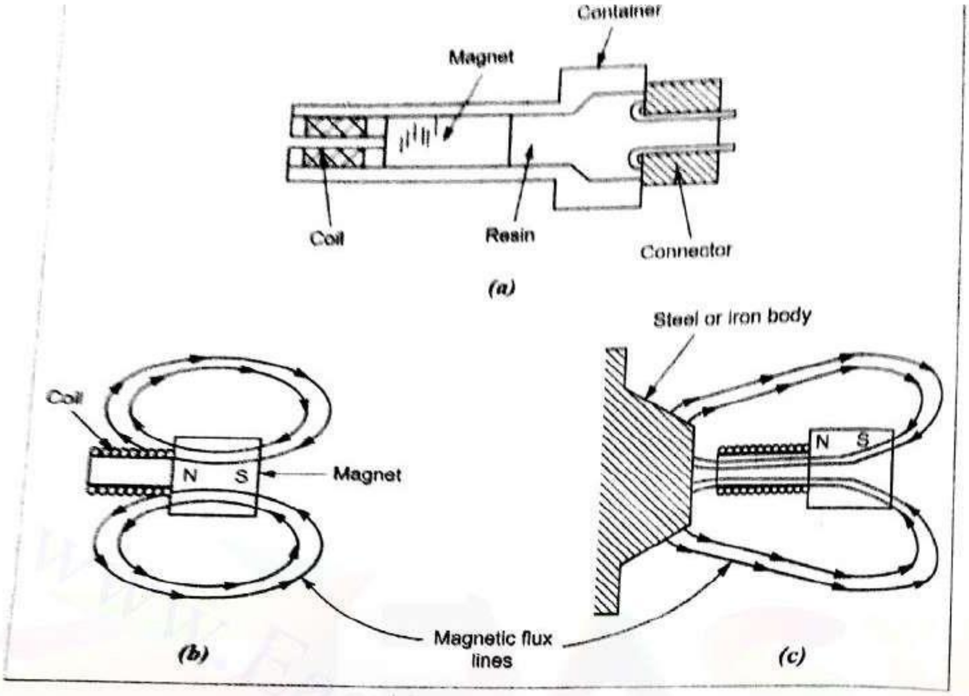
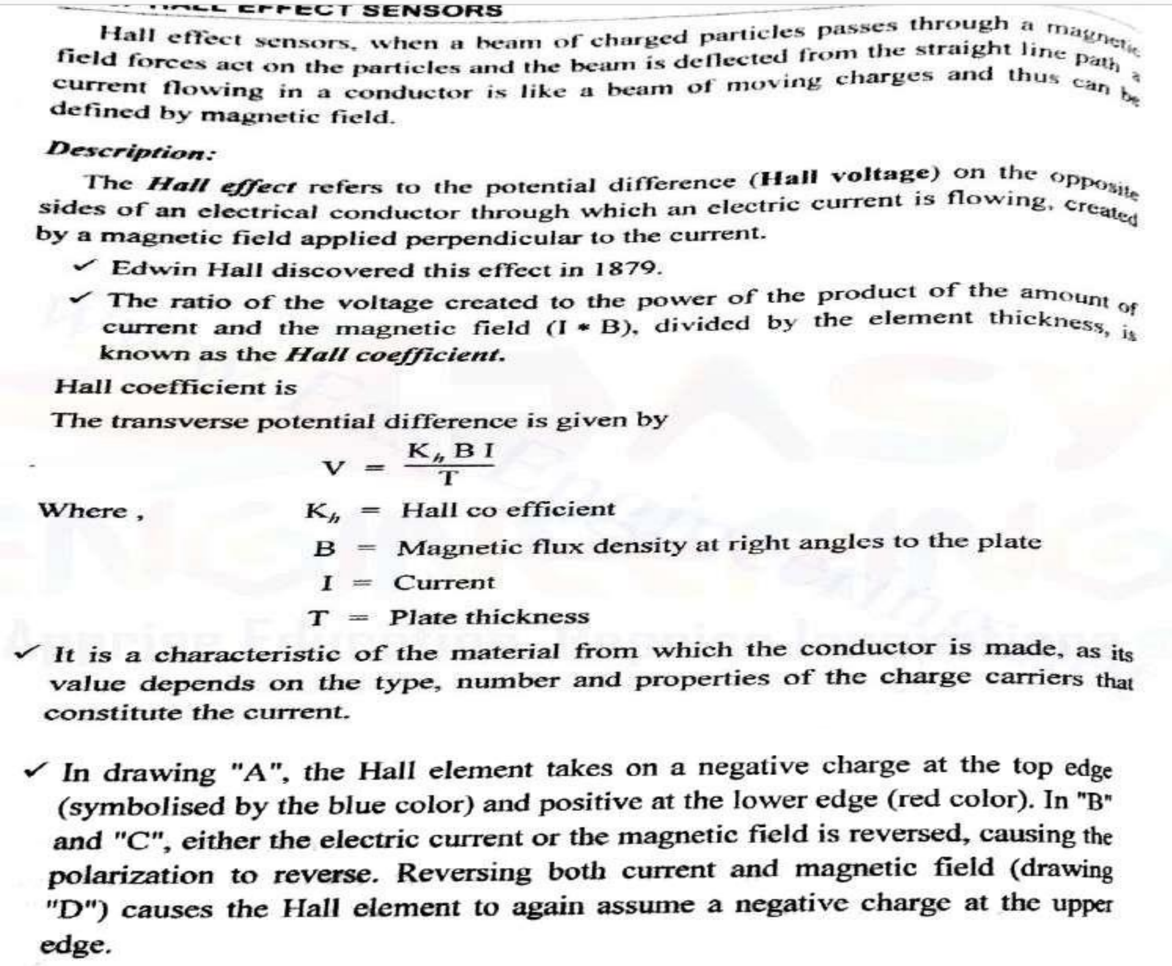


Fig. 4.17. (a) An inductive sensor
(b) Shape of flux lines in the absence of a ferromagnetic body
(c) Shape of flux lines when a ferromagnetic body is brought close to the sensor

- ✓ Under static conditions there is no movement of the flux lines and, therefore, no current is induced in the coil. However, as a ferromagnetic object enters or leaves the field of the magnet, the resulting change in the flux lines induces a current pulse whose amplitude and shape are proportional to the rate of change in the flux.

Hall effect sensor



HALL EFFECT SENSORS

Hall effect sensors, when a beam of charged particles passes through a magnetic field forces act on the particles and the beam is deflected from the straight line path, a current flowing in a conductor is like a beam of moving charges and thus can be defined by magnetic field.

Description:

The ***Hall effect*** refers to the potential difference (**Hall voltage**) on the opposite sides of an electrical conductor through which an electric current is flowing, created by a magnetic field applied perpendicular to the current.

- ✓ Edwin Hall discovered this effect in 1879.
- ✓ The ratio of the voltage created to the power of the product of the amount of current and the magnetic field (I * B), divided by the element thickness, is known as the ***Hall coefficient.***

Hall coefficient is

The transverse potential difference is given by

$$V = \frac{K_h B I}{T}$$

Where , K_h = Hall co efficient

B = Magnetic flux density at right angles to the plate

I = Current

T = Plate thickness

- ✓ *It is a characteristic of the material from which the conductor is made, as its value depends on the type, number and properties of the charge carriers that constitute the current.*

- ✓ In drawing "A", the Hall element takes on a negative charge at the top edge (symbolised by the blue color) and positive at the lower edge (red color). In "B" and "C", either the electric current or the magnetic field is reversed, causing the polarization to reverse. Reversing both current and magnetic field (drawing "D") causes the Hall element to again assume a negative charge at the upper edge.

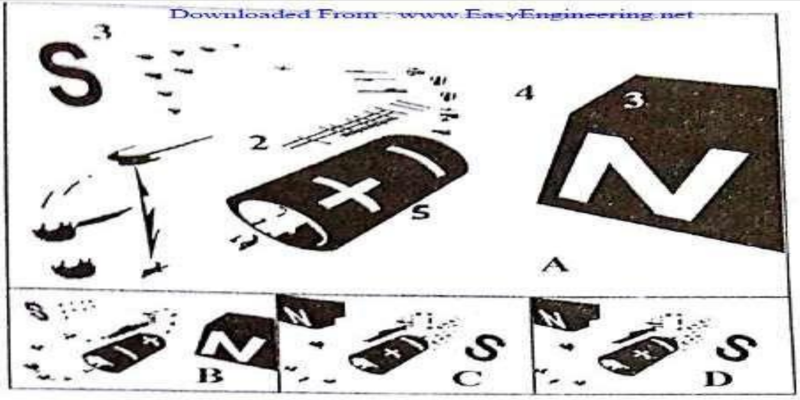
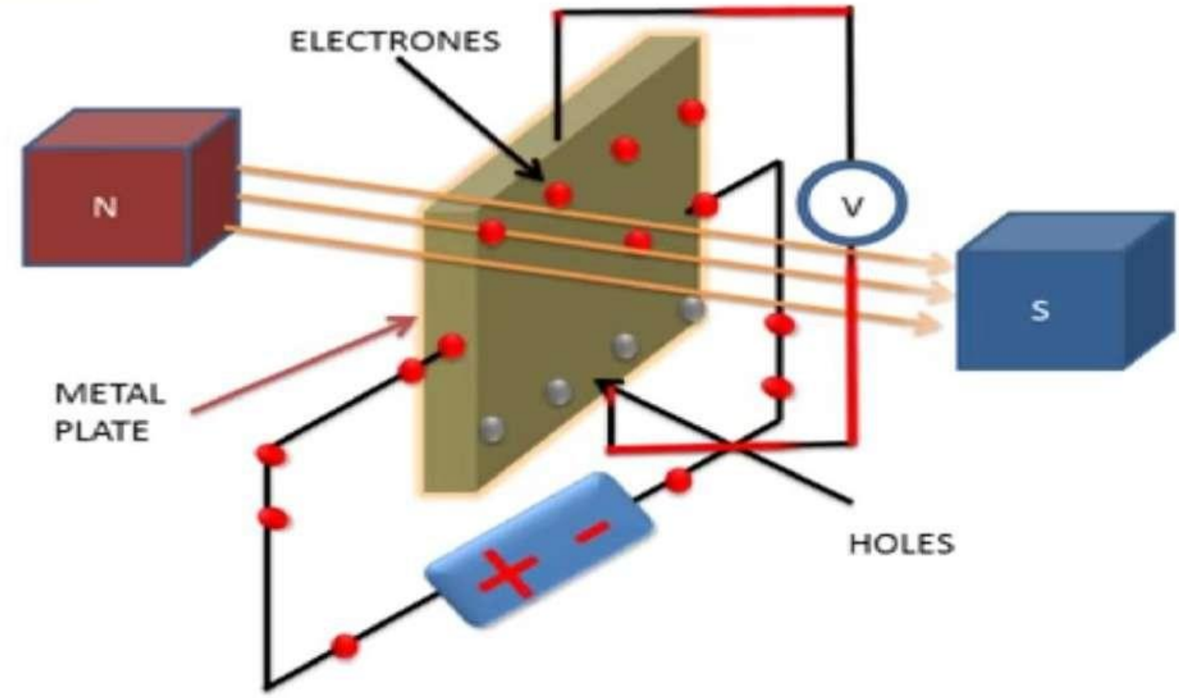


Fig. 4.19. Hall effect sensors

Hall effect diagram, showing electron flow.

- ✓ Electrons (not conventional current!)
- ✓ Hall element, or Hall sensor
- ✓ Magnets
- ✓ Magnetic field
- ✓ Power source



Principle:

✓ The Hall effect comes about due to the nature of the current flow in a conductor.

✓ Current consists of the movement of many small charge-carrying "particles" (typically, but not necessarily, electrons). Moving charges experience a force, called the Lorentz Force, when a magnetic field is present that is not parallel to their motion.

✓ When such a magnetic field is absent, the charges follow an approximately straight, 'line of sight' path. However, when a perpendicular magnetic field is applied, their path is curved so that moving charges accumulate on one face of the material.

- ✓ This leaves equal and opposite charges exposed on the other face, where there is a scarcity of mobile charges.
- ✓ The result is an asymmetric distribution of charge density across the hall element that is perpendicular to both the 'line of sight' path and the applied magnetic field.
- ✓ The separation of charge establishes an electric field that opposes the migration of further charge, so a steady electrical potential builds up for as long as the current is flowing.

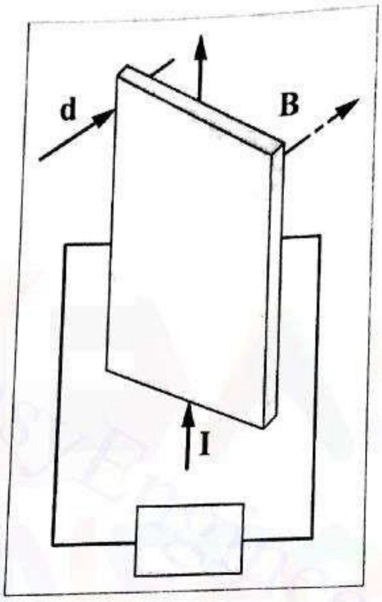


Fig. 4.20.

- ✓ For a simple metal where there is only one type of charge carrier (electrons) the Hall voltage V_H is given by

$$V_H = \frac{-IB/d}{ne}$$

✓ The Hall coefficient is defined as

$$R_H = \frac{E_y}{j_x B} = \frac{V_H}{I B/d} = -\frac{1}{n e}$$

where I is the current across the plate length, *B* is the magnetic flux density, *d* is the depth of the plate, *e* is the electron charge, and *n* is the charge carrier density of the carrier electrons.

✓ As a result, the Hall effect is very useful as a means to measure both the carrier density and the magnetic field.

✓ One very important feature of the Hall effect is that it differentiates between positive charges moving in one direction and negative charges moving in the opposite. The Hall effect offered the first real proof that electric currents in metals are carried by moving electrons, not by protons. The Hall effect also showed that in some substances (especially semiconductors), it is more appropriate to think of the current as positive "holes" moving rather than negative electrons.

Uses

✓ Hall probes are often used to measure magnetic fields, or inspect materials (such as tubing or pipelines) using the principles of Magnetic flux leakage.

✓ Hall effect sensors can detect stray magnetic fields easily, including that of earth, so they work well as electronic compasses

Advantages

✓ Hall effect devices when appropriately packaged are immune to dust, dirt, mud, and water. These characteristics make Hall effect devices better for position sensing than alternative means such as optical and electromechanical sensing.

✓ Hall effect current sensor with internal integrated circuit amplifier.

✓ Non-zero current response is proportional to the voltage supplied and is linear to 60 amperes for this particular (25 A) device.

✓ No additional resistance (a *shunt*, required for the most common current sensing method) need be inserted in the primary circuit.

✓ Also, the voltage present on the line to be sensed is not transmitted to the sensor, which enhances the safety of measuring equipment.

Touch Sensors

4.18. TOUCH SENSOR

Touch sensor is sensor, which senses the presence or absence of the object by having physical contact between the objects.

- ✓ Works like a light switch in our house. When the button is pressed, an electrical circuit is closed inside the sensor. This lets electricity flow.
- ✓ When the button is released, the circuit is broken and no electricity flows.
- ✓ The RCX can sense this flow of electricity, so it knows if the touch sensor if pressed or released.
- ✓ Touch sensors send a signal when physical contact is made.
- ✓ Micro switch is the simplest touch sensor which either turns on or off as contact is made.
- ✓ A force sensor used as a touch sensor may not only send touch information but also report the magnitude of touching forces.

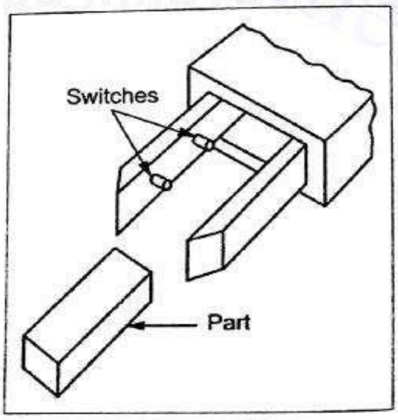


Fig. 4.25. Touch sensors

- ✓ Touch sensors are used in robotics to obtain information associated with the contact between a manipulator hand and objects in the workspace.
- ✓ Touch information can be used, for example, for object location and recognition, as well as to control the force exerted by a manipulator on a given object.
- ✓ Touch sensors can be subdivided into two principal categories:
  - (1) Binary sensors
  - (2) Analog sensors
- ✓ Binary sensors are basically switches which respond to the presence or absence of an object.
- ✓ Analog sensors, on the other hand, output a signal proportional to a local force.

4.19. BINARY SENSORS

- ✓ Binary touch sensors are contact devices, such as micro-switches.
- ✓ In the simplest arrangement, a switch is placed on the inner surface of each finger of a manipulator hand, as illustrated in Fig.4.26.

- ✓ This type of sensing is useful for determining if a part is present between the fingers.
- ✓ By moving the hand over an object and sequentially making contact with its surface, it is also possible to center the hand over the object for grasping and manipulation.
- ✓ Multiple binary touch sensors can be used on the inside surface of each finger to provide further tactile information.
- ✓ In addition, they are often mounted on the external surfaces of a manipulator hand to provide control signals useful for guiding the hand throughout the work space.
- ✓ This latter use of touch sensing is analogous to what humans do in feeling their way in a totally dark room.

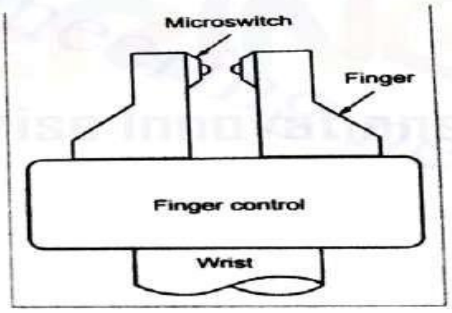


Fig. 4.26. Binary Sensors – A simple robot had equipped with binary touch sensors

4.20. ANALOG SENSORS

- ✓ An analog touch sensor is a compliant device whose output is proportional to a local force.
- ✓ The simplest of these devices consists of a spring-loaded rod (Fig.4.27) which is mechanically linked to a rotating shaft in such a way that the displacement of the rod due to a lateral force results in a proportional rotation of the shaft.
- ✓ The rotation is then measured continuously using a potentiometer or digitally using a code wheel. Knowledge of the spring constant yields the force corresponding to a given displacement.
- ✓ During the past few years, considerable effort has been devoted to the development of tactile sensing arrays capable of yielding touch information over a wider area than that afforded by a single sensor.
- ✓ The use of these devices is illustrated in Fig.4.28, which shows a robot hand in which the inner surface of each finger has been covered with a tactile sensing array.
- ✓ The external sensing plates are typically binary devices and have the function described at the end of Sec.

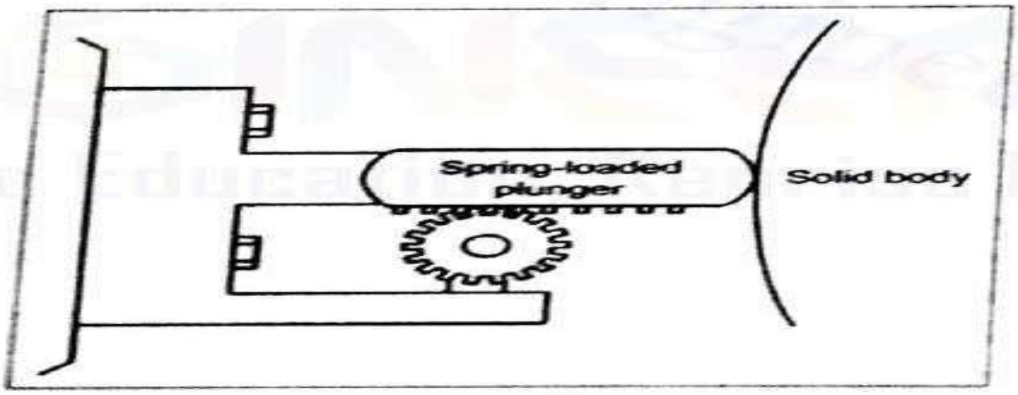


Fig. 4.27.

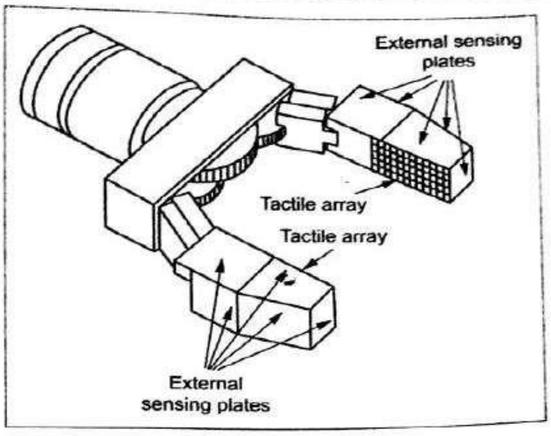
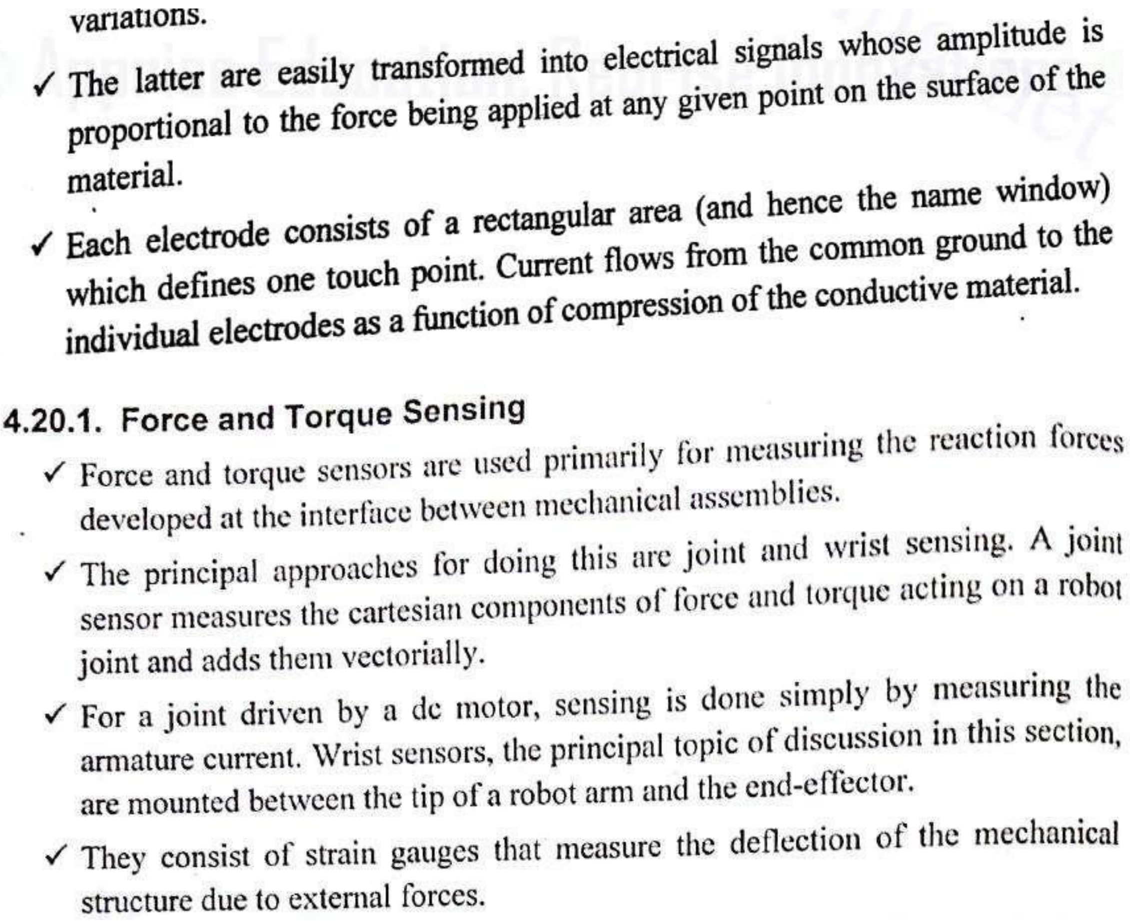


Fig. 4.28. A basic analog touch sensor robot hand equipped with tactile sensing arrays

✓ Although sensing arrays can be formed by using multiple individual sensors, one of the most promising approaches to this problem consists of utilizing an array of electrodes in electrical contact with a compliant conductive material (e.g., graphite-based substances) whose resistance varies as a function of compression.

✓ In these devices, often called artificial skins, an object pressing against the surface causes local deformations which are measured as continuous resistance variations.



variations.

- ✓ The latter are easily transformed into electrical signals whose amplitude is proportional to the force being applied at any given point on the surface of the material.
- ✓ Each electrode consists of a rectangular area (and hence the name window) which defines one touch point. Current flows from the common ground to the individual electrodes as a function of compression of the conductive material.

4.20.1. Force and Torque Sensing

- ✓ Force and torque sensors are used primarily for measuring the reaction forces developed at the interface between mechanical assemblies.
- ✓ The principal approaches for doing this are joint and wrist sensing. A joint sensor measures the cartesian components of force and torque acting on a robot joint and adds them vectorially.
- ✓ For a joint driven by a dc motor, sensing is done simply by measuring the armature current. Wrist sensors, the principal topic of discussion in this section, are mounted between the tip of a robot arm and the end-effector.
- ✓ They consist of strain gauges that measure the deflection of the mechanical structure due to external forces.

Industrial robot Applications:

The general characteristics of industrial work situations that tend to promote the substitution of robots for human labor are the following:

1. **Hazardous work environment for humans**.

When the work environment is unsafe, unhealthful, hazardous, uncomfortable, or otherwise unpleasant for humans, there is reason to consider an industrial robot for the work. In addition to die casting, there are many other work situations that are hazardous or unpleasant for humans, including forging, spray painting, continuous arc welding, and spot welding. Industrial robots are utilized in all of these processes.

2. **Repetitive work cycle**.

A second characteristic that tends to promote the use of robotics is a repetitive work cycle. If the sequence of elements in the cycle is the same, and the elements consist of relatively simple motions. a robot is usually capable of performing the work cycle with greater consistency and repeatability than a human worker Greater consistency and repeatability are usually manifested as higher product quality than can he achieved in a manual operation.

3. **Difficult handing for humans**.

If the task involves the handling of parts or tools that are heavy or otherwise difficult to manipulate, it is likely that an industrial robot is available that can perform the operation. Parts or tools that are too heavy for humans to handle conveniently arc well within the load carrying capacity of a large robot

4. Multi-shift operation.

In manual operations requiring second and third shifts, substitution of a robot will provide a much faster financial payback than a single shift operation. Instead of replacing one worker, the robot replaces two or three workers.

5. Infrequent changeovers:

Most batch or job shop operations require a changeover of the physical workplace between one job and the next. The time required to make the changeover is non-productive time since parts are not being made. In an industrial robot application, not only must the physical setup be changed, but the robot must also be reprogrammed, thus adding to the downtime. Consequently, robots have traditionally been easier to justify for relatively long production runs where changeovers are infrequent. As procedures for off-line robot programming improve, it will be possible to reduce the time required to perform the reprogramming procedure. This will permit shorter production runs to become more economical.

6. Part position and orientation art' established in the work cell.

Most robots in today's industrial applications are without vision capability. Their capacity to pick up an object during each work cycle relies on the fact that the part is in a known position and orientation. A means of presenting the part to the robot at the same location each cycle must be engineered.

Applications of robots in Manufacturing:

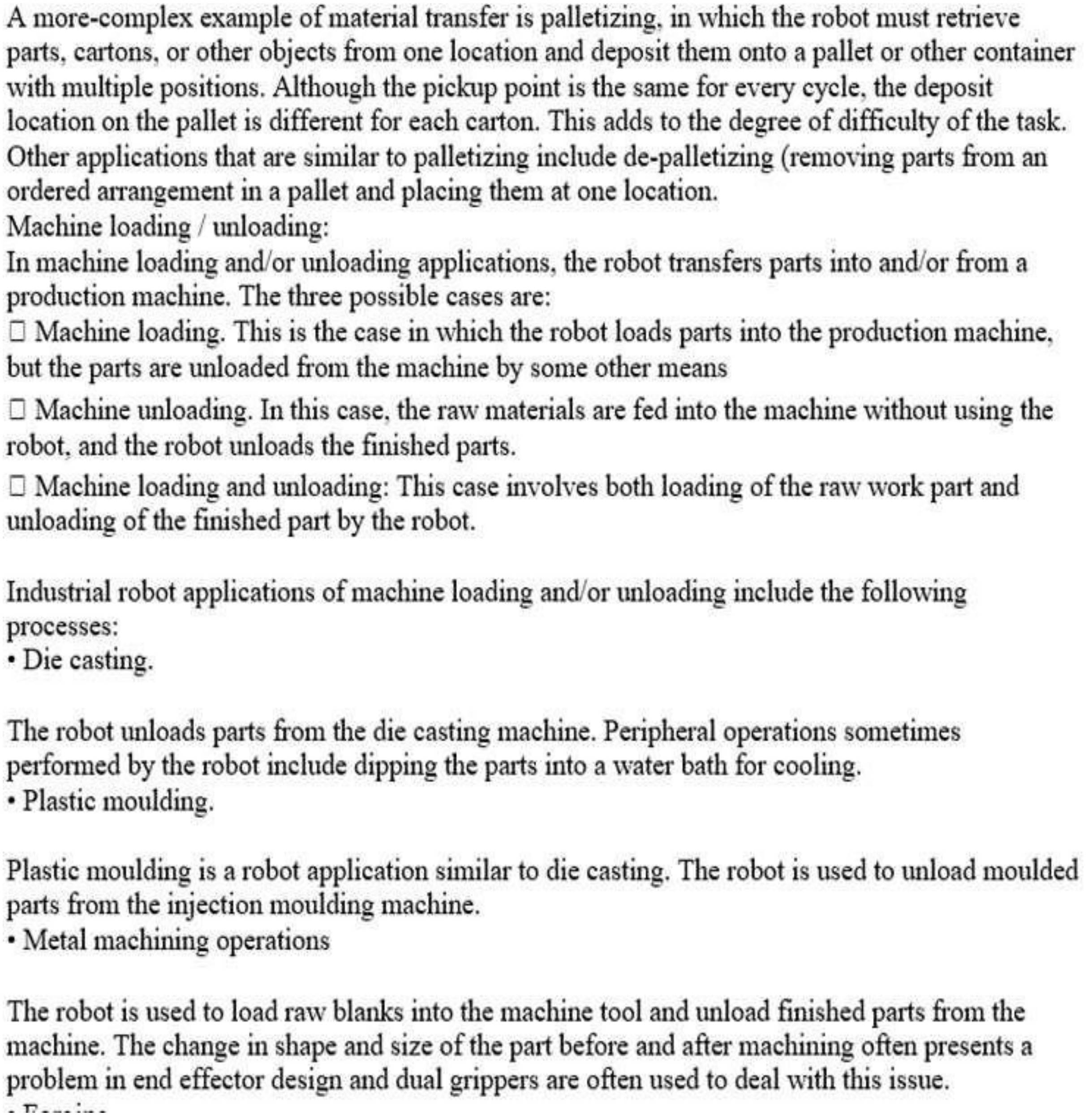
Most of the current applications of industrial robots are in manufacturing. The applications can usually be classified into one of the following categories: (1) material handling, (2) processing operations, and (3) assembly and inspection.

Material handling applications:

Material handling applications are those in which the robot moves materials or parts from one place to another. To accomplish the transfer, the robot is equipped with a gripper type end effector. The gripper must be designed to handle the specific part or parts that are to be moved in the application.

Material transfer:

The primary purpose of the robot is to pick up parts at one location and place them at a new location. In many cases, re-orientation of the part must be accomplished during the relocation. The basic



A more-complex example of material transfer is palletizing, in which the robot must retrieve parts, cartons, or other objects from one location and deposit them onto a pallet or other container with multiple positions. Although the pickup point is the same for every cycle, the deposit location on the pallet is different for each carton. This adds to the degree of difficulty of the task. Other applications that are similar to palletizing include de-palletizing (removing parts from an ordered arrangement in a pallet and placing them at one location.

Machine loading / unloading:

In machine loading and/or unloading applications, the robot transfers parts into and/or from a production machine. The three possible cases are:

☐ Machine loading. This is the case in which the robot loads parts into the production machine, but the parts are unloaded from the machine by some other means

☐ Machine unloading. In this case, the raw materials are fed into the machine without using the robot, and the robot unloads the finished parts.

☐ Machine loading and unloading: This case involves both loading of the raw work part and unloading of the finished part by the robot.

Industrial robot applications of machine loading and/or unloading include the following processes:

- Die casting.

The robot unloads parts from the die casting machine. Peripheral operations sometimes performed by the robot include dipping the parts into a water bath for cooling.

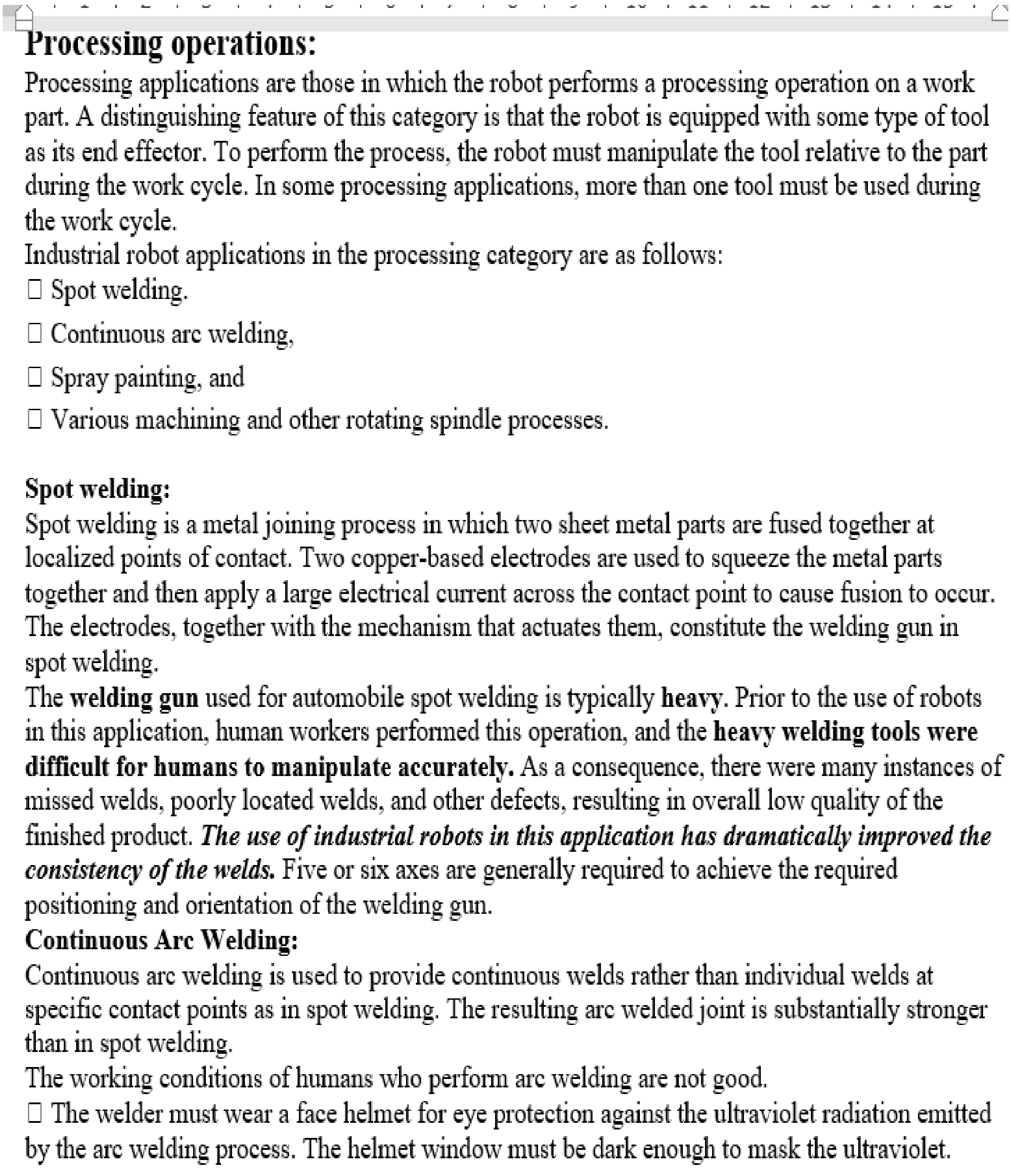
- Plastic moulding.

Plastic moulding is a robot application similar to die casting. The robot is used to unload moulded parts from the injection moulding machine.

- Metal machining operations

The robot is used to load raw blanks into the machine tool and unload finished parts from the machine. The change in shape and size of the part before and after machining often presents a problem in end effector design and dual grippers are often used to deal with this issue.

- Forging



Processing operations:

Processing applications are those in which the robot performs a processing operation on a work part. A distinguishing feature of this category is that the robot is equipped with some type of tool as its end effector. To perform the process, the robot must manipulate the tool relative to the part during the work cycle. In some processing applications, more than one tool must be used during the work cycle.

Industrial robot applications in the processing category are as follows:

- Spot welding.
- Continuous arc welding,
- Spray painting, and
- Various machining and other rotating spindle processes.

Spot welding:

Spot welding is a metal joining process in which two sheet metal parts are fused together at localized points of contact. Two copper-based electrodes are used to squeeze the metal parts together and then apply a large electrical current across the contact point to cause fusion to occur. The electrodes, together with the mechanism that actuates them, constitute the welding gun in spot welding.

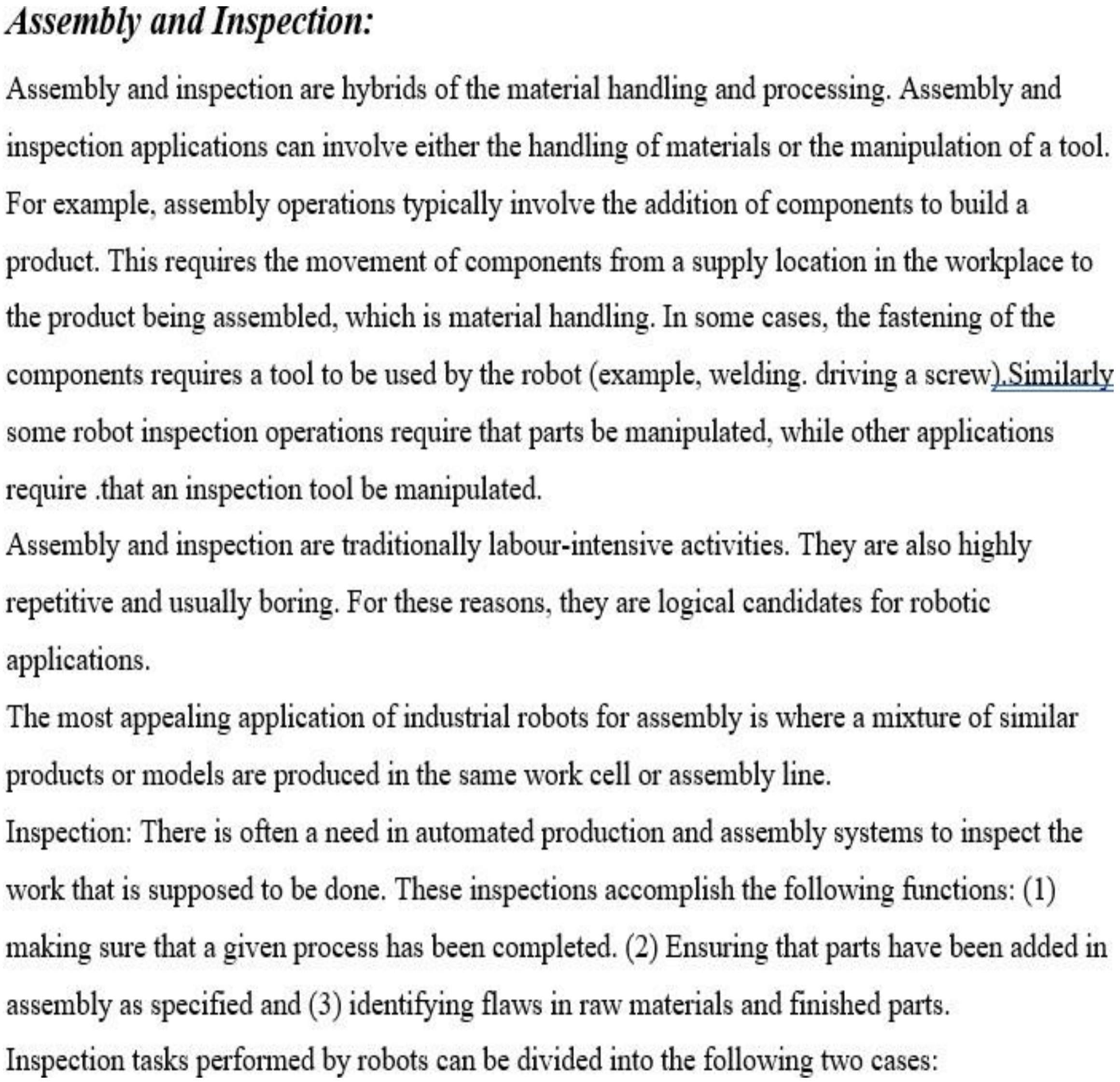
The **welding gun** used for automobile spot welding is typically **heavy**. Prior to the use of robots in this application, human workers performed this operation, and the **heavy welding tools were difficult for humans to manipulate accurately.** As a consequence, there were many instances of missed welds, poorly located welds, and other defects, resulting in overall low quality of the finished product. ***The use of industrial robots in this application has dramatically improved the consistency of the welds.*** Five or six axes are generally required to achieve the required positioning and orientation of the welding gun.

Continuous Arc Welding:

Continuous arc welding is used to provide continuous welds rather than individual welds at specific contact points as in spot welding. The resulting arc welded joint is substantially stronger than in spot welding.

The working conditions of humans who perform arc welding are not good.

- The welder must wear a face helmet for eye protection against the ultraviolet radiation emitted by the arc welding process. The helmet window must be dark enough to mask the ultraviolet.



Assembly and Inspection:

Assembly and inspection are hybrids of the material handling and processing. Assembly and inspection applications can involve either the handling of materials or the manipulation of a tool. For example, assembly operations typically involve the addition of components to build a product. This requires the movement of components from a supply location in the workplace to the product being assembled, which is material handling. In some cases, the fastening of the components requires a tool to be used by the robot (example, welding. driving a screw).Similarly some robot inspection operations require that parts be manipulated, while other applications require .that an inspection tool be manipulated.

Assembly and inspection are traditionally labour-intensive activities. They are also highly repetitive and usually boring. For these reasons, they are logical candidates for robotic applications.

The most appealing application of industrial robots for assembly is where a mixture of similar products or models are produced in the same work cell or assembly line.

Inspection: There is often a need in automated production and assembly systems to inspect the work that is supposed to be done. These inspections accomplish the following functions: (1) making sure that a given process has been completed. (2) Ensuring that parts have been added in assembly as specified and (3) identifying flaws in raw materials and finished parts.

Inspection tasks performed by robots can be divided into the following two cases:

Online –methods:

Lead through Programming: In lead through programming, the task is taught to the robot by moving the manipulator through the required motion cycle, simultaneously entering the program into the controller memory for subsequent playback.

Teach pendant Programming:

The Teach Pendant is a hand-held robot control terminal that provides a convenient means to move the robot, teach locations, and run robot programs. It features a four-line 20-character LCD display, a 45-key keypad, a live-man switch, and an emergency stop (e-stop) button. The teach pendant is a useful tool, allowing you to move away from the host computer terminal and control the robot locally. Typically, a robot application is programmed with teachable variables using the RAPL programming language. Once the application is setup, it is convenient to use the teach pendant to teach the locations for the application.

Off-line Method:

VAL Programming for PUMA

Task: Pick and place operation

VAL program

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

Other VAL commands

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

ALL THE BEST