

DIGITAL NOTES

ROBOTICS

R15A0338

B.Tech – IV Year – I Semester

DEPARTMENT OF MECHANICAL ENGINEERING



MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY

(An Autonomous Institution – UGC, Govt.of India)

Recognizes under 2(f) and 12(B) of UGC ACT 1956

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Certified)

ROBOTICS

MALLAREDDY COLLEGE OF ENGINEERING AND TECHNOLOGY

IV Year B. Tech MECH-I Sem

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(R15A0338) ROBOTICS (CORE ELECTIVE-IV)

Objectives:

- The objective of this subject is to provide knowledge of automation of Industries.
- To know about design of robot arm, kinematics and dynamics.
- To know about Trajectory planning of robot and its applications.

UNIT – II

Introduction: Automation and Robotics, CAD/CAM and Robotics – An over view of Robotics present and future applications – classification by coordinate system and control system.

Components of the Industrial Robotics: Function line diagram representation of robot arms, common types of arms. Components, Architecture, number of degrees of freedom – Requirements and challenges of end effectors, determination of the end effectors, comparison of Electric, Hydraulic and Pneumatic types of locomotion devices.

UNIT – II

Motion Analysis: Homogeneous transformations as applicable to rotation and translation – problems.

Manipulator Kinematics: Specifications of matrices, D-H notation joint coordinates and world coordinates **Forward kinematics** – problems.

UNIT – III

Differential transformation and manipulators : Jacobians – problems. Dynamics: Lagrange – Euler and Newton – Euler formations – Problems.

Trajectory planning and avoidance of obstacles, path planning, Skew motion, joint integrated motion – straight line motion – Robot programming, languages and software packages.

UNIT – IV

Robot actuators and Feedback components: Actuators: Pneumatic, Hydraulic actuators, electric & stepper motors. Feedback components: position sensors – potentiometers, resolvers, encoders – Velocity sensors.

UNIT-V

Robot Application in Manufacturing: Material Transfer - Material handling, loading and unloading- `Processing - spot and continuous arc welding & spray painting - Assembly and Inspection.

TEXT BOOKS:

1. Industrial Robotics / Groover M P /Pearson Edu.
2. Robotics and Control / Mittal R K & Nagrath I J / TMH.
3. Robotic Engineering / Richard D. Klafter, Prentice Hall

REFERENCE BOOKS:

1. Robotics / S.K.Fu / McGraw Hill.
2. An Introduction to Robot Technology, / P. Coiffet and M. Chaironze / Kogam Page Ltd. 1983 London.
3. Introduction to Robotics / John J Craig / Pearson Edu.

OUTCOMES:

After Completion of this course students will be able to

- Classify robots based on joints and arm configurations.
- Design application specific End Effectors for robots.
- Compute forward and inverse kinematics of robots and determine trajectory plan.

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II	Motion Analysis & Manipulator Kinematics	15 - 23
III	Differential transformation and manipulators	24 - 52
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V	Robot Application in Manufacturing	56 - 71

COURSE COVERAGE UNIT WISE

UNIT I

S.NO	TOPIC NAME	NAME OF THE TEXT BOOK	AUTHOR NAME	PAGE NUMBER
1	Automation and Robotics, Anatomy, DOF	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	8
2	classification by coordinate system and control system	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	13 - 17
3	Requirements and challenges of end effectors	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	18 - 20
4	Electric, Hydraulic and Pneumatic types of locomotion devices	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	297

UNIT II

S.NO	TOPIC NAME	NAME OF THE TEXT BOOK	AUTHOR NAME	PAGE NUMBER
1	Homogeneous transformation	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	48
2	rotation and translation – problems	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	49 - 56
3	D-H notation joint coordinates and world coordinates	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	72 -75
4	Forward kinematics & problems	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	78 - 80

UNIT III

S.NO	TOPIC NAME	NAME OF THE TEXT BOOK	AUTHOR NAME	PAGE NUMBER
1	Jacobians – problems	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	159 - 167
2	Lagrange – Euler and Newton – Euler formations	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	191 - 210
3	Trajectory planning	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	246 - 266
4	Robot programming, languages and software packages	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	25

UNIT IV

S.NO	TOPIC NAME	NAME OF THE TEXT BOOK	AUTHOR NAME	PAGE NUMBER
1	Actuators	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	297
2	position sensors	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	338
3	potentiometers	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	342
4	resolvers, encoders	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	348

UNIT V

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1	Material Transfer - Material handling	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	389 - 397
2	loading and unloading	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	389 - 397
3	Processing - spot and continuous arc welding & spray painting	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	389 - 397
4	Assembly and Inspection	ROBOTICS & CONTROL	R K MITTAL & I J NAGRATH	398 - 403

UNIT-I

INTRODUCTION

The field of robotics has its origins in science fiction. The term robot was derived from the English translation of a fantasy play written in Czechoslovakia around 1920. It took another 40 years before the modern technology of industrial robotics began. Today Robots are highly automated mechanical manipulators controlled by computers. We survey some of the science fiction stories about robots, and we trace the historical development of robotics technology. Let us begin our chapter by defining the term robotics and establishing its place in relation to other types of industrial automation.

Robotics: -

Robotics is an applied engineering science that has been referred to as a combination of machine tool technology and computer science. It includes machine design, production theory, micro electronics, computer programming & artificial intelligence.

OR

"Robotics" is defined as the science of designing and building Robots which are suitable for real life application in automated manufacturing and other non-manufacturing environments.

Industrial robot: -

The official definition of an industrial robot is provided by the robotics industries association (RIA). Industrial robot is defined as an automatic, freely programmed, servo-controlled, multi-purpose manipulator to handle various operations of an industry with variable programmed motions.

Automation and robotics:-

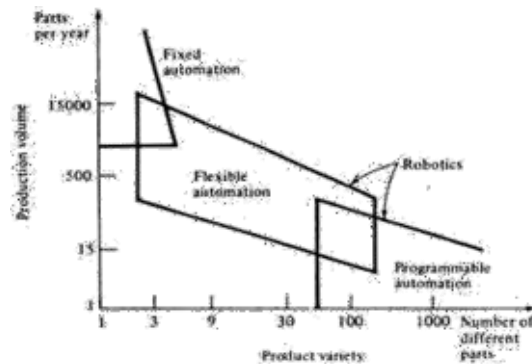
Automation and robotics are two closely related technologies. In an industrial context, we can define automation as a technology that is concerned with the use of mechanical, electronic, and computer-based systems in the operation and control of production. Examples of this technology include transfer lines, mechanized assembly machines, feedback control systems (applied to industrial processes), numerically controlled machine tools, and robots. Accordingly, robotics is a form of industrial automation.

Ex:- Robotics, CAD/CAM, FMS, CIMS

Types of Automation:-

Automation is categorized into three types. They are,

- 1) Fixed Automation
- 2) Programmable Automation
- 3) Flexible Automation.



Relationship of fixed automation, programmable automation, and flexible automation as a function of production volume and product variety.

(1) Fixed Automation:-

It is the automation in which the sequence of processing or assembly operations to be carried out is fixed by the equipment configuration. In fixed automation, the sequence of operations (which are simple) are integrated in a piece of equipment. Therefore, it is difficult to automate changes in the design of the product. It is used where high volume of production is required. Production rate of fixed automation is high. In this automation, no new products are processed for a given sequence of assembly operations.

Features:-

- i) High volume of production rates,
- ii) Relatively inflexible in product variety (no new products are produced). Ex:- Automobile industries ... etc.

(2) Programmable Automation:-

It is the automation in which the equipment is designed to accommodate various product configurations in order to change the sequence of operations or assembly operations by means of control program. Different types of programs can be loaded into the equipment to produce products with new configurations (i.e., new products). It is employed for batch production of low and medium volumes. For each new batch of different configured product, a new control program corresponding to the new product is loaded into the equipment. This automation is relatively economic for small batches of the product.

Features:-

- i) High investment in general purpose,
- ii) Lower production rates than fixed automation,
- iii) Flexibility & Changes in products configuration,
- iv) More suitable for batch production.

Ex:- Industrial robot, NC machines tools... etc.

(3) Flexible Automation:-

A computer integrated manufacturing system which is an extension of programmable automation is referred as flexible automation. It is developed to minimize the time loss between the changeover of the batch production from one product to another while reloading. The program to produce new products and changing the physical setup i.e., it produces different products with no loss of time. This automation is more flexible in interconnecting work stations with material handling and storage system.

Features:-

- i) High investment for a custom engineering system.
- ii) Medium Production rates
- iii) Flexibility to deal with product design variation,
- iv) Continuous production of variable mixtures of products. Ex:- Flexible manufacturing systems (FMS)

Advantages:-

1. High Production rates
2. Lead time decreases
3. Storing capacity decreases
4. Human errors are eliminated.
5. Labour cost is decreases.

Disadvantages:-

1. Initial cost of raw material is very high,
2. Maintenance cost is high,
3. Required high skilled Labour.
4. Indirect cost for research development & programming increases.

Reasons for implementation of automated systems in manufacture industries:-

The reasons for the implementation of automated systems in manufacturing industries are as follows,

- (i) To Increase the Productivity Rate of Labour
- (ii) To Decrease the Cost of Labour
- (iii) To Minimize the Effect of Shortage of Labour
- (iv) To Obtain High Quality of Products
- (v) A Non-automation nigh Cost is Avoided
- (vi) To Decrease the Manufacturing Lead Time
- (vii) To upgrade the Safety of Workers.

Need for using robotics in industries:-

Industrial robot plays a significant role in automated manufacturing to perform different kinds of applications.

1. Robots can be built a performance capability superior to those of human beings. In terms of strength, size, speed, accuracy...etc.
2. Robots are better than humans to perform simple and repetitive tasks with better quality and consistence's.
3. Robots do not have the limitations and negative attributes of human works .such as fatigue, need for rest, and diversion of attention.....etc.
4. Robots are used in industries to save the time compared to human beings.
5. Robots are in value poor working conditions
6. Improved working conditions and reduced risks.

CAD/CAM & Robotics:-

CAD/CAM is a term which means computer aided design and computer aided manufacturing. It is the technology concerned with the use of digital computers to perform certain functions in design & production.

CAD:- CAD can be defined as the use of computer systems to assist in the creation modification, analysis OR optimization of design.

Cam:- CAM can be defined as the use of computer system to plan, manage & control the operation of a manufacturing plant, through either direct or in direct computer interface with the plant's production resources.

Specifications of robotics:-

1. Axil of motion
2. Work stations
3. Speed
4. Acceleration
5. Pay load capacity
6. Accuracy
7. Repeatability etc...

Overview of Robotics:-

"Robotics" is defined as the science of designing and building Robots which are suitable for real life application in automated manufacturing and other non-manufacturing environments. It has the following objectives,

1. To increase productivity
2. Reduce production life
3. Minimize labour requirement
4. Enhanced quality of the products
5. Minimize loss of man hours, on account of accidents.

6. Make reliable and high speed production.

The robots are classified as,
Programmable/Reprogrammable purpose

robots

*Tele-operated, Man controlled robots

*Intelligent robots.

Robots are used in manufacturing and assembly units
such as,

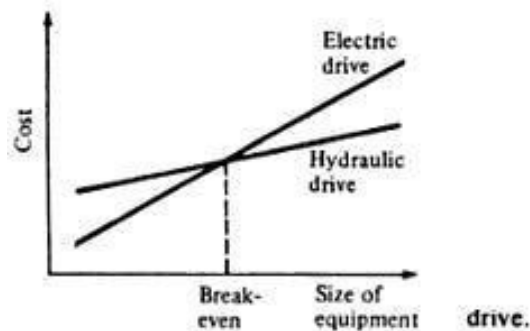
1. Spot or arc welding
2. Parts assembly
3. Paint spraying
4. Material, handling
5. Loading and unloading

The feature and capabilities of the robots are as follows,

1. Intelligence
2. Sensor capabilities
3. Telepresence
4. Mechanical design
5. Mobility and navigation
6. Universal gripper
7. System integration and networking.

Types of drive systems:-

1. Hydraulic drive
2. Electric drive
3. Pneumatic drive

**1. Hydraulic drive:-**

Hydraulic drive and electric drive are the two main types of drives used on more sophisticated robots.

Hydraulic drive is generally associated with larger robots, such as the Unimate 2000 series. The usual advantages of the hydraulic drive system are that it provides the robot with greater speed and strength. The disadvantages of the hydraulic drive system are that it typically adds to the floor space required by the robot, and that a hydraulic system is inclined to leak on which is a nuisance.

This type of system can also be called as non-air powered cylinders. In this system, oil is used as a working fluid instead of compressed air. Hydraulic system need pump to generate the required pressure and flow rate. These systems are quite complex, costly and require maintenance.

2. Electric drive:-

Electric drive systems do not generally provide as much speed or power as hydraulic systems. However, the accuracy and repeatability of electric drive robots are usually better. Consequently, electric robots tend to be smaller. Require less floor space, and their applications tend toward more precise work such as assembly.

In this System, power is developed by an electric current. It required little maintenance and the operation is noise less.

3. Pneumatic drive:-

Pneumatic drive is generally reserved for smaller robots that possess fewer degrees of freedom (two- to four-joint motions).

In this system, air is used as a working fluid, hence it is also called air-powered cylinders. Air is compressed in the cylinder with the aid of pump the compressed air is used to generate the power with required amount of pressure and flow rates.

Applications of robots:-

Present Applications of Robots:-

- (i) Material transfer applications
- (ii) Machine loading and unloading
- (iii) Processing operations like,
 - (a) Spot welding
 - (b) Continuous arc welding
 - (c) Spray coating
 - (d) Drilling, routing, machining operations
 - (e) Grinding, polishing debarring wire brushing
 - (g) Laser drilling and cutting etc.
- (iv) Assembly tasks, assembly cell designs, parts mating.
- (v) Inspection, automation.

Future Applications of Robots:-

The profile of the future robot based on the research activities will include the following,

- (i) Intelligence
- (ii) Sensor capabilities
- (iii) Telepresence
- (iv) Mechanical design

- (v) Mobility and navigation (walking machines)
- (vi) Universal gripper
- (vii) Systems and integration and networking
- (viii) FMS (Flexible Manufacturing Systems)
- (Ix) Hazardous and inaccessible non-manufacturing environments

- (x) Underground coal mining
- (xi) Fire fighting operations
- (xii) Robots in space
- (xiii) Security guards
- (xiv) Garbage collection and waste disposal operations
- (xv) Household robots
- (xvi) Medical care and hospital duties etc.

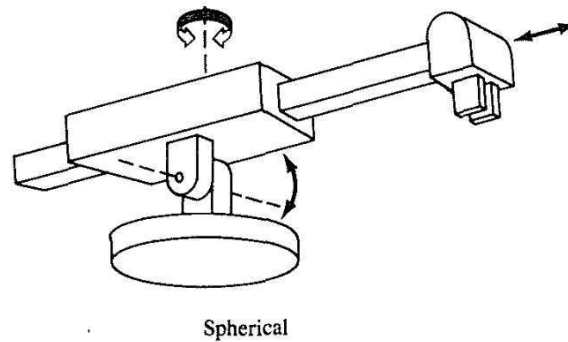
Classification of Robots (or) Classification by co-ordinate system and control system:-

Co-ordinate systems:-

Industrial robots are available in a wide variety of sizes, shapes, and physical configurations. The vast majority of today's commercially available robots possess one of the basic configurations:

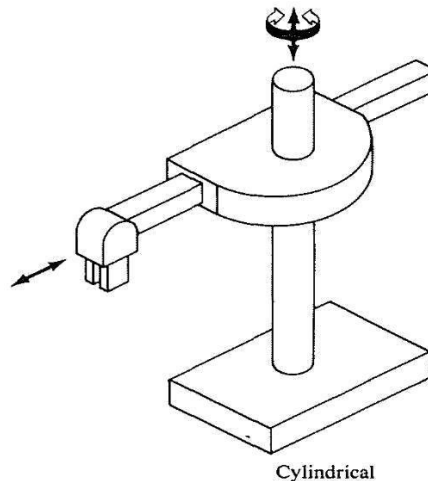
- I. Polar configuration
2. Cylindrical configuration
3. Cartesian coordinate configurable
4. Jointed-arm configuration

1. Polar configuration:-



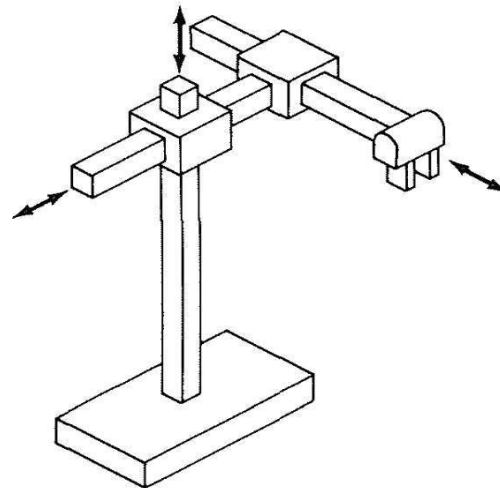
The polar configuration is pictured in part (a) of Fig. It uses a telescoping arm that can be raised or lowered about a horizontal pivot. The pivot is mounted on a rotating base. These various joints provide the robot with the capability to move its arm within a spherical space, and hence the name “spherical coordinate” robot is sometimes applied to this type. A number of commercial robots possess the polar configuration.

2. Cylindrical configuration:-



The cylindrical configurable, as shown in fig, uses a vertical column and a slide that can be moved up or down along the column. The robot arm is attached to the slide so that it can be moved radially with respect to the column. By rotating the column, the robot is capable of achieving a work space that approximates a cylinder.

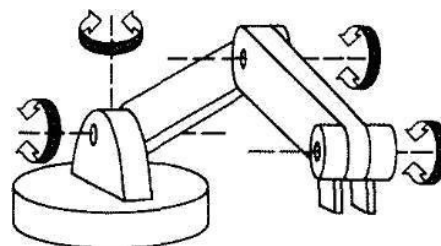
3. Cartesian coordinate configurable:-



Cartesian or xyz

The cartesian coordinate robot, illustrated in part Cc) of Fig, uses three perpendicular slides to construct the x, y, and z axes. Other names are sometimes applied to this configuration, including xyz robot and rectilinear robot, By moving the three slides relative to one another, the robot is capable of operating within a rectangular work envelope.

4. Jointed-arm configuration:-



Revolute

The jointed-arm robot is pictured in Fig. Its configuration is similar to that of the human arm. It consists of two straight components. Corresponding to the human forearm and upper arm, mounted on a vertical pedestal. These components are connected by two rotary joints corresponding to the shoulder and elbow.

Control systems:-

With respect to robotics, the motion control system used to control the movement of the end-effector or tool.

1. Limited sequence robots (Non-servo)
2. Playback robots with point to point (servo)
3. Play back robots with continuous path control,
4. Intelligent robots.

Limited sequence robots (Non-servo):-

Limited sequence robots do not give servo controlled to inclined relative positions of the joints; instead they are controlled by setting limit switches & are mechanical stops. There is generally no feedback associated with a limited sequence robot to indicate that the desired position, has been achieved generally thin type of robots involves simple motion as pick & place operations.

Point to point motion:-

These type robots are capable of controlling velocity acceleration & path of motion, from the beginning to the end of the path. It uses complex control programs, PLC's (programmable logic controller's) computers to control the motion.

The point to point control motion robots are capable of performing motion cycle that consists of a series of desired point location. The robot is tough & recorded, unit.

Continuous path motion:-

In this robots are capable of performing motion cycle in which the path followed by the robot in controlled. The robot move through a series of closely space point which describe the desired path.

Ex:- Spray painting, arc welding & complicate assembly operations.

Intelligent robots:-

This type of robots not only programmable motion cycle but also interact with its environment in a way that years intelligent. It taken make logical decisions based on sensor data receive from the operation.

There robots are usually programmed using an English like symbolic language not like a computer programming language.

Precision of movement (or) parameters of robot:-

The preceding discussion of response speed and stability is concerned with the dynamic performance of the robot. Another measure of performance is precision of the robot's movement. We will define precision as a function of three features:

- 1.Spatial resolution
2. Accuracy
3. Repeatability

These terms will be defined with the following assumptions.

- 1) The definitions will apply at the robot's wrist end with no hand attached to the wrist.
- 2) The terms apply to the worst case conditions, the conditions under which the robot's precision will be at its wont. This generally means that the robot's arm is fully extended in the case of a jointed arm or polar configurable.
- 3) Third, our definitions will he developed in the context of a point-to-point robot.

1. Spatial resolution:-

The spatial resolution of a robot is the smallest increment of movement into which the robot can divide its work volume. Spatial resolution depends on two factors: the system's control resolution and the robot's mechanical inaccuracies. It is easiest to conceptualize these factors in terms of a robot with 1 degree of freedom.

2. Accuracy:-

Accuracy refers to a robot's ability to position its wrist end at a desired target point within the work volume. The accuracy of a robot can be denned in terms of spatial resolution because the ability to achieve a given target point depends on how closely the robot can define the control increments for each of its joint motions.

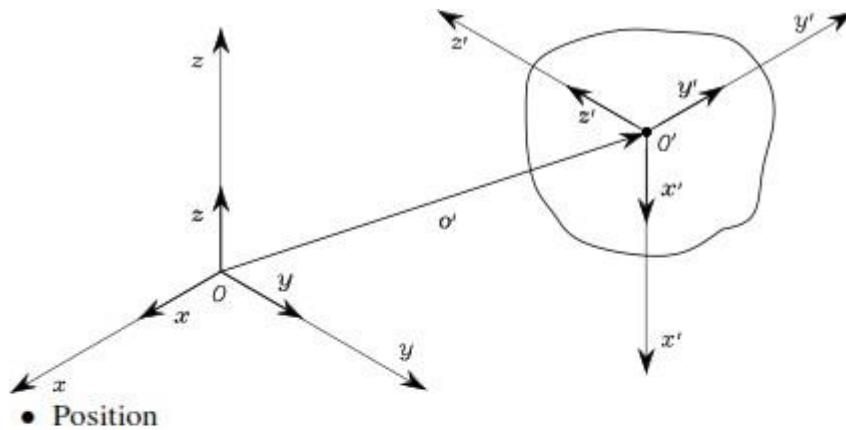
3. Repeatability:-

Repeatability is concerned with the robot's ability to position its wrist or an end effector attached to its wrist at a point in space is known as repeatability. Repeatability and accuracy refer to two different aspects of the robot's precision. Accuracy relates to the robot's capacity to be programmed to achieve a given target point. The actual programmed point will probably be different from the target point due to limitations of control resolution. Repeatability refers to the robot's ability to return to the programmed point when commanded to do so.

UNIT – II
KINEMATICS

Relationship between joint positions, end-effector position and orientation.

Position of a Rigid Body



$$\mathbf{o}' = \begin{bmatrix} o'_x \\ o'_y \\ o'_z \end{bmatrix}$$

• Orientation

$$x' = x'_x x + x'_y y + x'_z z$$

$$y' = y'_x x + y'_y y + y'_z z$$

$$z' = z'_x x + z'_y y + z'_z z$$

$$R = \begin{bmatrix} x' & y' & z' \end{bmatrix} = \begin{bmatrix} x'^T x & y'^T x & z'^T x \\ x'^T y & y'^T y & z'^T y \\ x'^T z & y'^T z & z'^T z \end{bmatrix}$$

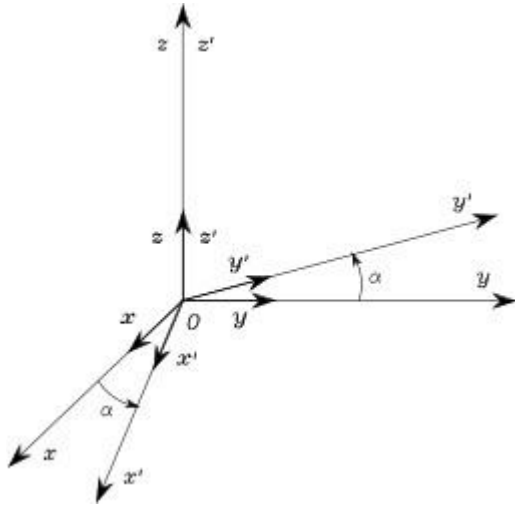
$$R^T R = I$$

$$R^T = R^{-1}$$

Rotation Matrix

Elementary Rotation

Rotation of α about Z



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

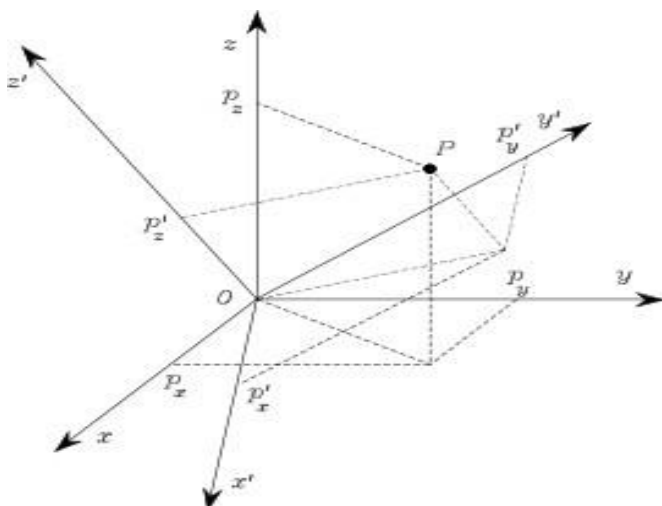
rotation of β about y

$$R_y(\beta) = \begin{bmatrix} \cos \beta & 0 & \sin \beta \\ 0 & 1 & 0 \\ -\sin \beta & 0 & \cos \beta \end{bmatrix}$$

rotation of γ about x

$$R_x(\gamma) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \gamma & -\sin \gamma \\ 0 & \sin \gamma & \cos \gamma \end{bmatrix}$$

Representation of a Vector



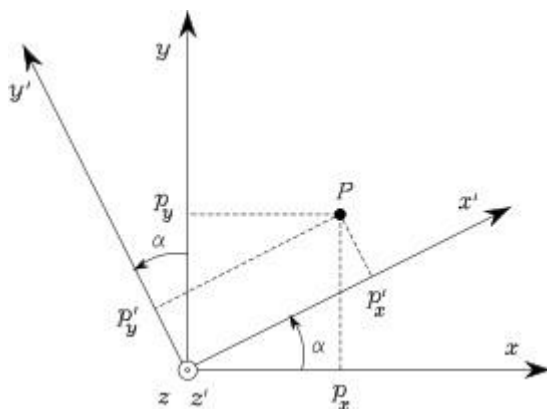
$$\mathbf{p} = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} \quad \mathbf{p}' = \begin{bmatrix} p'_x \\ p'_y \\ p'_z \end{bmatrix}$$

$$\mathbf{p} = \begin{bmatrix} x' & y' & z' \end{bmatrix} \mathbf{p}'$$

$$= \mathbf{R} \mathbf{p}'$$

$$\mathbf{p}' = \mathbf{R}^T \mathbf{p}$$

Example



$$p_x = p'_x \cos \alpha - p'_y \sin \alpha$$

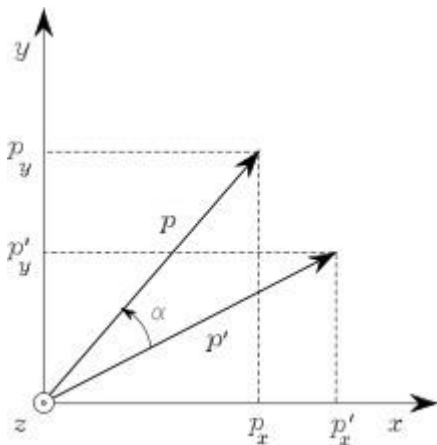
$$p_y = p'_x \sin \alpha + p'_y \cos \alpha$$

$$p_z = p'_z$$

Rotation of a Vector

$$\mathbf{p} = \mathbf{R}\mathbf{p}'$$

$$\mathbf{p}^T \mathbf{p} = \mathbf{p}'^T \mathbf{R}^T \mathbf{R} \mathbf{p}'$$

**Example**

$$p_x = p'_x \cos \alpha - p'_y \sin \alpha$$

$$p_y = p'_x \sin \alpha + p'_y \cos \alpha$$

$$p_z = p'_z$$

$$\mathbf{p} = \mathbf{R}_z(\alpha)\mathbf{p}'$$

Rotation matrix

It describes the mutual orientation between two coordinate frames; its column vectors are the direction cosines of the axes of the rotated frame with respect to the original frame.

It represents the coordinate transformation between the coordinates of a point expressed in two different frames (with common origin).

It is the operator that allows the rotation of a vector in the same coordinate frame.

COMPOSITION OF ROTATION MATRICES

$$p^1 = R_2^1 p^2$$

$$p^0 = R_1^0 p^1$$

$$p^0 = R_2^0 p^2$$

$$R_i^j = (R_j^i)^{-1} = (R_j^i)^T$$

Current frame rotation

$$R_2^0 = R_1^0 R_2^1$$

Fixed frame rotation

$$R_2^0 = R_2^1 R_1^0$$

EULER ANGLES

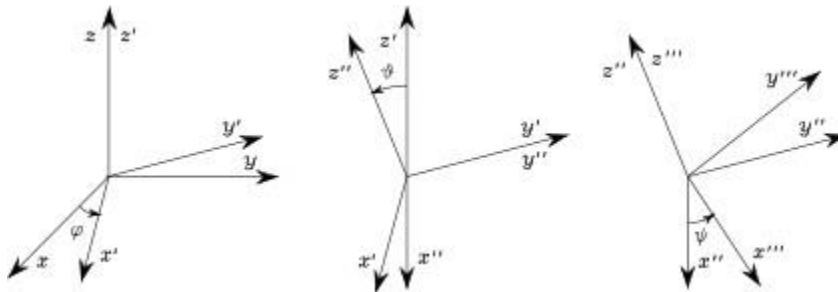
Rotation matrix

9 parameters with 6 constraints

minimal representation of orientation

3 independent parameters

ZYZ angles



$$R(\phi) = R_z(\varphi)R_{y'}(\vartheta)R_{z''}(\psi)$$

$$= \begin{bmatrix} C_\varphi C_\vartheta C_\psi - S_\varphi S_\psi & -C_\varphi C_\vartheta S_\psi - S_\varphi C_\psi & C_\varphi S_\vartheta \\ S_\varphi C_\vartheta C_\psi + C_\varphi S_\psi & -S_\varphi C_\vartheta S_\psi + C_\varphi C_\psi & S_\varphi S_\vartheta \\ -S_\vartheta C_\psi & S_\vartheta S_\psi & C_\vartheta \end{bmatrix}$$

Inverse problem

$$\mathbf{R} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

Given the

$$\varphi = \text{Atan2}(r_{23}, r_{13})$$

$$\vartheta = \text{Atan2}\left(\sqrt{r_{13}^2 + r_{23}^2}, r_{33}\right)$$

$$\psi = \text{Atan2}(r_{32}, -r_{31})$$

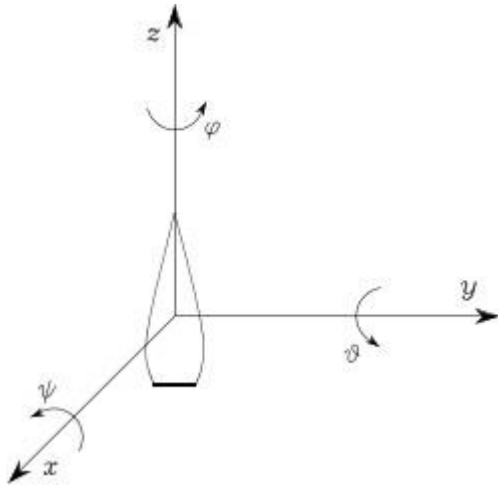
or ($\vartheta \in (-\pi, 0)$)

$$\varphi = \text{Atan2}(-r_{23}, -r_{13})$$

$$\vartheta = \text{Atan2}\left(-\sqrt{r_{13}^2 + r_{23}^2}, r_{33}\right)$$

$$\psi = \text{Atan2}(-r_{32}, r_{31})$$

three ZYZ angles are ($\vartheta \in (0, \pi)$)

RPY angles

$$\mathbf{R}(\phi) = \mathbf{R}_z(\varphi)\mathbf{R}_y(\vartheta)\mathbf{R}_x(\psi)$$

$$= \begin{bmatrix} c_\varphi c_\vartheta & c_\varphi s_\vartheta s_\psi - s_\varphi c_\psi & c_\varphi s_\vartheta c_\psi + s_\varphi s_\psi \\ s_\varphi c_\vartheta & s_\varphi s_\vartheta s_\psi + c_\varphi c_\psi & s_\varphi s_\vartheta c_\psi - c_\varphi s_\psi \\ -s_\vartheta & c_\vartheta s_\psi & c_\vartheta c_\psi \end{bmatrix}$$

Inverse problem

$$\mathbf{R} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

Given

the three RPY angles are ($\vartheta \in (-\pi/2, \pi/2)$)

$$\varphi = \text{Atan2}(r_{21}, r_{11})$$

$$\vartheta = \text{Atan2}\left(-r_{31}, \sqrt{r_{32}^2 + r_{33}^2}\right)$$

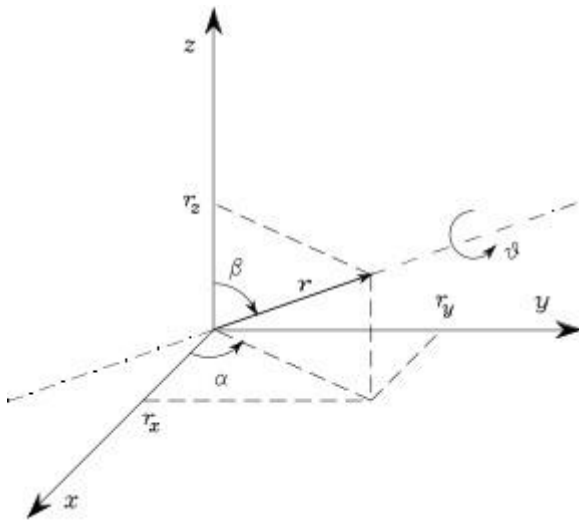
$$\psi = \text{Atan2}(r_{32}, r_{33})$$

or ($\vartheta \in (\pi/2, 3\pi/2)$)

$$\varphi = \text{Atan2}(-r_{21}, -r_{11})$$

$$\vartheta = \text{Atan2}\left(-r_{31}, -\sqrt{r_{32}^2 + r_{33}^2}\right)$$

$$\psi = \text{Atan2}(-r_{32}, -r_{33})$$

ANGLE AND AXIS

$$\mathbf{R}(\vartheta, \mathbf{r}) = \mathbf{R}_z(\alpha)\mathbf{R}_y(\beta)\mathbf{R}_z(\vartheta)\mathbf{R}_y(-\beta)\mathbf{R}_z(-\alpha)$$

$$\sin \alpha = \frac{r_y}{\sqrt{r_x^2 + r_y^2}} \quad \cos \alpha = \frac{r_x}{\sqrt{r_x^2 + r_y^2}}$$

$$\sin \beta = \frac{\sqrt{r_x^2 + r_y^2}}{r} \quad \cos \beta = \frac{r_z}{r}$$

$$\mathbf{R}(\vartheta, \mathbf{r}) = \begin{bmatrix} r_x^2(1 - c_\vartheta) + c_\vartheta & r_x r_y(1 - c_\vartheta) - r_z s_\vartheta & r_x r_z(1 - c_\vartheta) + r_y s_\vartheta \\ r_x r_y(1 - c_\vartheta) + r_z s_\vartheta & r_y^2(1 - c_\vartheta) + c_\vartheta & r_y r_z(1 - c_\vartheta) - r_x s_\vartheta \\ r_x r_z(1 - c_\vartheta) - r_y s_\vartheta & r_y r_z(1 - c_\vartheta) + r_x s_\vartheta & r_z^2(1 - c_\vartheta) + c_\vartheta \end{bmatrix}$$

$$\mathbf{R}(\vartheta, \mathbf{r}) = \mathbf{R}(-\vartheta, -\mathbf{r})$$

Inverse problem

Given

$$R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

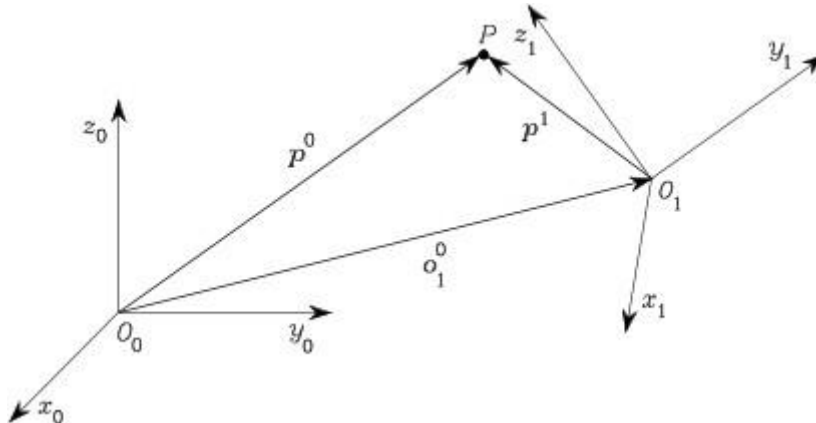
the angle and axis of rotation are ($\sin \vartheta \neq 0$)

$$\vartheta = \cos^{-1} \left(\frac{r_{11} + r_{22} + r_{33} - 1}{2} \right)$$

$$r = \frac{1}{2 \sin \vartheta} \begin{bmatrix} r_{32} - r_{23} \\ r_{13} - r_{31} \\ r_{21} - r_{12} \end{bmatrix}$$

$$r_x^2 + r_y^2 + r_z^2 = 1$$

With

HOMOGENEOUS TRANSFORMATIONS

$$p^0 = o_1^0 + R_1^0 p^1$$

- Coordinate transformation (translation + rotation)

$$p^1 = -R_0^1 o_1^0 + R_0^1 p^0$$

- Inverse transformation
- Homogeneous representation

$$\tilde{\mathbf{p}} = \begin{bmatrix} \mathbf{p} \\ 1 \end{bmatrix}$$

$$\mathbf{A}_1^0 = \begin{bmatrix} \mathbf{R}_1^0 & \mathbf{o}_1^0 \\ \mathbf{0}^T & 1 \end{bmatrix}$$

- Homogeneous transformation matrix
- Coordinate transformation

$$\tilde{\mathbf{p}}^0 = \mathbf{A}_1^0 \tilde{\mathbf{p}}^1$$

$$\tilde{\mathbf{p}}^1 = \mathbf{A}_0^1 \tilde{\mathbf{p}}^0 = (\mathbf{A}_1^0)^{-1} \tilde{\mathbf{p}}^0$$

$$\mathbf{A}_0^1 = \begin{bmatrix} \mathbf{R}_0^1 & -\mathbf{R}_0^1 \mathbf{o}_1^0 \\ \mathbf{0}^T & 1 \end{bmatrix}$$

$$\mathbf{A}^{-1} \neq \mathbf{A}^T$$

- Inverse transformation
- Sequence of coordinate transformations

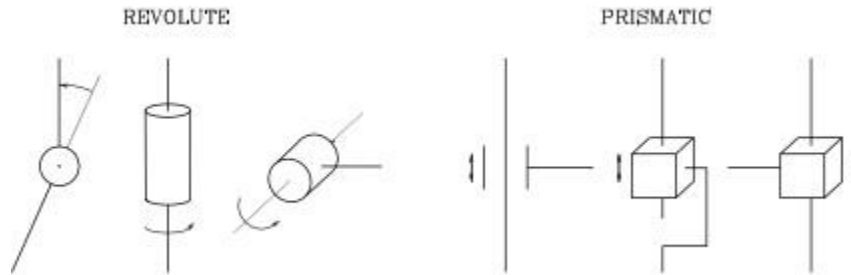
$$\tilde{\mathbf{p}}^0 = \mathbf{A}_1^0 \mathbf{A}_2^1 \dots \mathbf{A}_n^{n-1} \tilde{\mathbf{p}}^n$$

UNIT-III

DIRECT KINEMATICS

• Manipulator

series of links connected by means of joints



Kinematic chain (from base to end-effector)

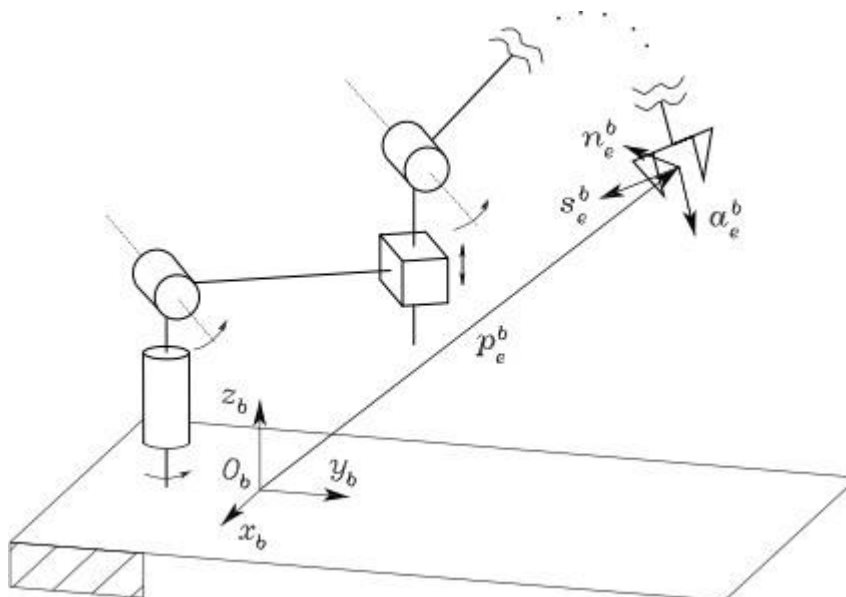
open (only one sequence)

closed (loop)

Degree of freedom

associated with a joint articulation = joint variable

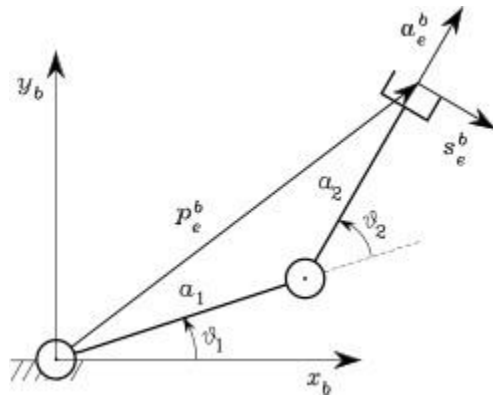
Base frame and end-effector frame



Direct kinematics equation

$$T_e^b(q) = \begin{bmatrix} n_e^b(q) & s_e^b(q) & a_e^b(q) & p_e^b(q) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

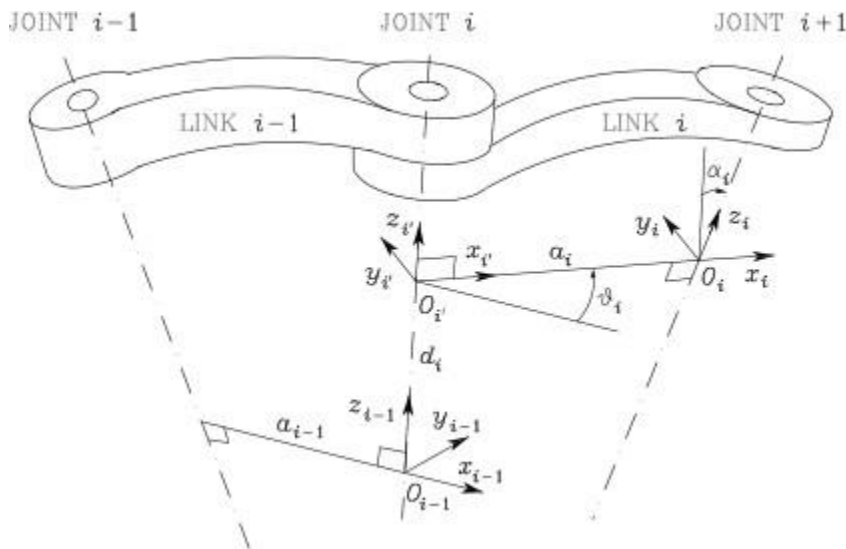
Two-link planar arm



$$T_e^b(q) = \begin{bmatrix} n_e^b & s_e^b & a_e^b & p_e^b \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 0 & s_{12} & c_{12} & a_1 c_1 + a_2 c_{12} \\ 0 & -c_{12} & s_{12} & a_1 s_1 + a_2 s_{12} \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Denavit–Hartenberg convention



- choose axis z_i along axis of Joint $i + 1$
- locate O_i at the intersection of axis z_i with the common normal to axes z_{i-1} and z_i , and O'_{i-1} at intersection of common normal with axis z_{i-1}
- choose axis x_i along common the normal to axes z_{i-1} and z_i with positive direction from Joint i to Joint $i + 1$
- choose axis y_i so as to complete right-handed frame
- Nonunique definition of link frame:
For Frame 0, only the direction of axis z_0 is specified: then O_0 and X_0 can be chosen

arbitrarily.

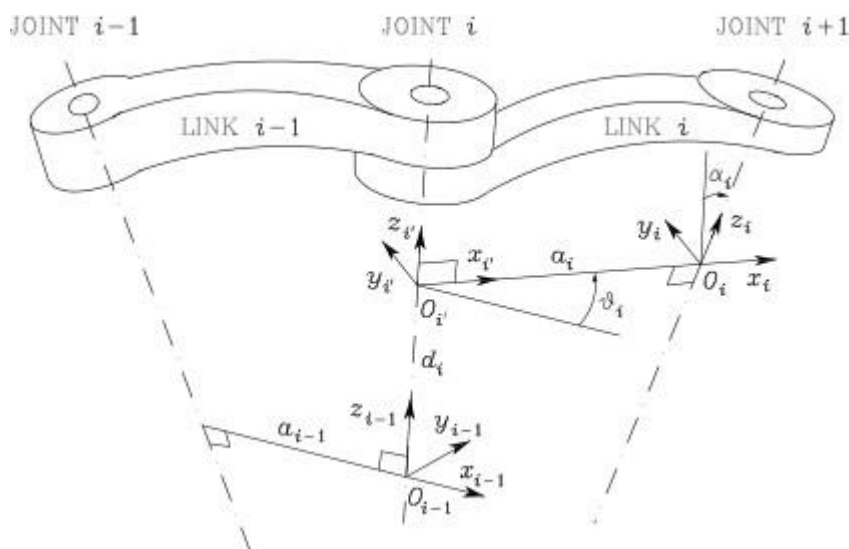
For Frame n, since there is no Joint n + 1, z_n is not uniquely defined while x_n has to be normal to axis z_{n-1}; typically Joint n is revolute and thus z_n can be aligned with z_{n-1}.

when two consecutive axes are parallel, the common normal between them is not uniquely defined.

when two consecutive axes intersect, the positive direction of x_i is arbitrary.

When Joint i is prismatic, only the direction of z_{i-1} is specified.

Denavit–Hartenberg parameters



a_i distance between O_i and O_{i-1};

d_i coordinate of O_i and z_{i-1};

α_i angle between axes z_{i-1} and z_i about axis x_i to be taken positive when rotation is made counter-clockwise

θ_i angle between axes x_{i-1} and x_i about axis z_{i-1} to be taken positive when rotation is made counter-clockwise

a_i and α_i are always constant

if Joint i is revolute the variable is θ_i

if Joint i is prismatic the variable is d_i

• Coordinate transformation

$$A_{i-1}^{i'} = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & 0 \\ s\theta_i & c\theta_i & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_i^{i'} = \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & c\alpha_i & -s\alpha_i & 0 \\ 0 & s\alpha_i & c\alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_i^{i-1}(q_i) = A_i^{i-1} A_i^{i'} = \begin{bmatrix} c_{\theta_i} & -s_{\theta_i} c_{\alpha_i} & s_{\theta_i} s_{\alpha_i} & a_i c_{\theta_i} \\ s_{\theta_i} & c_{\theta_i} c_{\alpha_i} & -c_{\theta_i} s_{\alpha_i} & a_i s_{\theta_i} \\ 0 & s_{\alpha_i} & c_{\alpha_i} & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

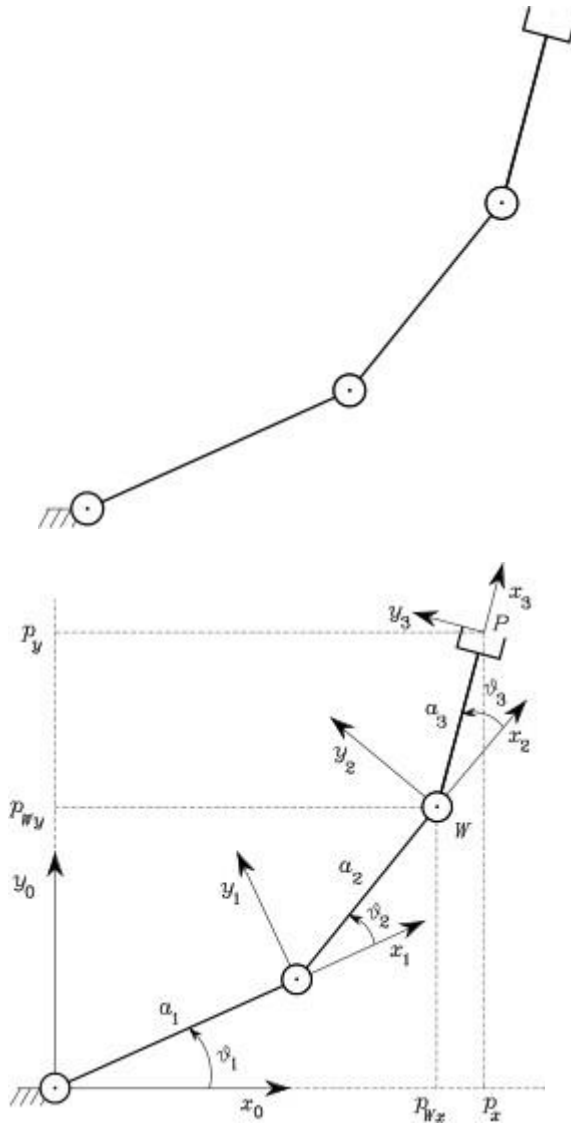
Procedure

1. Find and number consecutively the joint axes; set the directions of axes z_0, \dots, z_{n-1} .
2. Choose Frame 0 by locating the origin on axis z_0 ; axes x_0 and y_0 are chosen so as to obtain a righthanded frame. If feasible, it is worth choosing Frame 0 to coincide with the base frame.

Execute steps from 3 to 5 for $i = 1, \dots, n - 1$:

3. Locate the origin O_i at the intersection of z_i with the common normal to axes z_{i-1} and z_i . If axes z_{i-1} and z_i are parallel and Joint i is revolute, then locate O_i so that $d_i=0$; if Joint i is prismatic, locate O_i at a reference position for the joint range, e.g., a mechanical limit.
4. Choose axis x_i along the common normal to axes z_{i-1} and z_i with direction from Joint i to Joint $i + 1$.
5. Choose axis y_i so as to obtain a right-handed frame to complete.
6. Choose Frame n ; if Joint n is revolute, then align z_n with z_{n-1} , otherwise, if Joint n is prismatic, then choose z_n arbitrarily. Axis x_n is set according to step 4.
7. For $i = 1, \dots, n$, form the table of parameters a_i, d_i, α_i, v_i .
8. On the basis of the parameters in 7, compute the homogeneous transformation matrices $A_i^{i-1}(q)$ for $i = 1, \dots, n$.
9. Compute the homogeneous transformation $T^n(q) = A^0 \dots A^{n-1}$ they yields the position and orientation of Frame n with respect to Frame 0.
10. Given T_0^b and T_e^n , compute the direct kinematics function as $T_e^b(q) = T_0^b T_n^0 T_e^n$ that yields the position and orientation of the end-effector frame with respect to the base frame.

Three-link planar arm



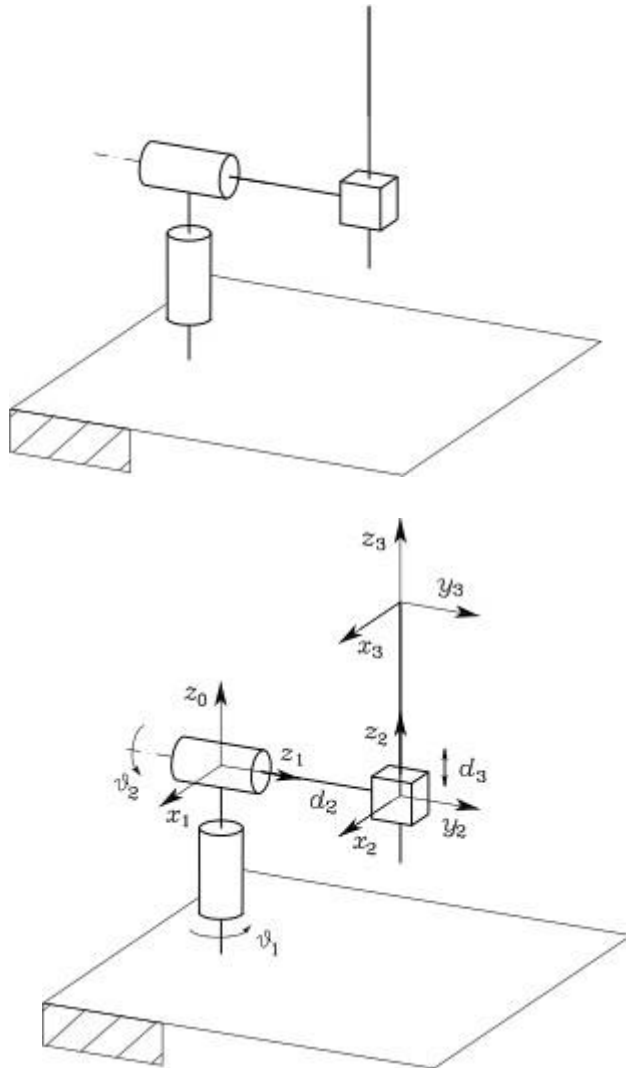
Link	a_i	α_i	d_i	ϑ_i
1	a_1	0	0	ϑ_1
2	a_2	0	0	ϑ_2
3	a_3	0	0	ϑ_3

$$A_i^{i-1} = \begin{bmatrix} c_i & -s_i & 0 & a_i c_i \\ s_i & c_i & 0 & a_i s_i \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad i = 1, 2, 3$$

$$T_3^0 = A_1^0 A_2^1 A_3^2$$

$$= \begin{bmatrix} c_{123} & -s_{123} & 0 & a_1 c_1 + a_2 c_{12} + a_3 c_{123} \\ s_{123} & c_{123} & 0 & a_1 s_1 + a_2 s_{12} + a_3 s_{123} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Spherical arm



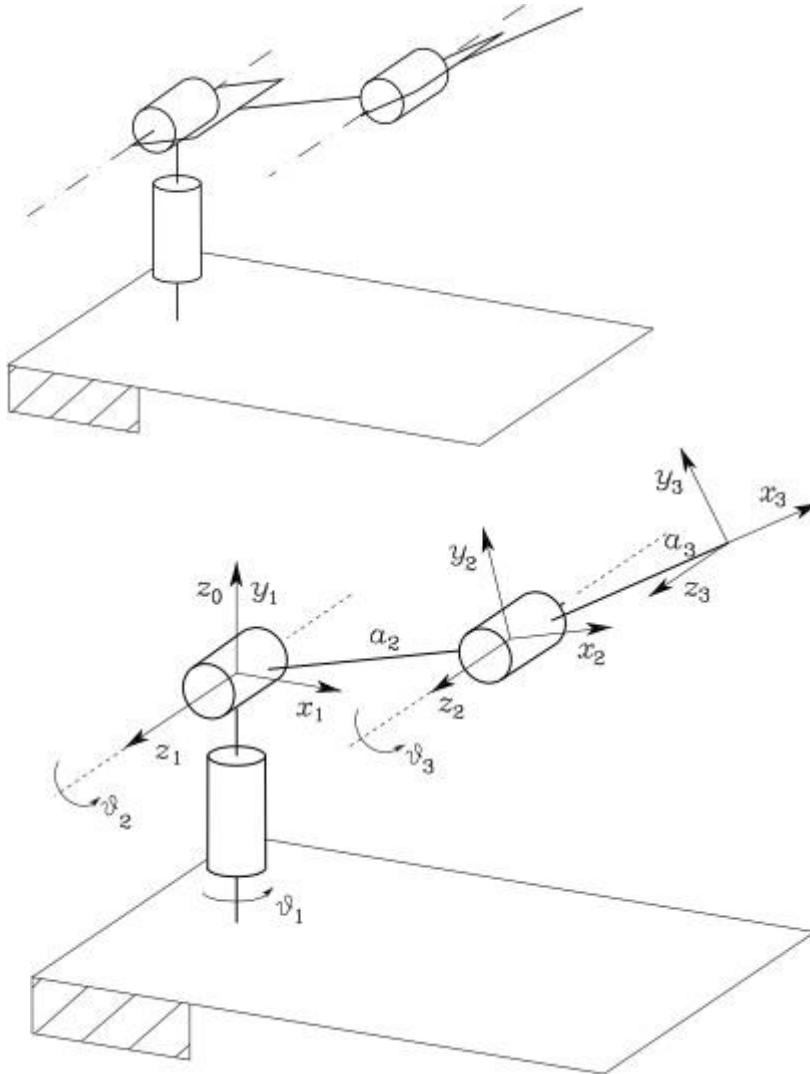
Link	a_i	α_i	d_i	ϑ_i
1	0	$-\pi/2$	0	ϑ_1
2	0	$\pi/2$	d_2	ϑ_2
3	0	0	d_3	0

$$A_1^0 = \begin{bmatrix} c_1 & 0 & -s_1 & 0 \\ s_1 & 0 & c_1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad A_2^1 = \begin{bmatrix} c_2 & 0 & s_2 & 0 \\ s_2 & 0 & -c_2 & 0 \\ 0 & 1 & 0 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad A_3^2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_3^0 = A_1^0 A_2^1 A_3^2$$

$$= \begin{bmatrix} c_1 c_2 & -s_1 & c_1 s_2 & c_1 s_2 d_3 - s_1 d_2 \\ s_1 c_2 & c_1 & s_1 s_2 & s_1 s_2 d_3 + c_1 d_2 \\ -s_2 & 0 & c_2 & c_2 d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Anthropomorphic arm



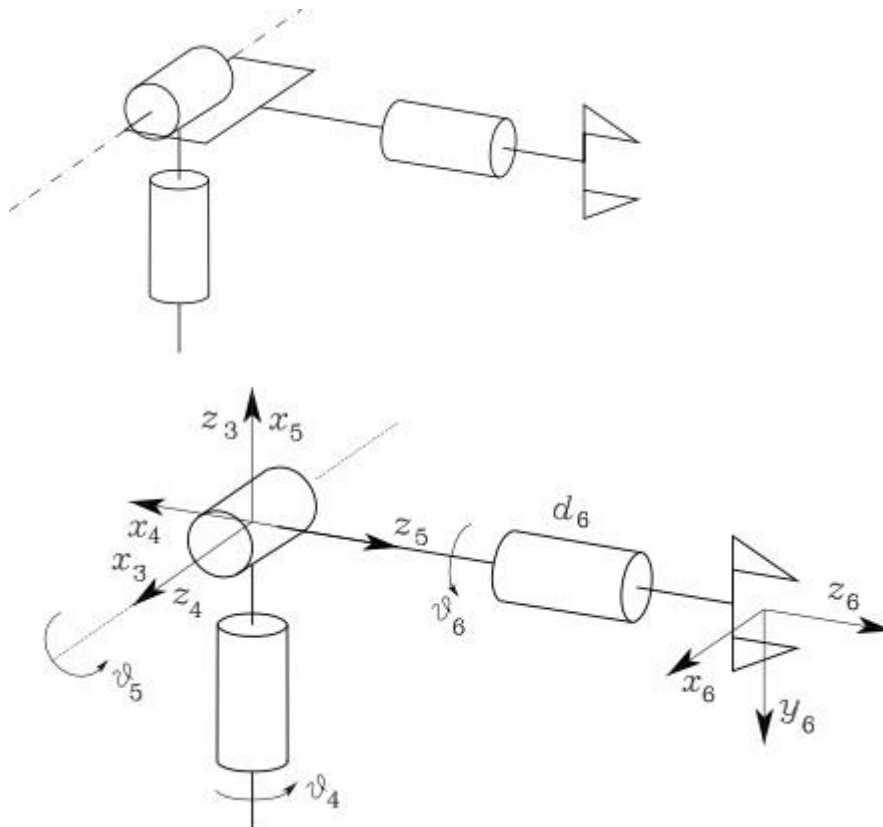
Link	a_i	α_i	d_i	ϑ_i
1	0	$\pi/2$	0	ϑ_1
2	a_2	0	0	ϑ_2
3	a_3	0	0	ϑ_3

$$A_1^0 = \begin{bmatrix} c_1 & 0 & s_1 & 0 \\ s_1 & 0 & -c_1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad A_i^{i-1} = \begin{bmatrix} c_i & -s_i & 0 & a_i c_i \\ s_i & c_i & 0 & a_i s_i \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad i = 2, 3$$

$$T_3^0 = A_1^0 A_2^1 A_3^2$$

$$= \begin{bmatrix} c_1 c_{23} & -c_1 s_{23} & s_1 & c_1(a_2 c_2 + a_3 c_{23}) \\ s_1 c_{23} & -s_1 s_{23} & -c_1 & s_1(a_2 c_2 + a_3 c_{23}) \\ s_{23} & c_{23} & 0 & a_2 s_2 + a_3 s_{23} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Spherical wrist



Link	a_i	α_i	d_i	ϑ_i
4	0	$-\pi/2$	0	ϑ_4
5	0	$\pi/2$	0	ϑ_5
6	0	0	d_6	ϑ_6

$$A_4^3 = \begin{bmatrix} c_4 & 0 & -s_4 & 0 \\ s_4 & 0 & c_4 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad A_5^4 = \begin{bmatrix} c_5 & 0 & s_5 & 0 \\ s_5 & 0 & -c_5 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_6^5 = \begin{bmatrix} c_6 & -s_6 & 0 & 0 \\ s_6 & c_6 & 0 & 0 \\ 0 & 0 & 1 & d_6 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_6^3 = A_4^3 A_5^4 A_6^5$$

$$= \begin{bmatrix} c_4 c_5 c_6 - s_4 s_6 & -c_4 c_5 s_6 - s_4 c_6 & c_4 s_5 & c_4 s_5 d_6 \\ s_4 c_5 c_6 + c_4 s_6 & -s_4 c_5 s_6 + c_4 c_6 & s_4 s_5 & s_4 s_5 d_6 \\ -s_5 c_6 & s_5 s_6 & c_5 & c_5 d_6 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

JOINT SPACE AND OPERATIONAL SPACE

Joint space

$$q = \begin{bmatrix} q_1 \\ \vdots \\ q_n \end{bmatrix}$$

$q_i = \theta_i$ (revolute joint)

$q_i = d_i$ (prismatic joint)

Operational space

$$x = \begin{bmatrix} p \\ \phi \end{bmatrix}$$

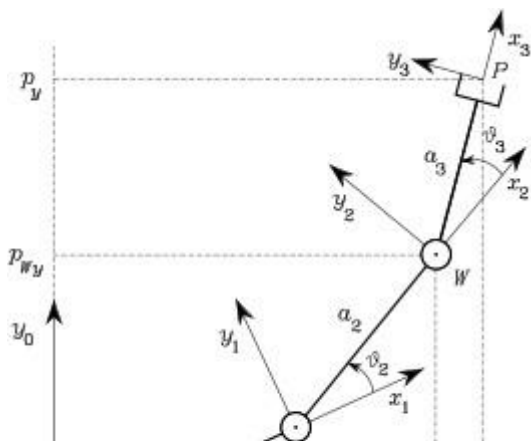
P (position)

Φ (orientation)

Direct kinematics equation

$$x = k(q)$$

Example



$${}^M F x = \begin{bmatrix} p_x \\ p_y \\ \phi \end{bmatrix} = k(q) = \begin{bmatrix} a_1 c_1 + a_2 c_{12} + a_3 c_{123} \\ a_1 s_1 + a_2 s_{12} + a_3 s_{123} \\ \theta_1 + \theta_2 + \theta_3 \end{bmatrix}$$

Workspace

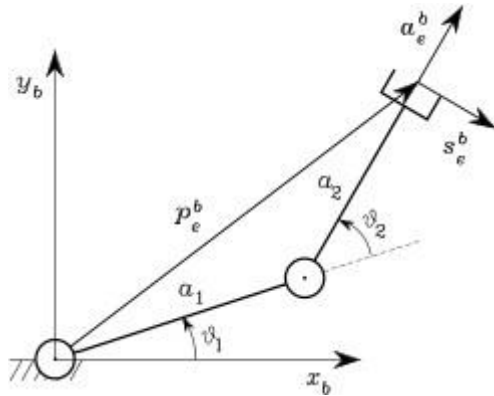
- Reachable workspace

$$p = p(q) \quad q_{im} \leq q_i \leq q_{iM} \quad i = 1, \dots, n$$

surface elements of planar, spherical, toroidal and cylindrical type.

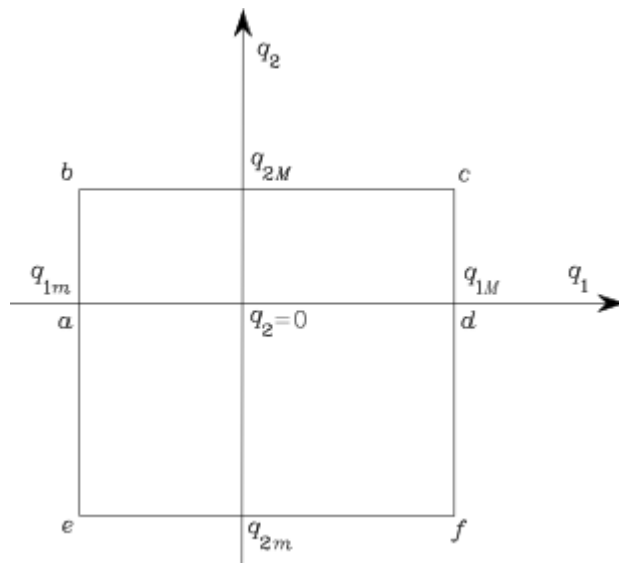
Dexterous workspace

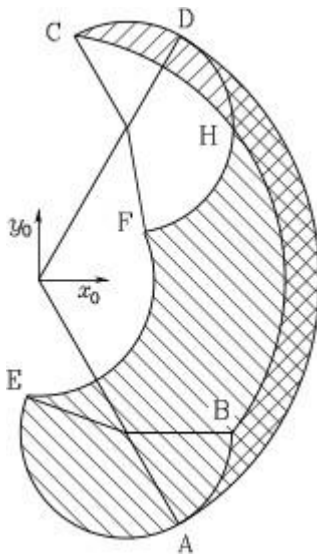
different orientations



Example

admissible configurations



Workspace**KINEMATIC CALIBRATION**

- Accurate estimates of DH parameters to improve manipulator accuracy.
- Direct kinematics equation as a function of all parameters.

$$x = k(a, \alpha, d, \vartheta)$$

x_m measured pose

x_n nominal pose (fixed parameters + joint variables)

$$\begin{aligned} \Delta x &= \frac{\partial k}{\partial a} \Delta a + \frac{\partial k}{\partial \alpha} \Delta \alpha + \frac{\partial k}{\partial d} \Delta d + \frac{\partial k}{\partial \vartheta} \Delta \vartheta \\ &= \Phi(\zeta_n) \Delta \zeta \end{aligned}$$

$$\Delta \bar{x} = \begin{bmatrix} \Delta x_1 \\ \vdots \\ \Delta x_l \end{bmatrix} = \begin{bmatrix} \Phi_1 \\ \vdots \\ \Phi_l \end{bmatrix} \Delta \zeta = \bar{\Phi} \Delta \zeta$$

l measurements ($l_m \gg 4n$)

Solution

$$\Delta \zeta = (\bar{\Phi}^T \bar{\Phi})^{-1} \bar{\Phi}^T \Delta \bar{x}$$

$$\zeta' = \zeta_n + \Delta \zeta$$

... until $\Delta \zeta$ converges

more accurate estimates of fixed parameters.

corrections on transducers measurements.

INVERSE KINEMATICS PROBLEM

- Direct kinematics

$q \Rightarrow T$

$q \Rightarrow x$

- Inverse kinematics

$T \Rightarrow q$

$x \Rightarrow q$

- Complexity

closed-form solution

multiple solutions

infinite solutions

no admissible solutions

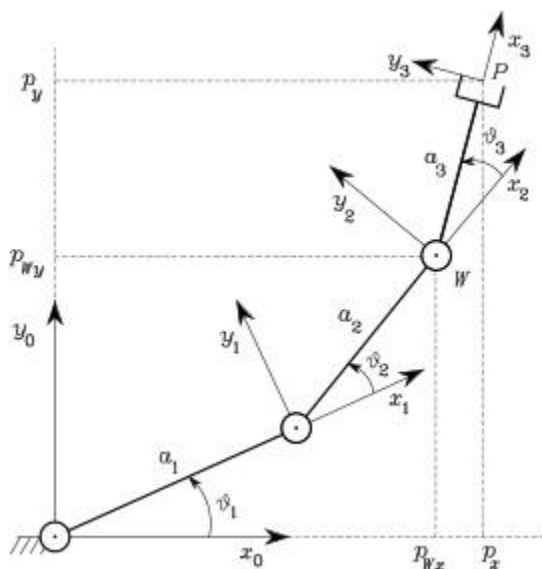
- Intuition

Algebraic

Geometric

- Numerical techniques

Solution of three-link planar arm



Algebraic solution

$$\phi = \vartheta_1 + \vartheta_2 + \vartheta_3$$

$$p_{Wx} = p_x - a_3 c_\phi = a_1 c_1 + a_2 c_{12}$$

$$p_{Wy} = p_y - a_3 s_\phi = a_1 s_1 + a_2 s_{12}$$

$$c_2 = \frac{p_{Wx}^2 + p_{Wy}^2 - a_1^2 - a_2^2}{2a_1a_2}$$

$$s_2 = \pm \sqrt{1 - c_2^2}$$

$$\vartheta_2 = \text{Atan2}(s_2, c_2)$$

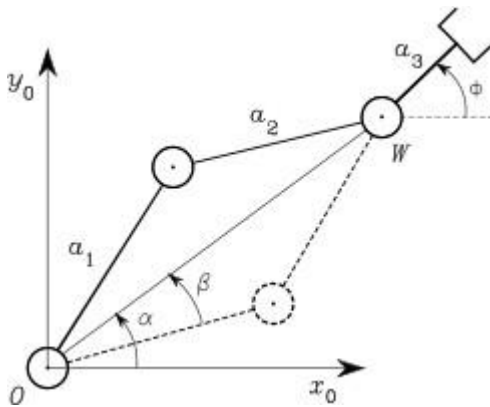
$$s_1 = \frac{(a_1 + a_2c_2)p_{Wy} - a_2s_2p_{Wx}}{p_{Wx}^2 + p_{Wy}^2}$$

$$c_1 = \frac{(a_1 + a_2c_2)p_{Wx} + a_2s_2p_{Wy}}{p_{Wx}^2 + p_{Wy}^2}$$

$$\vartheta_1 = \text{Atan2}(s_1, c_1)$$

$$\vartheta_3 = \phi - \vartheta_1 - \vartheta_2$$

Geometric solution



$$c_2 = \frac{p_{Wx}^2 + p_{Wy}^2 - a_1^2 - a_2^2}{2a_1a_2}$$

$$\vartheta_2 = \cos^{-1}(c_2)$$

$$\alpha = \text{Atan2}(p_{Wy}, p_{Wx})$$

$$c\beta \sqrt{p_{Wx}^2 + p_{Wy}^2} = a_1 + a_2c_2$$

$$\beta = \cos^{-1} \left(\frac{p_{Wx}^2 + p_{Wy}^2 + a_1^2 - a_2^2}{2a_1 \sqrt{p_{Wx}^2 + p_{Wy}^2}} \right)$$

$$\vartheta_1 = \alpha \pm \beta$$

TRAJECTORY PLANNING

- generation of reference inputs to motion control system.

Path and trajectory

Joint space trajectories

Operational space trajectories

PATH AND TRAJECTORY

★ generation of suitably smooth trajectories

- Path: locus of points in joint space (operational space) which the manipulator has to follow in the execution of the assigned motion (pure geometric description)
- Trajectory: path on which a timing law is specified (e.g. velocities and/or accelerations)

Trajectory planning algorithm

★ inputs

1. path description path constraints
2. constraints imposed by manipulator dynamics

★ outputs

1. joint (end-effector) trajectories in terms of time sequence of values attained by position, velocity and acceleration
2. Reduced number of parameters

★ path

extremal points

possible intermediate points geometric primitives

★ timing law

total time

max velocity and/or acceleration

velocity and/or acceleration at given points

- Operational space trajectories

- ★ natural task description

- ★ path constraints

- ★ singularities

- ★ redundancy

- Joint space trajectories

- ★ inverse kinematics

- ★ control action

JOINT SPACE TRAJECTORIES

- Generation of function $q(t)$ interpolating the given vectors of joint variables at each point, in respect of the imposed constraints
 - ★ the generated trajectories should be not very demanding from a computational viewpoint
 - ★ the joint positions and velocities (and accelerations) should be continuous functions of time
 - ★ undesirable effects should be minimized (e.g., nonsmooth trajectories)
- Point-to-point motion
 - ★ initial and final points, and traveling time
- Motion through a sequence of points
 - ★ initial and final points, intermediate points, and traveling times

Point-to-point motion

- ★ generation of $q(t)$ describing motion from q_i to q_f in a time t_f

- Cubic polynomial

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

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

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

- computation of coefficients

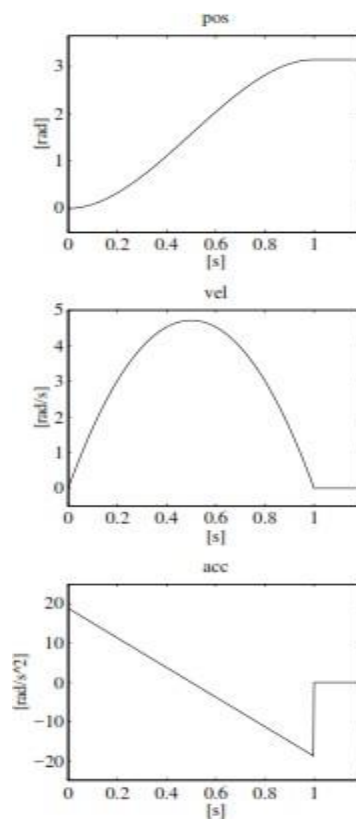
$$a_0 = q_i$$

$$a_1 = \dot{q}_i$$

$$a_3 t_f^3 + a_2 t_f^2 + a_1 t_f + a_0 = q_f$$

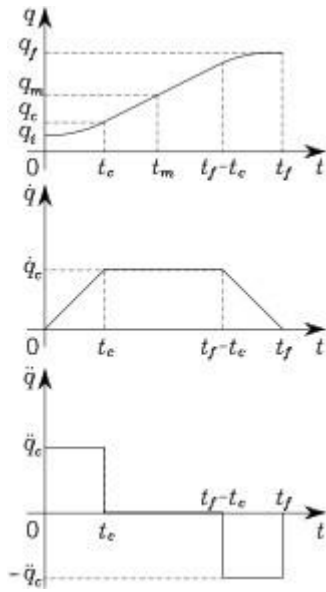
$$3a_3 t_f^2 + 2a_2 t_f + a_1 = \dot{q}_f$$

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



- Quintic polynomial (initial and final accelerations)

• Trapezoidal velocity profile



$$\ddot{q}_c t_c = \frac{q_m - q_c}{t_m - t_c}$$

$$q_c = q_i + \frac{1}{2} \ddot{q}_c t_c^2$$

$$\ddot{q}_c t_c^2 - \ddot{q}_c t_f t_c + q_f - q_i = 0$$

\ddot{q}_c specified ($\text{sgn } \ddot{q}_c = \text{sgn}(q_f - q_i)$)

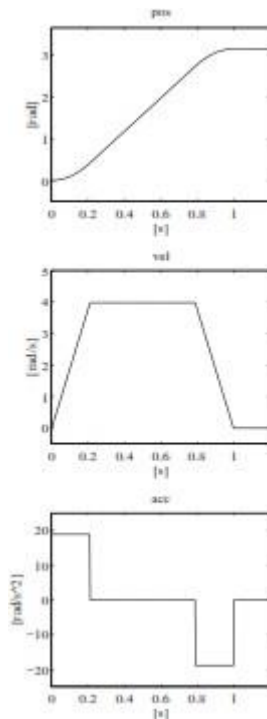
$$t_c = \frac{t_f}{2} - \frac{1}{2} \sqrt{\frac{t_f^2 \ddot{q}_c - 4(q_f - q_i)}{\ddot{q}_c}}$$

$$|\ddot{q}_c| \geq \frac{4|q_f - q_i|}{t_f^2}$$

★ trajectory

$$q(t) = \begin{cases} q_i + \frac{1}{2} \ddot{q}_c t^2 & 0 \leq t \leq t_c \\ q_i + \ddot{q}_c t_c (t - t_c/2) & t_c < t \leq t_f - t_c \\ q_f - \frac{1}{2} \ddot{q}_c (t_f - t)^2 & t_f - t_c < t \leq t_f \end{cases}$$

- **Example**



\dot{q}_c specified

$$\frac{|q_f - q_i|}{t_f} < |\dot{q}_c| \leq \frac{2|q_f - q_i|}{t_f}$$

$$t_c = \frac{q_i - q_f + \dot{q}_c t_f}{\dot{q}_c}$$

$$\ddot{q}_c = \frac{\dot{q}_c^2}{q_i - q_f + \dot{q}_c t_f}$$

Motion through a sequence of points

★ opportunity to assign intermediate points (sequence of points).

- For given N path points, find an interpolating function through these points N – 1 order polynomial

It is not possible to assign initial and final velocities as the order of polynomial increases, its oscillatory behaviour increases (not natural trajectories)

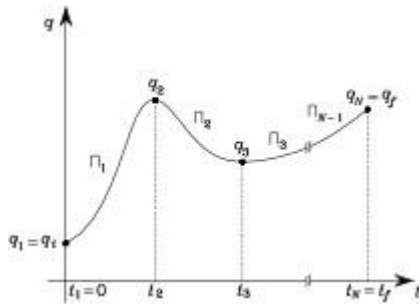
Numerical accuracy for computation of polynomial coefficients decreases as order increases

the resulting system of constraint equations is heavy to solve polynomial coefficients

depend on all the assigned points

⇒ if it is desired to change a point, all of them have to be recomputed

Sequence of low-order (cubic) interpolating polynomials continuous at path points.



- * arbitrary values of $\dot{q}(t)$ are imposed at path points
- * the values of $\dot{q}(t)$ at path points are assigned according to a certain criterion
- * acceleration $\ddot{q}(t)$ has to be continuous at path points
- Interpolating polynomials of order less than three which determine trajectories passing nearby path points at given instants of time
- Interpolating polynomials with imposed velocities at path points.

$$\Pi_k(t_k) = q_k$$

$$\Pi_k(t_{k+1}) = q_{k+1}$$

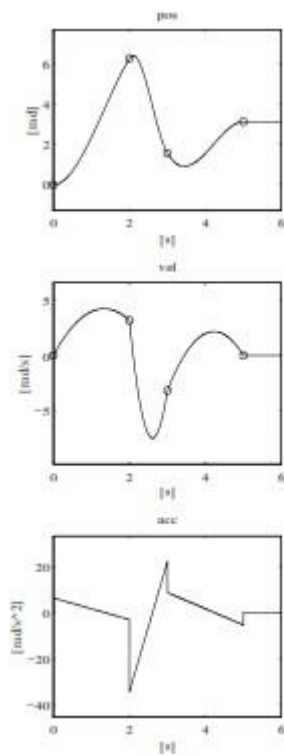
$$\dot{\Pi}_k(t_k) = \dot{q}_k$$

$$\dot{\Pi}_k(t_{k+1}) = \dot{q}_{k+1}$$

$$\dot{\Pi}_k(t_{k+1}) = \dot{\Pi}_{k+1}(t_{k+1})$$

- * continuity of velocity at path points

- Example

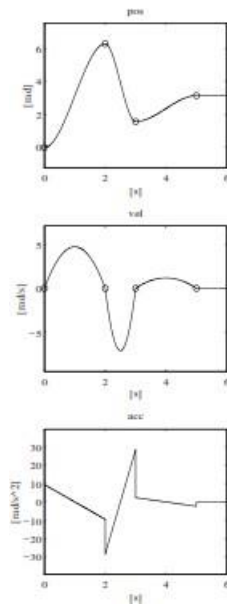


Interpolating polynomials with computed velocities at path points

$$\begin{aligned} \dot{q}_1 &= 0 \\ \dot{q}_k &= \begin{cases} 0 & \text{sgn}(v_k) \neq \text{sgn}(v_{k+1}) \\ \frac{1}{2}(v_k + v_{k+1}) & \text{sgn}(v_k) = \text{sgn}(v_{k+1}) \end{cases} \\ \dot{q}_N &= 0 \end{aligned}$$

$$v_k = (q_k - q_{k-1}) / (t_k - t_{k-1})$$

- Example



- Interpolating polynomials with continuous accelerations at path points (splines)

$$\begin{aligned} \Pi_{k-1}(t_k) &= q_k \\ \dot{\Pi}_{k-1}(t_k) &= \dot{\Pi}_k(t_k) \\ \ddot{\Pi}_{k-1}(t_k) &= \ddot{\Pi}_k(t_k) \end{aligned}$$

★ $4N - 2$ equations in $4(N - 1)$ unknown coefficients (fourth-order polynomials for first and last segment?)

★ 2 virtual points (continuity on position, velocity and acceleration) $\Rightarrow N + 1$ cubic polynomials

$4(N - 2)$ equations for the $N - 2$ intermediate path points:

$$\begin{aligned} \Pi_{k-1}(t_k) &= q_k \\ \dot{\Pi}_{k-1}(t_k) &= \dot{\Pi}_k(t_k) \\ \ddot{\Pi}_{k-1}(t_k) &= \ddot{\Pi}_k(t_k) \end{aligned}$$

$$\begin{aligned} \Pi_1(t_1) &= q_i \\ \dot{\Pi}_1(t_1) &= \dot{q}_i \\ \ddot{\Pi}_1(t_1) &= \ddot{q}_i \end{aligned}$$

$$\begin{aligned} \Pi_{N+1}(t_{N+2}) &= q_f \\ \dot{\Pi}_{N+1}(t_{N+2}) &= \dot{q}_f \\ \ddot{\Pi}_{N+1}(t_{N+2}) &= \ddot{q}_f \end{aligned}$$

6 equations for the initial and final points

6 equations for the virtual points

$$\begin{aligned} \Pi_1(t_1) &= q_i \\ \dot{\Pi}_1(t_1) &= \dot{q}_i \\ \ddot{\Pi}_1(t_1) &= \ddot{q}_i \\ \Pi_{N+1}(t_{N+2}) &= q_f \\ \dot{\Pi}_{N+1}(t_{N+2}) &= \dot{q}_f \\ \ddot{\Pi}_{N+1}(t_{N+2}) &= \ddot{q}_f \end{aligned}$$

* computationally efficient algorithm

$$\ddot{\Pi}_k(t) = \frac{\ddot{\Pi}_k(t_k)}{\Delta t_k}(t_{k+1} - t) + \frac{\ddot{\Pi}_k(t_{k+1})}{\Delta t_k}(t - t_k)$$

$$\begin{aligned} \Pi_k(t) = & \frac{\ddot{\Pi}_k(t_k)}{6\Delta t_k}(t_{k+1} - t)^3 + \frac{\ddot{\Pi}_k(t_{k+1})}{6\Delta t_k}(t - t_k)^3 \\ & + \left(\frac{\Pi_k(t_{k+1})}{\Delta t_k} - \frac{\Delta t_k \ddot{\Pi}_k(t_{k+1})}{6} \right) (t - t_k) \\ & + \left(\frac{\Pi_k(t_k)}{\Delta t_k} - \frac{\Delta t_k \ddot{\Pi}_k(t_k)}{6} \right) (t_{k+1} - t) \end{aligned}$$

4 unknowns

N variables q_k for $k = 2, N + 1$ specified

continuity on q_2 and q_{N+1}

continuity on q_k for $k = 3, \dots, N$

q_i and q_f specified

continuity on q_k for $k = 2, \dots, N + 1$

$$\begin{aligned} \dot{\Pi}_1(t_2) &= \dot{\Pi}_2(t_2) \\ &\vdots \\ \dot{\Pi}_N(t_{N+1}) &= \dot{\Pi}_{N+1}(t_{N+1}) \end{aligned}$$

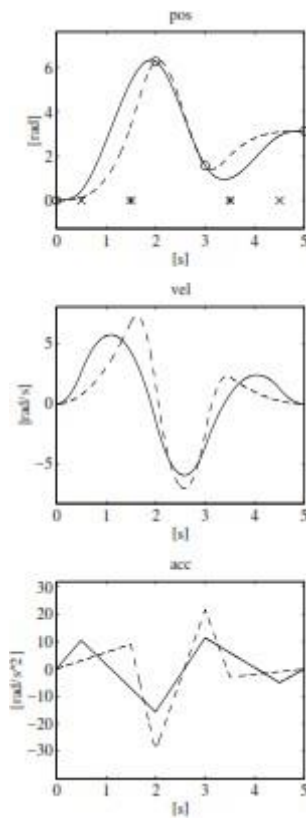
q_i and q_f specified

• **System of linear equations**

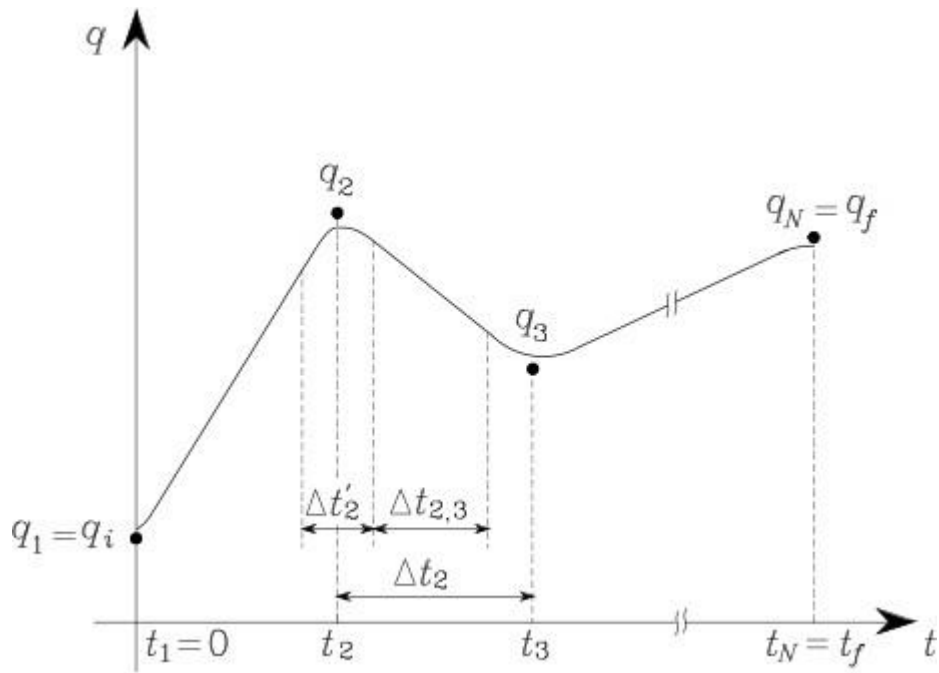
$$A [\ddot{\theta}_2(t_2) \quad \dots \quad \ddot{\theta}_{N+1}(t_{N+1})]^T = \mathbf{b}$$

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & 0 & 0 \\ a_{21} & a_{22} & \dots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \dots & a_{N-1,N-1} & a_{N-1,N} \\ 0 & 0 & \dots & a_{N,N-1} & a_{NN} \end{bmatrix}$$

• **Example**



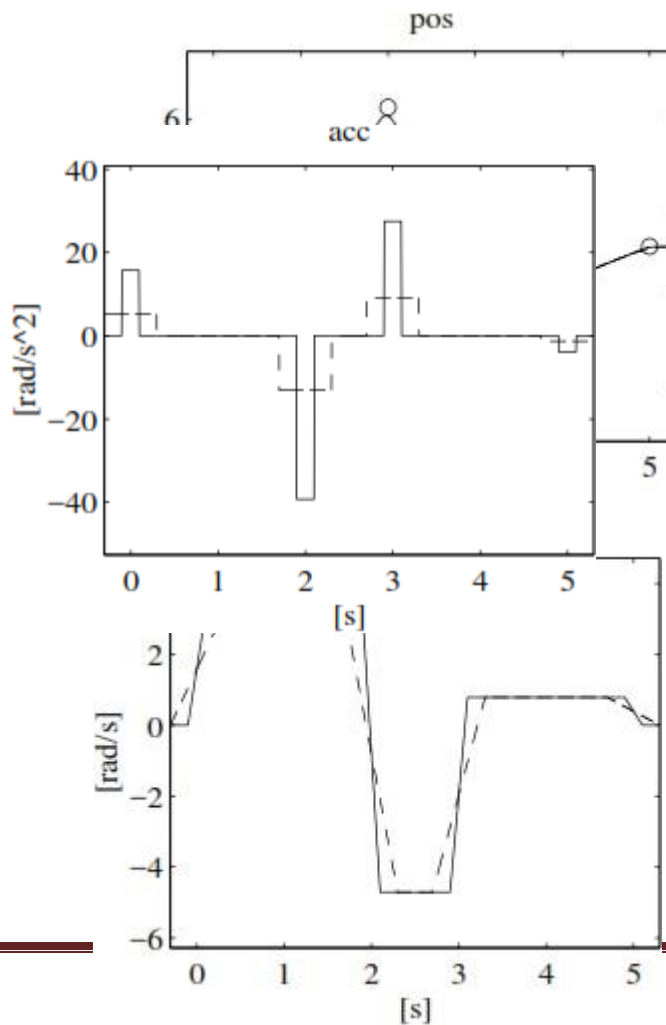
- Interpolating linear polynomials with parabolic blends



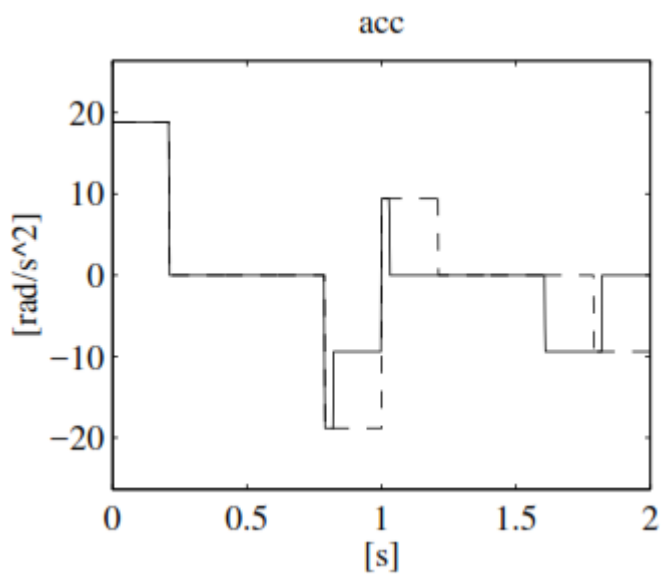
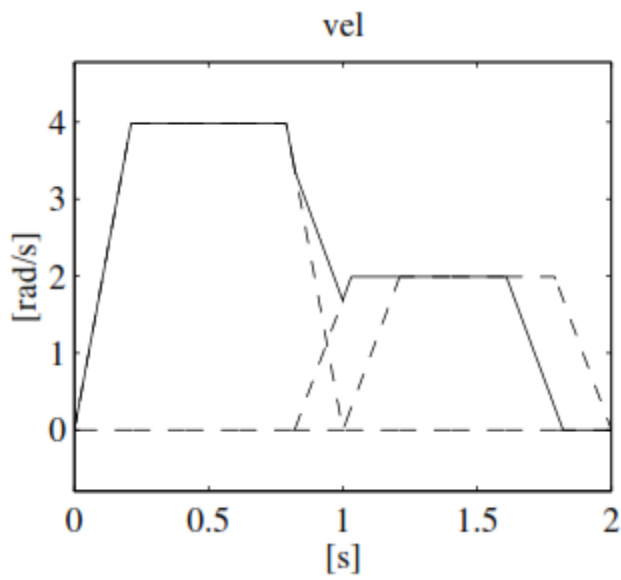
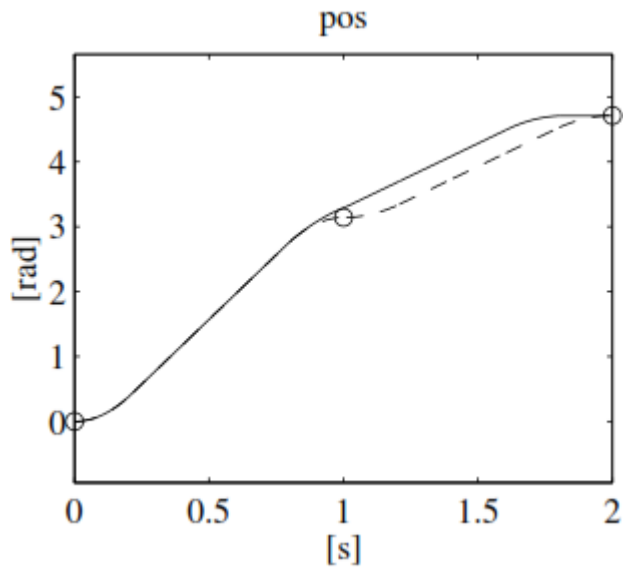
$$\dot{q}_{k-1,k} = \frac{q_k - q_{k-1}}{\Delta t_{k-1}}$$

$$\ddot{q}_k = \frac{\dot{q}_{k,k+1} - \dot{q}_{k-1,k}}{\Delta t'_k}$$

- Example



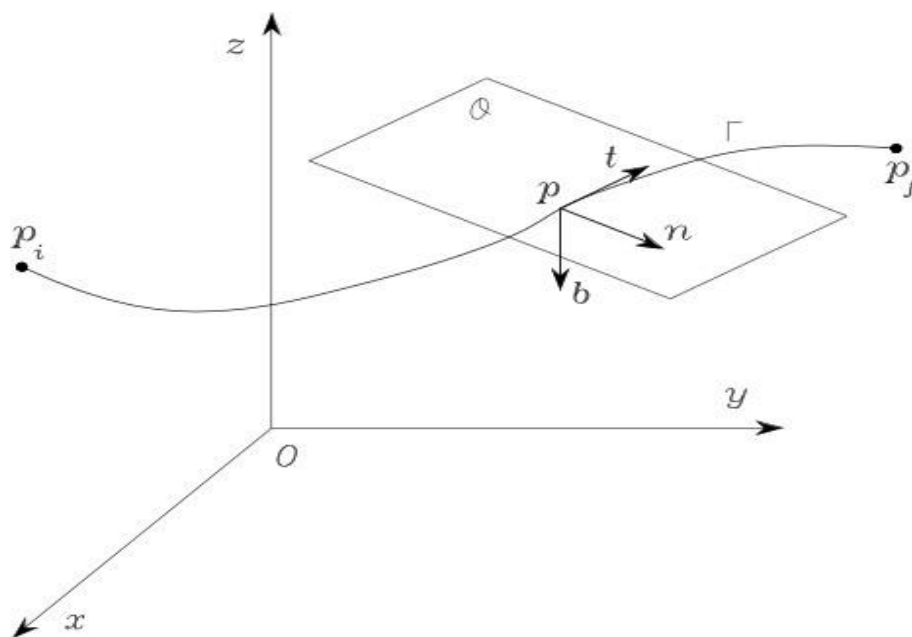
- Application of Trapezoidal Velocity Profile Law to Interpolation Problem



OPERATIONAL SPACE TRAJECTORIES

- Sequence of path points
 - ★ inverse kinematics
 - ★ joint space trajectories
 - ★ microinterpolation
- Path points $x(t_k)$
 - ★ components $x_i(t_k)$ interpolated with sequence of polynomials
- Path primitives
 - ★ analytical description of motion

Path primitives



- Parametric description of path in space
 $p = f(s)$

$$\mathbf{t} = \frac{d\mathbf{p}}{ds}$$

$$\mathbf{n} = \frac{1}{\left\| \frac{d^2\mathbf{p}}{ds^2} \right\|} \frac{d^2\mathbf{p}}{ds^2}$$

$$\mathbf{b} = \mathbf{t} \times \mathbf{n}$$

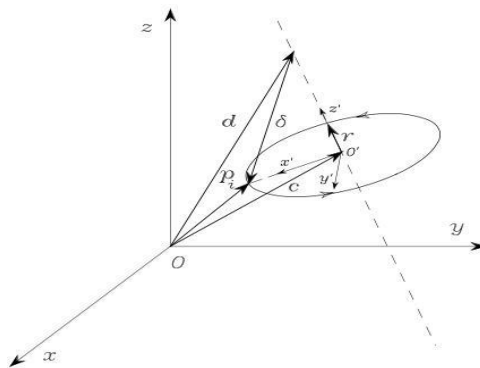
Rectilinear path

$$\mathbf{p}(s) = \mathbf{p}_i + \frac{s}{\|\mathbf{p}_f - \mathbf{p}_i\|} (\mathbf{p}_f - \mathbf{p}_i)$$

$$\frac{d\mathbf{p}}{ds} = \frac{1}{\|\mathbf{p}_f - \mathbf{p}_i\|} (\mathbf{p}_f - \mathbf{p}_i)$$

$$\frac{d^2\mathbf{p}}{ds^2} = \mathbf{0}$$

Circular path



$$\mathbf{p}'(s) = \begin{bmatrix} \rho \cos (s/\rho) \\ \rho \sin (s/\rho) \\ 0 \end{bmatrix}$$

$$\mathbf{p}(s) = \mathbf{c} + \mathbf{R}\mathbf{p}'(s)$$

$$\frac{d\mathbf{p}}{ds} = \mathbf{R} \begin{bmatrix} -\sin (s/\rho) \\ \cos (s/\rho) \\ 0 \end{bmatrix}$$

$$\frac{d^2\mathbf{p}}{ds^2} = \mathbf{R} \begin{bmatrix} -\cos (s/\rho)/\rho \\ -\sin (s/\rho)/\rho \\ 0 \end{bmatrix}$$

UNIT - IV

ROBOT ACTUATORS AND FEEDBACK COMPONENTS

Actuators and Drive Systems

Actuators are one of the key components contained in a robotic system. A robot has many degrees of freedom, each of which is a servoed joint generating desired motion. We begin with basic actuator characteristics and drive amplifiers to understand behavior of servoed joints.

Most of today's robotic systems are powered by electric servomotors. Therefore, we focus on electromechanical actuators.

4.1 DC Motors

Figure 2-1 illustrates the construction of a DC servomotor, consisting of a stator, a rotor, and a commutation mechanism. The stator consists of permanent magnets, creating a magnetic field in the air gap between the rotor and the stator. The rotor has several windings arranged symmetrically around the motor shaft. An electric current applied to the motor is delivered to individual windings through the brush-commutation mechanism, as shown in the figure. As the rotor rotates the polarity of the current flowing to the individual windings is altered. This allows the rotor to rotate continually.

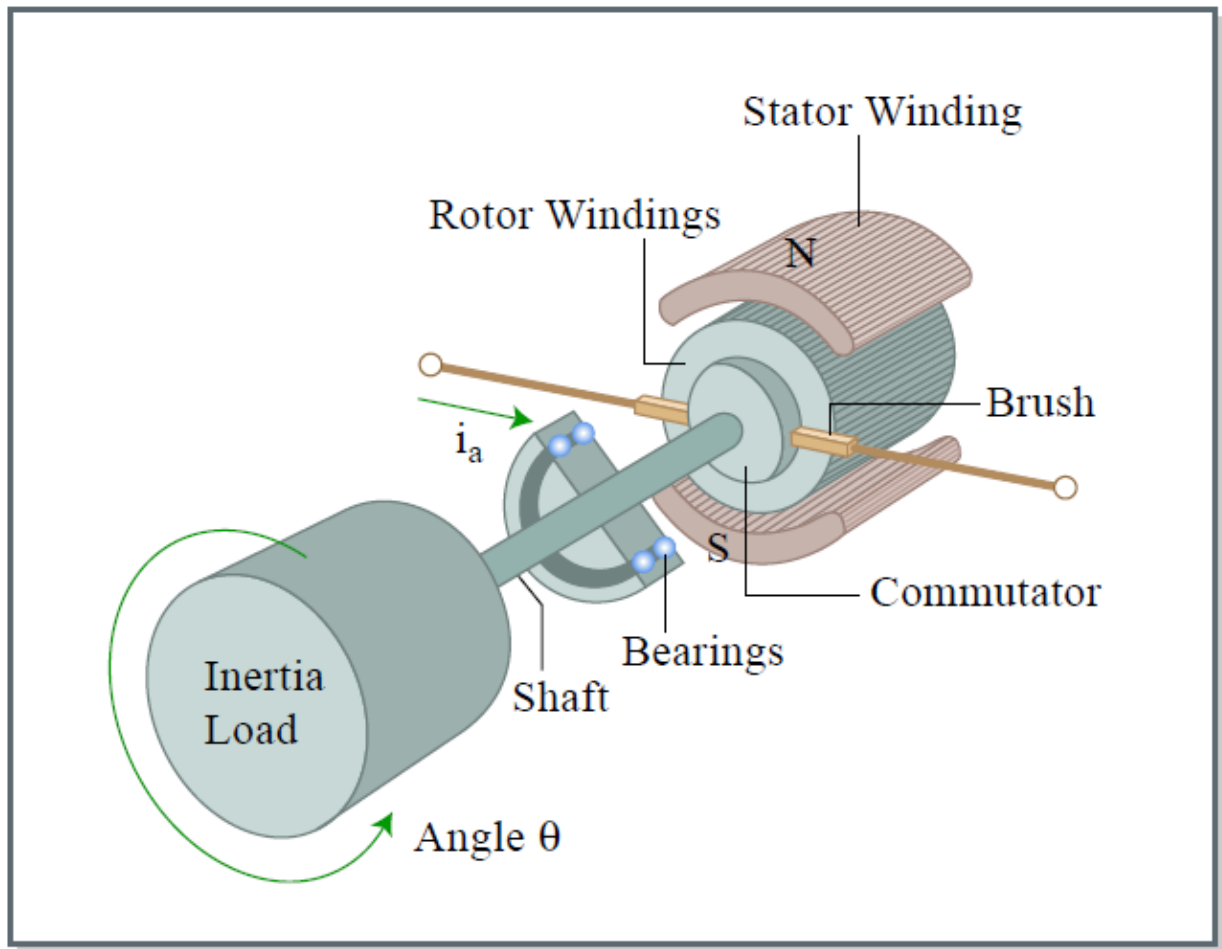


Figure 4.1.1 Construction of DC motor

Sensors and Controllers in robots

Sensors and controllers (sensor types)

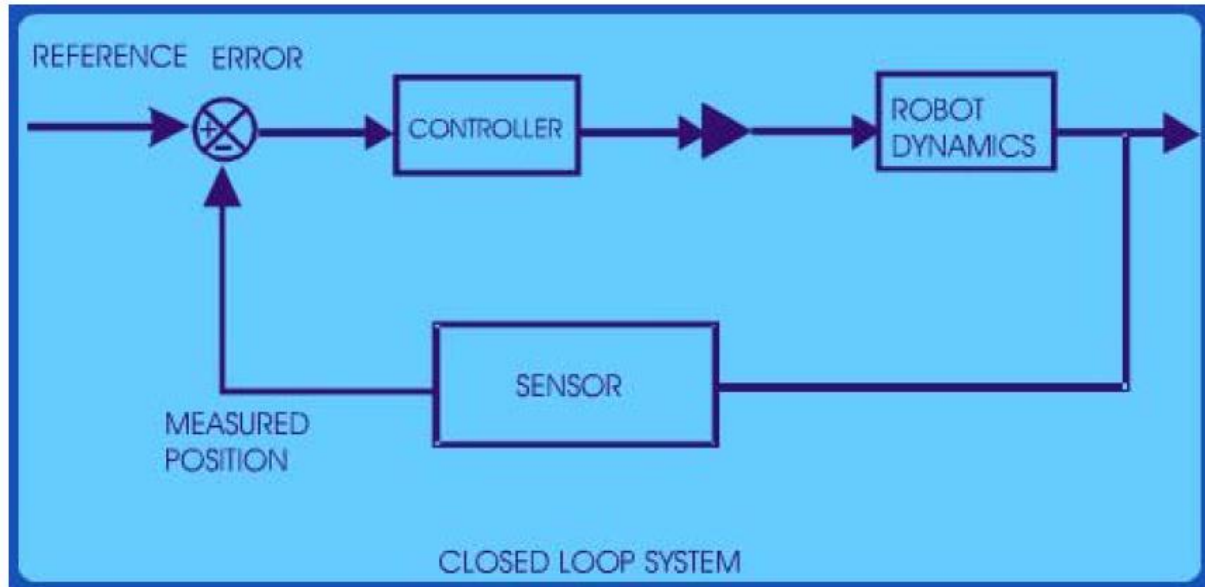
Objectives

In this course you will learn about

- Actuators: Stepper Motors, Electric DC motors, Hydraulic & Pneumatic Actuators
- Temperature, Bearing Forces, Frequency response
- Brawn Vs. Brain
- Sensors
- Internal State / External State
- Basic Movements – Position, Velocity, Acceleration

- Interaction with environment – Torques, Forces, Touch, Slip, Range, Vision

CLOSED LOOP SYSTEM



UNIT - V

ROBOT APPLICATION IN MANUFACTURING

Introduction

There are many robot applications in which the robot is required to move a workpart or other material from one location to another. The most basic of these applications is where the robot picks the part up from one position and transfers it to another position. In other applications, the robot is used to load and/or unload a production machine of some type. We divide material-handling applications into two specific categories:

1. Material transfer applications
2. Machine loading/unloading applications.

GENERAL CONSIDERATIONS IN ROBOT MATERIAL HANDLING:-

In planning an application in which the robot will be used to transfer parts, load a machine, or other similar operation, there are several considerations that must be reviewed.

1. **Part positioning and orientation:** In most parts-handling applications the parts must be presented to the robot in a known position and orientation.
2. **Gripper design:** Special end effectors must be designed for the robot to grasp and hold the workpart during the handling operation
3. **Minimum distances moved:** The material-handling application should be planned so as to minimize the distances that the parts must be moved.
4. **Robot work volume:** The cell layout must be designed with proper consideration given to the robot's capability to reach the required extreme locations in the cell and still allow room to maneuver the gripper.
5. **Robot weight capacity:** There is an obvious limitation on the material handling operation that the load capacity of the robot must not be exceeded. A robot with sufficient weight-carrying capacity must be specified for the application.
6. **Accuracy and repeatability:** Some applications require the materials to be handled with very high precision. Other applications are less demanding in this respect.
7. **Robot configuration, degrees of freedom, and control:** Many parts transfer operations are simple enough that they can be accomplished by a robot with two to four joints of motion. Machine-loading applications often require more degrees of freedom. Palletizing operations, and picking parts from a moving conveyor are examples where the control

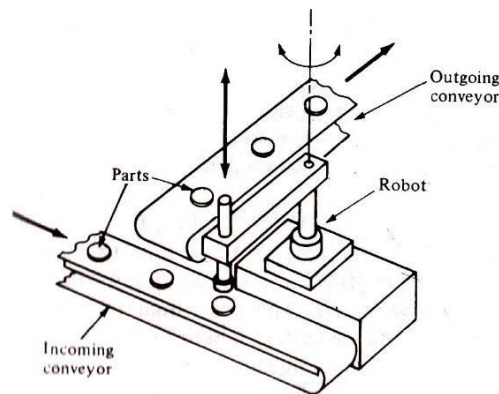
requirements are more demanding

8. **Machine utilization problems:** It is important for the application to effectively utilize all pieces of equipment in the cell. In a machine loading/unloading operation, it is common for the robot to be idle while the machine is working, and the machine to be idle while the robot is working.

MATERIAL TRANSFER APPLICATIONS OF ROBOT:

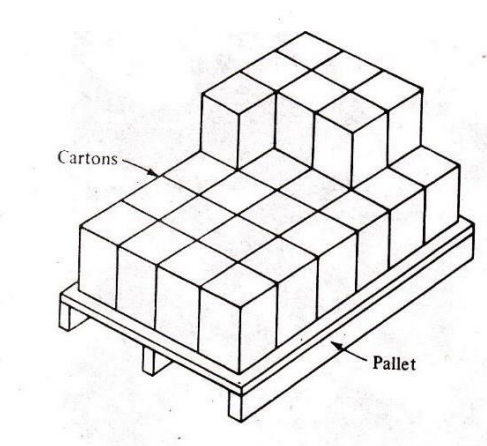
Material transfer applications are defined as operations in which the primary objective is to move a part from one location to another location. They are usually considered to be among the most straightforward of robot applications to implement.

Pick-and-Place Operations:



In pick and-place operation, the robot pick up the part at one location and moves it to another location. The part is available to the robot by mechanical feeding device or belt conveyor in a known location and orientation. A simple limit switch is used to stop the component to allow the part to grasp by robot pick up, move with part and position the part at a desired location. The orientation of the part remains unchanged during the travelling. The basic operation are shown in figure. In this case, 2 DOF is involved, one degree of freedom is required to lift the component from pickup point and put it down at the drop-off point and second! DOF is needed to move the part between these two positions. In some cases, a reorientation of the component is accomplished during the move period.

Palletizing and related operations:



In material transfer application of robot, the use of pallets for material handling and storage is done. Large number of containers are placed on a pallet for material handling and storage is done. Large number of containers are placed on a pallet, instead of handling individual cartons. The pallets are moved mechanically within the manufacturing plant or warehouse by fork lift trucks or conveyors. The only handling of the individual cartons arises when the component is placed onto the pallet or when it is removed from the pallet. The loading of cartons onto pallets is typically heavy work performed manually by unskilled labour. A typical pallet configuration is shown configure below. Each carton is placed at a different location on the pallet, the variation in carton location is in three dimensions. The pallets are usually stacked on top of each other in layers as shown in figure.

MACHINE LOADING AND UNLOADING OF ROBOT:-

These applications are material-handling operations in which the robot is us to service a production machine by transferring parts to and/or from the machine. There are three cases that fit into this application category:

Machine load/unload: The robot loads a raw workpart into the process and unloads a finished part. A machining operation is an example of this case.

Machine loading: The robot must load the raw workpart or materials into if machine but the part is ejected from the machine by some other means a press working operation the robot may be programmed to load metal blanks into the press but the finished parts are allowed to drop out of the press by gravity.

Machine unloading: The machine produces finished parts from raw material that are loaded directly into the machine without robot assistance. The robot unloads the part from the machine. Examples in this category include die casting and plastic modeling applications.

Robots have been successfully applied to accomplish the loading and/or unloading function in the following production operations:

- Die casting
- Plastic molding
- Forging and related operations
- Machining operations
- Stamping press operations
-

Die casting:

Die casting is a manufacturing process in which molten metal is forced into the cavity of a mold under high pressure. The mold is called a die (hence the name, die casting). The process is used to cast metal parts with sufficient accuracy so that subsequent finishing operations are usually not required. Common metals used for die-casted parts include alloys of zinc, tin, lead, aluminum, magnesium, and copper.

The die consists of two halves that are opened and closed by a die casting machine. During operation the die is closed and molten metal is injected into the cavity by a pump. To ensure that the cavity is filled, enough molten metal is forced into the die that it overflows the cavity and creates “flash” in the space between the die halves. When the metal has solidified, the die is opened and the cast part is ejected, usually by pins which push the part away from the mold cavity. When the part is removed from the machine, it is often quenched (to cool the part) in a water bath. The flash that is created during the casting process must be removed subsequently by a trimming operation which cuts around the periphery of the part. Thus, the typical die-casting production cycle consists of casting, removing the part from the machine, quenching, and trimming.

The production rates in the die-casting process range from about 100 up to 700 openings of the die per hour, depending on type of machine, the metal being cast, and the design of the part.

The die-casting process represents a relatively straightforward application for industrial robots.

Plastic Molding:

Plastic molding is a batch-volume or high-volume manufacturing process used to make plastic parts to final shape and size. The term plastic molding covers a number of processes, including compression molding, injection molding, thermoforming, blow molding, and extrusion. Injection molding is the most important commercially, and is the process in this group for which robots are

most often used. The injection-molding operation is quite similar to die casting except for the differences in materials being processed. A thermoplastic material is introduced into the process in the form of small pellets or granules from a storage hopper. It is heated in a heating chamber to 200 to 300 C to transform it into semifluid (plastic) state and injected into the mold cavity under high pressure. The plastic travels from the heating chamber into the part cavity through a sprue-and-runner network that is designed into the mold. If too much plastic is injected into the mold Hash is created where the two halves of the mold come together. If too little material is injected into the unacceptable. When the plastic material has hardened sufficiently the mold opens and the part(s) are removed from the mold.

Forging and related operations:

Forging is a metalworking process in which metal is pressed or hammered into the desired shape. It is one of the oldest processes and derived from the kinds of metalworking operations performed by blacksmiths in ancient times. It is most commonly performed as a hot working process in which the metal is heated to a high temperature prior to forging. It can also be done as a cold working process. Cold forging adds considerable strength to the metal and is used for high-quality products requiring this property such as hand tools (e.g., hammers and wrenches). Even in hot forging, the metal flow induced by the hammering process adds strength to the formed part.

Machining operations:

Machining is a metal working process in which the shape of the part is changed by removing excess material with a cutting tool. It is considered to be a secondary process in which the final form and dimensions are given to the part after a process such as casting or forging has provided the basic shape of the part. There are a number of different categories of machining operations. The principal types include turning, drilling, milling, shaping, planing, and grinding.

The machine tools that perform machining operations have achieved a relatively high level of automation after many years of development. In particular the use of computer control (e.g., computer numerical control and direct numerical control) permits this type of equipment to be interfaced with relative ease to similarly controlled equipment such as robots.

Robots have been successfully utilized to perform the loading and unloading functions in machining operations. The robot is typically used to load a raw workpart (a casting, forging, or other basic form) into the machine tool and to unload the finished part at the completion of the machining cycle.

The following robot features generally contribute to the success of the machine tool load/unload application:

Dual gripper: The use of a dual gripper permits the robot to handle the raw workpart and the finished part at the same time. This permits the production cycle time to be reduced.

Up to six joint motions: A large number of degrees of freedom of the arm and wrist are required to manipulate and position the part in the machine tool.

Good repeatability: A relatively high level of precision is required to properly position the part into the chuck or other work holding fixture in the machine tool.

Palletizing and depalletizing capability: In mid volume production, the raw parts are sometimes most conveniently presented to the workcell and delivered away from the workcell on pallets. The robot's controller and programming capabilities must be sufficient to accommodate this requirement.

Programming features: There are several desirable programming features that facilitate the use of robots in machining applications. In machine cells used for batch production of different parts, there is the need to perform some sort of changeover of the setup between batches. Part of this changeover procedure involves replacing the robot program for the previous batch with the program for the next batch. The robot should be able to accept disk, tape, or other storage medium for ease in changing programs. Another programming feature needed for machining is the capability to handle irregular elements, such, as tool changes or pallet changes, in the program.

Stamping press operations:

Stamping press operations are used to cut and form sheet metal parts. The process is performed by means of a die set held in a machine tool called a press (or stamping press). The sheet metal stock used as the raw material in the process comes in several forms, including coils, sheets, and individual flat blanks. When coil stock is fed into the press, the process can be made to operate in a highly automated manner at very high cycle rates. When the starting material consists of large flat sheets or individual blanks, automation becomes more difficult. These operations have traditionally been performed by human workers, who must expose themselves to considerable jeopardy by placing their hands inside the press in order to load the blanks. During the last decade, the Occupational Safety and Health Act (OSHA) has required certain alterations in the press in order to make its operation safer. The economics of the OSHA requirements have persuaded many manufacturers to consider the use of robots for press loading as alternatives to human operators. Noise is another factor which makes press working an unfriendly environment for humans.

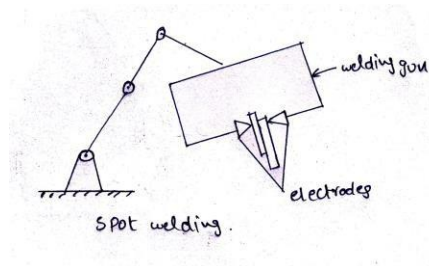
PROCESSING OPERATIONS:-

In processing operations, the robots uses a tool as end effector to accomplish some processing operations on a work part. Manipulates the tooling relative to the working part during the cycle.

In processing operation, the robot performed by the following categories:

- Spot welding
- Continuous arc welding
- Spray coating
- Other processing operations.

Spot welding:



As the term suggests, spot welding is a process in which two sheet metal parts are fused together at localized points by passing a large electric current through the parts where the weld is to be made. The fusion is accomplished at relatively low voltage levels by using two copper (or copper alloy) electrodes to squeeze the parts together at the contact points and apply the current to the weld area. The electric current results in sufficient heat in the contact area to fuse the two metal parts, hence producing the weld.

Spot welding has traditionally been performed manually by either of two methods. The first method uses a spot-welding machine in which the parts are inserted between the pair of electrodes that are maintained in a fixed position. This method is normally used for relatively small, parts that can be easily handled.

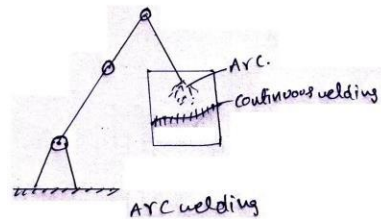
The second method involves manipulating a portable spot-welding gun into position relative to the parts. This would be used for larger work such as automobile bodies. The word “portable” is perhaps an exaggeration. The welding gun consists of the pair of electrodes and a frame to open and close the electrodes. In addition, large electrical cables are used to deliver the current to the electrodes from a control panel located near the workstation. The welding gun with cables attached is quite heavy and can easily exceed 100 lb in weight.

Capabilities and features of robot in spot welding:-

1. The robot must be relatively large.
2. It must be sufficient payload capacity.
3. The work volume must be adequate for the size of the product.
4. It should have increase number of DOF
5. The controller memory must have enough capacity to accomplish the many positioning steps required for the spot welding.

6. The robot must be able to switch from one program holding sequence to another as the model change.
7. Benefits of robot in spot welding:
8. Improved production quality
9. Operator safety
10. Better control over the production.

Continuous arc welding



Arc welding is a continuous welding process as opposed to spot welding which might be called a discontinuous process. Continuous arc welding is used to make long welded joints in which an airtight seal is often required between the two pieces of metal being joined. The process uses an electrode in the form of a rod or wire of metal to supply the high electric current needed for establishing the arc. Currents are typically 100 to 300A at voltages of 10 to 30 V. The arc between the welding rod and the metal parts to be joined produces temperatures that are sufficiently high to form a pool of molten metal to fuse the two pieces together. The electrode can also be used to contribute to the molten pool, depending on the type of welding process.

The high temperatures created in arc welding and the resulting molten metals are inherently dangerous. The high electrical current used to create the arc is also unsafe; Sparks and smoke are generated during the process and these are a potential threat to the operator.

Features of the Welding Robot:

Work volume and degrees of freedom: The robot's work volume must be large enough for the sizes of the parts to be welded.

Motion control system: Continuous-path control is required for arc welding. The robot must be capable of a smooth continuous motion in order to maintain uniformity of the welding seam.

Precision of motion: The accuracy and repeatability of the robot determines to a large extent the quality of the welding job.

Interface with other systems: The robot must be provided with sufficient input/output and control capabilities to work with the other equipment in the cell.

Programming: Programming the robot for continuous arc welding must be considered carefully.

Advantages and Benefits of Robot Arc Welding:

A robot arc-welding cell for batch production has the potential for achieving a number of advantages over a similar manual operation. These advantages include the following:

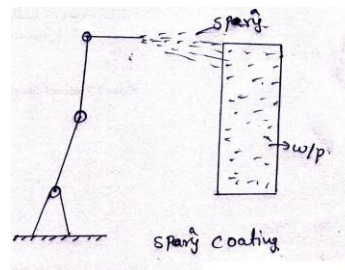
- Higher productivity
- Improved safety and quality-of-work life
- Greater quality of product
- Process rationalization.
- Sensors in Robotic Arc –Welding:

The robotic arc-welding sensor systems considered here are all designed to track the welding seam and provide information to the robot controller to help guide the welding path. The approaches used for this purpose divide into two basic categories: contact and noncontact sensors. There are two types of sensor systems,

Contact arc-welding sensors

Noncontact arc-welding sensors.

3. Spray coating:



Most products manufactured from metallic materials require some form of painted finish before delivery to the customer. The technology for applying these finishes varies in complexity from simple manual methods to highly sophisticated automatic techniques. We divide the common industrial coating methods into two categories:

1. Immersion and Flow-coating methods
2. Spray-coating methods.

Immersion and flow-coating methods are generally considered to be low-technology methods of applying paint to the product. Immersion involves simply dipping the part or product into a tank of liquid paint. When the object is removed, the excess paint drains back into the tank. The tanks used in the process can range in size from 1 or 2 gallons for small objects to thousands of gallons for large fabricated metal products.

The second major category of industrial painting is spray coating. This method involves the use of

spray guns to apply the paint or other coating to the object. Spray painting is typically accomplished by human workers who manually direct the spray at the object so as to cover the desired areas. The paint spray systems come in various designs, including conventional air spray, airless spray, and electrostatic spray.

In general, the requirements of the robot for spray-coating applications are the following:

1. Continuous-path control
2. Hydraulic drive
3. Manual lead through programming
4. Multiple program storage.

Benefits of Robot Spray Coating:

1. Removals of operators from hazardous environment
2. Lower energy consumption
3. Consistency of finish
4. Reduced coating material usage
5. Greater productivity.

OTHER PROCESSING OPERATIONS USING ROBOTS:

In addition to spot welding, arc welding, and spray coating, there are a number of other robot applications which utilize some form of specialized tool as the end effector. Operations which are in this category include:

1. Drilling, routing, and other machining operations,
2. Grinding, polishing, deburring, wire brushing, and similar operations, Riveting,
3. Waterjet cutting,
4. Laser drilling and cutting.

Assembly operations:

1. The term assembly is defined here to mean the fitting together of two or more discrete parts to form a new subassembly. The assembly operations are,
2. Parts presentation methods
3. Assembly tasks
4. Assembly cell designs.

Parts presentation methods:

In order for a robot to perform an assembly task, the part that is to be assembled must be presented to the robot. There are several ways to accomplish this presentation function, involving various levels of structure in the workplace:

1. Parts located within a specific area (parts not positioned or oriented)
2. Parts located at a known position (parts not oriented)
3. Parts located in a known position and orientation.
- 4.

Parts located within a specific area (parts not positioned or oriented):

In this case, the robot is required to use some form of sensory input to guide it to the part location and to pick up the part.

Parts located at a known position (parts not oriented):

In the second case, the robot would know where to go to get the part, but would then have to solve the orientation problem. This might require the robot to perform an additional handling operation to orient the part.

Parts located in a known position and orientation:

The third way of presenting the part to the robot (known position and orientation) is the most common method currently used, and is in fact the method used in automatic assembly that precedes the advent of robotics.

There are a number of methods for presenting parts in a known position and orientation, they are

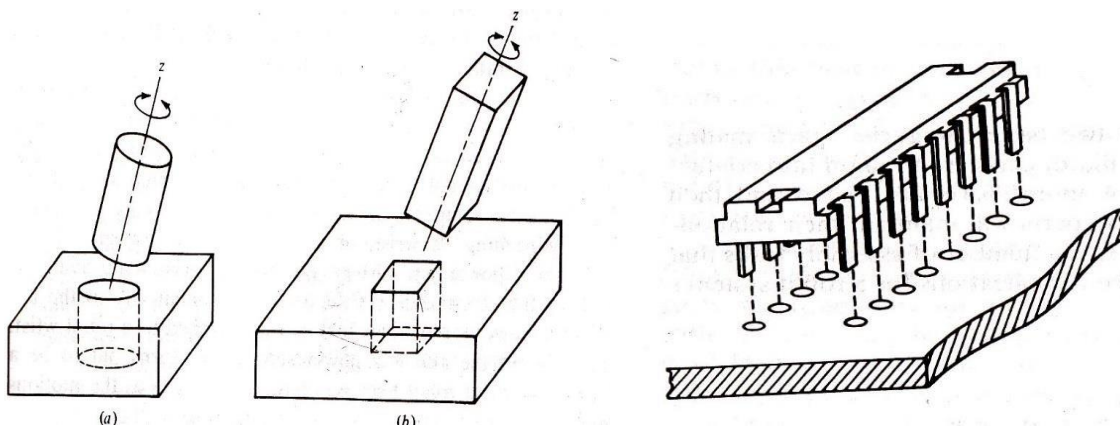
1. Bowl feeders
2. Magazine feeders
3. Trays and pallets
4. Assembly tasks:

Assembly operations can be divided into two basic categories:

- parts mating and
- parts joining.

parts mating :

In parts mating, two (or more) parts are brought into contact with each other. The variety of parts mating operations include the following assembly situations:



1. Peg-in-hole. This operation involves the insertion of one part (the peg) into another part (the hole). It represents the most common assembly task.
2. Hole-on-peg. This is a variation of the peg-in-hole task. Similar problems exist in defining the degrees of freedom needed to execute the mating of the two parts. A typical example of the hole-on-peg task would be the placement of a bearing or gear onto a shaft.
3. Multiple peg-in-hole. This is another variation on case 1 except that one.

parts joining:

In parts joining, two (or more) parts are mated and then additional steps are taken to ensure that the parts will maintain their relationship with each other.

The possible joining operations include the following:

- Fastening screws
- Retainers
- Press fits
- Snap fits
- Welding and related joining methods
- Adhesives
- Crimping
- Sewing.

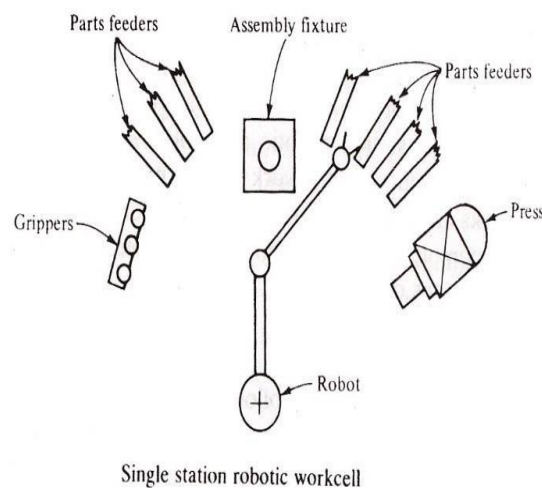
ASSEMBLY SYSTEM CONFIGURATIONS:

There are two basic configurations of assembly systems, a single workstation, and a series of workstations (an assembly line). Combinations of these two basic types are also possible.

Single-Workstation Assembly:

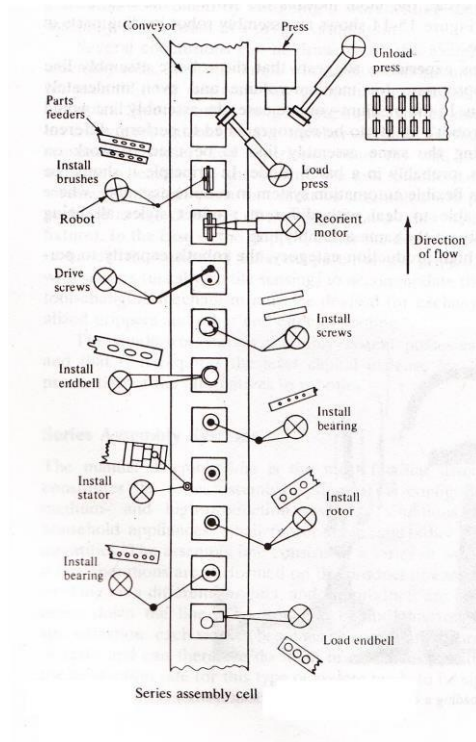
In this configuration all of the parts which are required to complete the desired assembly are

presented to the operator or robot at a single workstation. All of the parts mating and joining tasks for the assembly are accomplished at the single workstation. In manual assembly, this configuration is generally used for low-volume products (e.g., custom-engineered machinery). In robotic assembly, the conditions warranting the use of this configuration are different from those for manual assembly. A single-station robotic assembly system would typically be used for low- and medium-volume work in which there were a limited number of assembly tasks and parts to be handled. This means that the product is of low to medium complexity. The features and problems of this configuration are illustrated by means of an example.

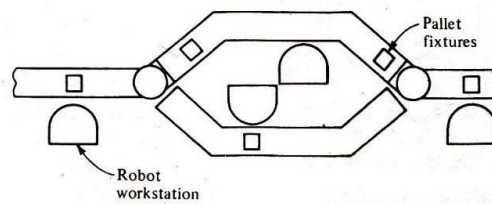


Series Assembly Systems:

The manual assembly line is the most familiar assembly configuration. It constitutes the series assembly system. This configuration is used in many medium- and high-production assembly situations, such as automobiles, household appliances, small power tools, and other products made in large quantities. The assembly line consists of a series of workstations at which only a few operations are performed on the product at each station. Each station is working on a different product, and the products are gradually built up as they move down the line.



Parallel Assembly Systems:



The concept of a parallel arrangement in a robotic workcell is pictured in Fig. In essence the work can take either of two (or more) routes to have the same operations performed. There are two conditions under which parallel workstations would normally be considered.

Assembly cell designs:-

Certain assembly tasks are more difficult for a robot to perform than others. If possible, this difficulty factor should be considered in the design of the product. As an example, for a robot to accomplish the screw-fastening operation without the use of an automatic screwdriver is difficult.

Even with a powered device to perform the operation, the process of turning the screw into the part requires time. If the objective of using a threaded fastener is to allow for subsequent disassembly (e.g., for service of the product), then the use of screws may be an appropriate design decision.

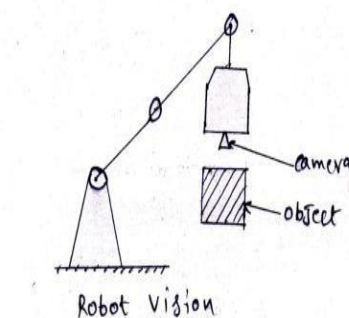
Inspection operations:

Inspection is a quality control operation that involves the checking of parts, assemblies, or products for conformance to certain criteria generally specified by the design engineering department. The inspection function is commonly done for incoming raw materials at various stages of the production process, and at the completion of manufacturing prior to shipping the product. Testing is another quality control operation often associated with inspection. The distinction between the two terms is that testing normally involves the functional aspects of the product, such as testing to ensure that the product operates properly, fatigue testing, environmental testing, and similar procedures.

Robotics can be used to accomplish inspection or testing operations for mechanical dimensions and other physical characteristics, and product function and performance. Generally the robot must work with other pieces of equipment in order to perform the operations. Examples include machine vision systems, robot manipulated inspection and/or testing equipment, and robot loading and unloading operation with automatic test equipment. The following subsections will discuss these three categories of robotic inspection systems.

Vision Inspection Systems:

Machine vision as a sensor in robotics was discussed in Chap. Some of the robotic applications of



vision systems include part location, parts identification, and bin picking. Machine vision can also be used to implement a robotic inspection system. Typical robotic vision systems are capable of analyzing two- dimensional scenes by extracting certain features from the images. Examples of

inspection tasks carried out by this procedure include dimensional accuracy, surface finish, and completeness and correctness of an assembly or product.

Robot-Manipulated Inspection or Test Equipment:

This method of robotic inspection involves the robot moving an inspection or testing device around the part or product. An example would be for a robot to manipulate an electronic inspection probe or a laser probe along the surface of the object to be measured. As long as the accuracy of the measurement is not required to exceed the repeatability of the robot, the approach is feasible.

Robot-Loaded Test Equipment:

The third application area in robotic inspection is loading and unloading inspection and testing equipment. This application is very similar to machine tool loading/unloading. There are various types of inspection and testing equipment that can be loaded by a robot. These include mechanical, electrical, and pneumatic gauges, and functional testing devices.

Unit-I**PART-A**

1. a. Sketch and explain the four basic robot configurations classified according to the co-ordinate system?
b. Differentiate CAD/CAM and robotics?
2. a. What is the importance of automation in industry? Explain?
b. Give the classification of robot by control systems?
3. a. Discuss in detail about magnetic gripper with neat sketch?
b. what do you understand degree of freedom (DOF)? How many DOFS are required to position an effector at any point in 3-D space?
4. a. Explain about robot anatomy in detail with neat sketch?
b. What are the future applications of robots?
5. a. How do you specify a robot? Is robotics automation? Discuss the different classification systems of robots?
b. Define the terms 'robot' and "robotics" discuss the role of robots in engineering?
6. a. Explain how robotics is a technology for future?
b. What are the types of automation? Explain them with examples?
7. a. Explain the importance of robots in automation?
b. Explain about the controllers in detail?
8. a. On what criteria robots are selected for performing tasks assigned?
b. What are the basic components of robotics? Explain them briefly with sketch?
9. a. Name and discuss the future arm configurations that are used in robotic manipulators?
b. Discuss the advantages and disadvantages of using robots in industry?
10. a. Enlist the applications and characteristics of future robots?
b. Sketch and explain two views to indicate the work envelope of a (i). Cartesian robot (ii). Polar robot

Unit-II**PART-A**

1. Define and illustrate the link and joint parameters. Explain their uses.
2. Write short notes on
 - a. Direct and inverse kinematics
 - b. DH convention
3. Write short notes on inverse transforms
4. a. Explain co-ordinate frame assignment of DH representation.
b. List the steps involved in DH convention.
5. Compute the homogeneous transformation representing a translation of 3 units along the x-axis followed by a rotating of $\pi/2$ about the current z-axis followed by a translation of 1 unit along the fixed y-axis. Sketch the frame. What are the coordinates of the o1 with respect to the original frame in each case.
6. A Cartesian co-ordinate robot of configuration L L L is to move its three axes from position $(x,y,z)=(0,5,5)$ to position $(x,y,z)=(20,35,15)$. All distance measures are given in mm the maximum velocities for the three joints are respectively 20mm/sec 15 mm/sec and 10mm/sec determine the time required to move each joint if slew motion is used.
7. a. Explain the importance of homogenous transformations.
b. For the vector $v=25i+10j+20k$, perform a translation by a distance of 8 in the x-direction, 5 in the y- direction and 0 in the z-direction.
8. Draw any two Euler angle systems and show rotation and angles
9. Give Euler angles representation for the RPY system and derive the rotation matrix.
10. a. Find the transformation matrices for the following operations on the point

$$2\hat{i} - 8\hat{j} + 3\hat{k}$$
 - i. Rotate 300 about x-axis and then translate -5 units along y-axis.
 - ii. Translate 2 units along y-axis and rotate 600 about z-axis
11. For the point a $uvw=(6,2,4)T$ perform following operations.
 - a. Rotate 300 about the X axis, followed by translation of 6 units anling Y axis.
 - b. Translate 6 units along Y axis, followed by rotation of 300 about X axis.

- c. Rotate 600 about Z axis followed by translation of 10 units along the rotated U axis.

Unit-III

PART-A

1. a. Explain the Lagrange Euler's formulation for robot arm.
b. Differentiate clearly with reference to 2-jointed manipulate or of RR type and LL type.
2. Explain the following
 - i. Manual programming
 - ii. Lead through teaching
3. Explain the parameters involved in the path planning with 3rd degree polynomial.
4. Discuss the advantages and disadvantages between joint space and scheme and Cartesian-space schemes
5. Enumerate trajectory generation polynomial types.
6. Describe different path control modes in robotics.
7. Explain trajectory planning and show how trajectory planning is done in case of PTP (Point-to-point) robot having constant maximum velocity and finite acceleration and deceleration.
8. a. Explain the following terms
 - i. Trajectory
 - ii. Joint space trajectory planning.
- b. A single link robot with a rotary joint is motionless at $\Theta_0=150$ it is desired to move the joint in a smooth manner to $\Theta_f=750$ in 3sec. Find the coefficients of a cubic which accomplishes this motion and brings the arm to rest at the goal.
9. a. Explain the parameters involved in path planning with 3rd degree polynomial.
b. A single link rotary robot is required to move from $\Theta(0)=450$ to $\Theta(2)=900$ in two seconds. Joint velocity and acceleration are zero at initial and final positions. What is the highest degree polynomial that can be used to accomplish the motion
10. a. Determine the time required for each joint of a three-axis RRR manipulator to travel the following distances using slew motion; joint 1, 1000; joint 2, 300; and joint 3, 600. All joints travel at a rotation velocity of 150/s.
b. Find expressions for the joint motion parameters by using cubic polynomial fit in joint space scheme. Use the following data: $\Theta_0=20$, $\Theta_f=70$ $t=3$ sec.
13. a. Enumerate trajectory generation of polynomial type.
b. One of the joints of articulated robot has to travel from initial angle of 200 to final angle of 840 in 4 seconds. Using 3rd degree polynomials calculate joint angles at one, two, three seconds.

Unit-IV**PART-A**

1. Enlist the main elements of a hydraulic system used in robot and explain their functions briefly.
 - a. Explain the working of DC servo Motor.
 - b. Discuss the principle of a Resolver.
2. a. Explain principle and construction of inductive type proximity sensors.
 - b. Explain the constructions and operation of ultrasonic proximity sensors.
3. Explain the types of touch sensors with neat sketches
4. With a neat sketch explain the tactile sensors and the range sensors
5. Explain the performance and selection criteria of electric motors in robotics
6. Compare the features of most commonly used electric actuators in robotics
7. With a neat sketch explain the following hydraulic actuator.
 - i. Rotary actuator
 - ii. Linear actuator
8. a. With a neat sketch explain tactile sensors and range sensors.
 - b. Explain features and application of hydraulic actuators in robotics
9. a. Give a brief classification of actuators used in robots.
 - b. Explain various types of touch sensors with neat sketch.
- 10 a. Explain the following hydraulic actuator with a neat sketch:
 - i. Robot actuators
 - ii. Linear actuators
11. a. Compare the features of most commercially used electrical actuators in robots.

Unit-V**PART-A**

1. What is spot welding? Describe briefly the operations involved in robotic spot welding.
2. What are the advantages of robotic welding over manual welding?
3. (a) Explain the applications robots in an industrial use.
(b) Explain the following: (i) Accuracy. (ii) Precision.
4. Explain the importance of robots in: (a) Spot welding. (b) Spray painting. (c) Arc welding. (d) Assembly.
5. What type of robot manipulator is best suited for: (a) Machine loading and unloading. (b) Assembly operations.
6. With neat sketches, illustrate the use of robot in a layout of spot welding
7. Explain the applications of a robot in a layout for spray painting.
8. Write a short note on
 - a. work volume
 - b. general considerations of robot in material handling
9. a. What are the considerations of Robots in material handling?
b. What are the features of robot in machine loading and unloading applications?
10. a. What are the applications of robots?
b. Explain spray painting by robots.
11. Explain function of robots in assembly and inspection
12. Explain various methods of part presentation in assembly process
13. Explain pick and palce robots for machining operation die costing and plastic moulding.
14. Explain use of Robots in the fields of welding and painting.
15. Explain with the neat diagram how Robot can be gainfully employed in the inspection methods of component made in large number.
16. Explain automation in inspection.
17. Explain various assembly systems configuration.
18. Explain compliances and remote control compliance device for assembly operations.

SHORT ANSWER QUESTIONS**PART-A**

- 1) What are the advantages of cylindrical arm configuration over a polar arm configuration?
- 2) What are the various types of joints used in robots?
- 3) Write short notes on DH convention.
- 4) What is Manipulator Jacobian?
- 5) What are the functions of robot software?
- 6) Explain the working of position sensors.
- 7) Define payload and work volume of a robot.
- 8) List the advantages of Pneumatic manipulators.
- 9) Write short notes on inverse kinematics.
- 10) Distinguish between Euler-Lagrange and Newton-Euler formulation.
- 11) Define path and trajectory of a robot.
- 12) Discuss robot application for welding and machine loading.
- 13) With help of sketch describe pitch, yaw and roll motion of a robot wrist.
- 14) What are the basic components of a robotic system?
- 15) Explain the importance of homogeneous transformations.
- 16) What are the advantages of Euler-Lagrange formulation?
- 17) Write short notes on joint integrated motion.
- 18) Discuss robot application for assembly and inspection.
- 19) Define a robot and give its applications.
- 20) What are the common types of arms of a robot?
- 21) What is meant by position and orientation of robot?
- 22) What is dynamic modeling?
- 23) What are the advantages of offline programming?
- 24) What are the merits and demerits of moving coil dc motors?
- 25) What is work volume?
- 26) What are the three degrees of freedom associated with the arm and body motion?
- 27) What is meant by pitch, yaw and roll?
- 28) What is jacobian?
- 29) Define skew motion
- 30) List out the types of Drive systems used in Robots.
- 31) What are different types of control system?
- 32) What are the types of locomotive devices?
- 33) What is inverse kinematics explain?
- 34) What is Lagrange – Euler formulations? What are its applications?
- 35) What are different robot programming languages?
- 36) Explain about electric & stepper motors.
- 37) Mention some future applications of robots.
- 38) What are Requirements and challenges of end effectors?
- 39) Differentiate between joint coordinates and world coordinates?
- 40) What is Newton – Euler formulations? What are its applications?
- 41) Illustrate and explain straight line motion.
- 42) Explain about Hydraulic actuators.
- 43) How do you classify robots by coordinate system?

- 44) What are common types of arms?
- 45) What is D-H notation explain in brief?
- 46) What is the purpose of Differential transformation?
- 47) Illustrate and explain joint integrated motion.
- 48) What is potentiometer?
- 49) What is Automation in robotics?
- 50) What are degrees of freedom?
- 51) What is Forward Kinematics Explain?
- 52) What is meant by Jacobian?
- 53) Illustrate and explain Skew motion.
- 54) Explain in brief about spray painting application in robots.
- 55) What are the advantages of Robot when compared with NC Machine Tool?
- 56) What are the different parts of robotic arm? Explain.
- 57) What are the properties of Homogenous Transformation Matrix?
- 58) Draw the Block diagram of Jacobian Forward differential Motion Model.
- 59) What are the different interpolations used for Robot Programming?
- 60) Explain the working principle of Pneumatic actuators.
- 61) Differentiate servo controlled robot and non-servo controlled robot?
- 62) What are the limitations of Adhesive gripper?
- 63) What do you mean by homogeneous transformation?
- 64) What do you mean by manipulator jacobian?
- 65) What are the methods of teaching a robot?
- 66) What are the limitations of potentiometer?
- 67) Give the classification of robot by control system.
- 68) What do you mean by magnetic gripper?
- 69) Define DH parameters.
- 70) What do you mean by Jacobian matrix?
- 71) What are the software packages available for robot programming?
- 72) What features are required for robot in spot welding?
- 73) Differentiate flexible automation and fixed automation.
- 74) What are the types of End effectors?
- 75) Differentiate forward and inverse kinematics.
- 76) What do you mean by Torque sensor?
- 77) List out different robot programming languages.
- 78) What features are required for robot in spray painting?
- 79) What are the future applications of Robot?
- 80) How many DOF does a wrist have? What is the purpose of these degrees of freedom?
- 81) Differentiate joint coordinates and world coordinates.
- 82) Differentiate between Lagrange Euler and Newton Euler Formulation.
- 83) Differentiate joint space trajectory and Cartesian trajectory planning.
- 84) List the advantages and disadvantages of pneumatic actuator.
- 85) Define the term "Automation".
- 86) List out the classification of automated manufacturing systems.
- 87) What do you mean by "Line efficiency" of an assembly line?
- 88) Classify the work part transfer mechanisms.
- 89) Name the basic robot configurations (arm and body).

- 90) Define “Detent torque” with respect to a stepper motor.
- 91) Write the rotational matrix for a rotating of “ ” angle about Z-axis.
- 92) What do you mean by “Inverse kinematics”?
- 93) Define a “Robot programming”.
- 94) List out the industrial robot applications in manufacturing.

PART-A

1. Differentiate automation and robotics?
2. Differentiate CAD/CAM and robotics?
3. Explain about robot anatomy in detail with neat sketch?
4. What are the future applications of robots? / Mention some future applications of robots?
5. Define robot and give its applications?
6. How do you classify robots by co-ordinate system?
7. What are the basic components of a robot system?
8. What are common types of arms?
9. What are the different types of control systems?
10. What are requirements and challenges of end effectors?
11. What are the types of locomotive devices?
12. What are the types of end effectors?
13. Give the classification of robot by control systems?
14. What are the advantages of cylindrical arm configuration over a polar arm configuration?

CASE STUDIES AND GROUP PROJECTS

1. Prepare different types of robot configurations with proto type models.
2. Explain the Components of industrial Robots with video lecture and its applications.
3. Explain the motion analysis and manipulator kinematics with working prototype models and video lectures.
4. Explain the different types of actuators and sensors and applications with working models.
5. Study of pick and place operation by robotic arm and working model.
6. To demonstrate that design processes typically involve a multitude of skills and knowledge for development of different robots.
7. To provide students with hands on experience building a simple programmable robot.
8. Explain Different types of robots and its industrial applications with videos and prototype models.