RAJEEV GANDHI MEMORIAL COLLEGE OF ENGINEERING AND TECHNOLOGY

AUTONOMOUS

NANDYAL-518501, KURNOOL DIST., A.P., INDIA

DEPARTMENT OF MECHANICAL ENGINEERING

B.Tech –IV Year – II Sem

(2017-2021)

DEPARTMENT OF MECHANICAL ENGINEERING

EDUCATION FOR PEACE

(ESTD-1995)

Course File

Industrial Automation and Robotics

R-15 Regulations

Prepared By

Dr. Manoj Panchal

Assistant Professor,

Department of Mechanical Engineering, RGMCET, Nandyal

Dr K. THIRUPATHI REDDY
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MECHANICAL ENGINEERING

((Affiliated to J.N.T.U.A, Anantapuramu)

Table of Contents

Dr K. THIRUPATHI REDDY
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Institute Vision and Mission

Vision

- To develop this rural based engineering college into an institute of technical education with global standards
- To become an institute of excellence which contributes to the needs of society
- To inculcate value based education with noble goal of " Education for peace and progress"

Mission

- To build a world class undergraduate program with all required infrastructure that provides strong theoretical knowledge supplemented by the state of art skills
- To establish postgraduate programs in basic and cutting edge technologies
- To create conductive ambiance to induce and nurture research
- To turn young graduates to success oriented entrepreneurs
- To develop linkage with industries to have strong industry institute interaction
- To offer demand driven courses to meet the needs of the industry and society
- To inculcate human values and ethos into the education system for an all-round development of students

Quality Policy

- To improve the teaching and learning
- To evaluate the performance of students at regular intervals and take necessary steps for betterment
- To establish and develop centers of excellence for research and consultancy
- To prepare students to face the competition in the market globally and realize the responsibilities as true citizen to serve the nation and uplift the country's pride.

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The Vision of the Department:

- To be a center of excellence by offering UG, PG and Research programs in cutting edge technologies of Mechanical Engineering in collaboration with industries.

The Mission of the Department:

- To Produce Mechanical Engineers who are exceptionally competent, disciplined and have a sense of devotion to their profession by adapting modern teaching and learning process.
- To establish modern laboratory facilities to impart quality education in association with Industry- Institute interaction.
- To inculcate research orientation among the student

Program Outcomes (POs)

Engineering Graduates will be able to:

1. **Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
2. **Problem analysis**: Identify, formulate, review research literature, and analyse complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
3. **Design/development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.
4. **Conduct investigations of complex problems**: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.
5. **Modern tool usage**: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modelling to complex engineering activities with an understanding of the limitations.

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

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

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

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

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

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

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

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Program Educational Objectives (PEOs)

PEO1 is Consistent with the mission statement that the Mechanical Engineers who are exceptionally competent to face the challenges in Mechanical engineering stream.

PEO2 is consistent with mission statement that, the Mechanical Engineers are able to design and construct mechanical systems with industry collaboration.

PEO3 is consistent with the mission statement that, the mechanical engineers have an ethical attitude and have an interest towards research.

PEO4 is Consistent with the mission statement that, the mechanical engineers can learn leadership quality and entrepreneurial skills when they are working with industry.

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Program Specific outcomes (PSOs)

PSO 1	The graduate will be able to design systems, components or process for broadly defined engineering technology problems appropriate to Programme educational objectives.
PSO2	The graduates will be able to apply modern engineering tools viz., CAD/CAM packages for modeling, analysis and predicting simple to complex engineering activities with an understanding of the limitations.
PSO3	The graduate will be able to apply oral and graphical communication in both technical and non-technical environment.
PSO4	The graduate will be able to engage in self dir ected continuing professional development and have a strong commitment to address ethical and professional responsibilities.

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Academic Calendar

RAJEEV GANDHI MEMORIAL COLLEGE OF ENGINEERING & TECHNOLOGY
(AUTONOMOUS)

Academic Diary for IV-B.Tech., II-Sem 2020-21

	Apr-21		May-21		Jun-21	
Day	Date	Class	Date	Class	Date	Class
Mon						
Tue					1	42
Wed					2	43
Thu	1				3	44
Fri	2				4	45
Sat	3		1	20	5	46
Sun	4		2		6	
Mon	5		3	21	7	47
Tue	6	1	4	22	8	48
Wed	7	2	5	23	9	49
Thu	8	3	6	24	10	50
Fri	9	4	7	25	11	Mid-II
Sat	10	5	8	26	12	Mid-II
Sun	11		9		13	
Mon	12	6	10	27	14	Mid-II
Tue	13	Ugadi	11	28	15	Mid-II
Wed	14	BRA's B'Day	12	29	16	Preparation
Thu	15	7	13	30	17	Preparation
Fri	16	8	14	Ramzan	18	Preparation
Sat	17	9	15	31	19	End Exam
Sun	18		16		20	
Mon	19	10	17	32	21	End Exam
Tue	20	11	18	33	22	
Wed	21	Sri Rama Navami	19	34	23	End Exam
Thu	22	12	20	35	24	
Fri	23	13	21	Mid-I	25	End Exam
Sat	24	14	22	Mid-I	26	Project & CVV
Sun	25		23		27	
Mon	26	15	24	Mid-I	28	Project & CVV
Tue	27	16	25	Mid-I	29	Project & CVV
Wed	28	17	26	37	30	Project & CVV
Thu	29	18	27	38		
Fri	30	19	28	39		
Sat			29	40		
Sun			30			
Mon			31	41		

1. **First Spell of Instructions** : **06/04/2021 – 20/05/2021**
2. **Slot for Assignment-I** : **18/05/2021 – 20/05/2021**
3. **Mid-I Examinations** : **21/05/2021 – 25/05/2021**
4. **Second Spell of Instructions** : **26/05/2021 – 10/06/2021**
5. **Slot for Assignment-II** : **07/06/2021 – 10/06/2021**
6. **Mid-II Examinations** : **11/06/2021 – 15/06/2021**
7. **Preparation** : **16/06/2021 – 18/06/2021**
8. **End Examinations** : **19/06/2021 – 25/06/2021**
9. **End Practical Examinations** : **26/06/2021 – 30/06/2021**

NOTE: 30% of syllabus should be completed in On-line mode

C.E. **PRINCIPAL**

Date: 01-04-2021

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Time Table

DEPARTMENT OF MECHANICAL ENGINEERING, RGMCET (Autonomous) :: NANDYAL - 518 501
CENTRAL TIME TABLE FOR II B.TECH. II SEM. (W.e.f: 19.04.2021) & III & IV B.TECH II SEM (W.e.f: 06.04.2021) FOR 2020 - 2021

DAY	PERIOD → / CLASS	9.00 - 09.50	09.50 - 10.40	11.00 - 11.50	11.50 - 12.40	01.40 - 02.30	02.30 – 03.20	03.20 – 04.10
MON	II-A	DT	MFT/FMHM/TE LAB			MFT	BEEE	DT
	II-B	DT	TOM	MFT	BEEE	FMHM	DT	ES
	II-C	DT	BEEE	ATD	ES	MFT/FMHM/TE LAB		
	III-A	HT	HT/MMT/PM-I LAB			EM	IEM	TD(S)
	III-B	TD	IEM	DME-II	PESS	DME-II	HT	EM(S)
	III-C	EM	HT		PM-I	TD	DME-II	DME-II(S)
	IV-A	POM	M&A	SEM	SEM	IAR	POM	IAR
	IV-B	IAR	M&A	POM	M&A	M&A LAB		
	IV-C	IAR	POM	M&A	POM	IAR	SEMINAR	
TUE	II-A	TOM	DT	BEEE	MFT	FMHM		MFT
	II-B	MFT	MFT/FMHM/TE LAB			MFT	TOM	
	II-C	MFT	BEEE	FMHM	TOM	MFT	ATD	DT
	III-A	IEM	EM	PESS	TD	EM	HT	HT(S)
	III-B	DME-II	TD	HT	EM	PM-I	TD	IEM(S)
	III-C	PM-I	HT/MMT/PM-I LAB			HT	PESS	EM(S)
	IV-A	IAR	POM	POM	M&A	M&A LAB		
	IV-B	M&A	SEM	IAR	SEM	IAR	POM	POM
	IV-C	M&A	IAR	IAR	SEM	POM	SEMINAR	SEMINAR
WED	II-A	BEEE	TOM	FMHM	ES	BEEE	ATD	
	II-B	FMHM	DT	ATD		MFT/FMHM/TE LAB		
	II-C	TOM	MFT/FMHM/TE LAB			DT	ES	BEEE
	III-A	EM	HT	TD	DME-II	PM-I	PESS	IEM(S)
	III-B	IEM	HT/MMT/PM-I LAB			EM	HT	HT(S)
	III-C	IEM	TD	PESS	TD	IEM	EM	HT(S)
	IV-A	M&A	IAR	IAR	SEMINAR	POM	SEMINAR	SEMINAR
	IV-B	POM	PROJECT WORK			IAR	IAR	POM
	IV-C	POM	IAR	POM	M&A	M&A LAB		
THU	II-A	FMHM	MFT/FMHM/TE LAB			DT	TOM	ES
	II-B	ES	BEEE	MFT	TOM	FMHM	ATD	
	II-C	BEEE	DT	MFT	FMHM	TOM	FMHM	ATD
	III-A	TD	HT/MMT/PM-I LAB			HT	DME-II	DME-II(S)
	III-B	EM	IEM	TD	DME-II	PESS	PM-I	TD(S)
	III-C	HT	EM	IEM	DME-II	HT/MMT/PM-I LAB		
	IV-A	IAR	POM	M&A	SEM	PROJECT WORK		
	IV-B	M&A	SEM	POM	SEM	PROJECT WORK		
	IV-C	IAR	POM	M&A	SEM	PROJECT WORK		
FRI	II-A	ES	DT	ATD		MFT/FMHM/TE LAB		
	II-B	DT	MFT/FMHM/TE LAB			ATD	ES	BEEE
	II-C	FMHM	TOM	ATD	BEEE	MFT	FMHM	TOM
	III-A	DME-II		TD	HT	PM-I	IEM	EM(S)
	III-B	PESS	HT	EM	PM-I	HT/MMT/PM-I LAB		
	III-C	PESS	HT/MMT/PM-I LAB			DME-II	IEM	TD(S)
	IV-A	IAR	SEM	POM	SEM	PROJECT WORK		
	IV-B	POM	SEM	IAR	IAR	PROJECT WORK		
	IV-C	POM	IAR	SEM	SEM	PROJECT WORK		
SAT	II-A	MFT	ATD	TOM		MFT	FMHM	BEEE
	II-B	BEEE	FMHM		DT	BEEE	TOM	MFT
	II-C	ES	MFT/FMHM/TE LAB			DT	ATD	MFT
	III-A	PESS	PM-I	DME-II	IEM	HT/MMT/PM-I LAB		
	III-B	HT	HT/MMT/PM-I LAB			IEM	DME-II	DME-II(S)
	III-C	DME-II		TD	PM-I	EM	HT	IEM(S)
	IV-A	PROJECT WORK				PROJECT WORK		
	IV-B	PROJECT WORK				PROJECT WORK		
	IV-C	PROJECT WORK				PROJECT WORK		

II B.TECH

MFT- Dr. G. Venkatesh (A&B)
Dr. B. Rama Krishna (C)
TOM- Dr. V. Nageswara Reddy (A&B)
Mr. N. Upendra (C)
BEEE- Mr. T. Ashok Kumar (A,B &C)
FMHM- Mr. T. John Babu (A&B)
Mr. G.V. Satya Narayana (C)
ATD- Dr. V.Siva Reddy (A&B)
Mr. B. Dinesh Babu (C)
ES- Dr. B. Arun Babu (A,B &C)
DT- Dr. D. Abhishek(A), Dr. Ashif Pervez(B)
& Dr. Y.Siva Kumar Reddy (C)
MFT LAB- Mr. Y.Suresh Babu(A),
Dr. M.Ashok Kumar(B) &
Dr. B. Rama Krishna (C)
FMHM LAB- Mr. T. John Babu (A),
Dr. V. Nageswara Reddy (B) &
Mr. G.V. Satya Narayana (C)
TE LAB- Dr. Ashif Pervez(A)
Dr. K.T.Reddy(B) & Mr. B. Dinesh Babu (C)

III B.TECH

IEM - Mr. B. Chinna Ankanna (A&B)
Mr. B. Dinesh Babu (C)
DME-II – Dr. K.Sudha Madhuri (A&B)
Dr. M. Ashok Kumar (C)
HT - Mr. B.Suresh (A&B) &
Mr. G.V. Satya Narayana (C)
EM – Dr. B. Sidda Reddy (A&B) &
Dr. B. Rama Krishna (C)
TD – Mr. M. Khaja Gulam Hussain (A&B) &
Dr. Y.Siva Kumar Reddy (C)
PESS – Mr. A.K.Gopi Krishna (A),
Mr. C. Parameshswar Reddy(B) &
Mr. P.Kousar Bhasa (C)
HT LAB - Mr. B.Suresh (A),
Dr. V. Chandrasekhar(B) & Dr. Y.Siva
Kumar Reddy (C)
MMT LAB - Dr. B. Sidda Reddy (A), Dr. G.
Venkatesh(B) & Mr. B. Chinna Ankanna(C)
PM-I LAB- Dr. Manoj Panchal(A), Dr. Syed
Altaf Hussain(B) & Mr. MD. Anees Shek(C)

IV B.TECH

IAR - Mr. Y.Suresh Babu(A&B) &
Dr. Manoj Panchal(C)
POM - Dr. V. Chandrasekhar (A&B) &
Dr. M. Ashok Kumar (C)
M&A - Dr. K.Sudha Madhuri(A),
Dr. Upendra Razak(B) & Mr.N. Upendra(C)
M&A LAB - Dr. K.Sudha Madhuri(A),
Dr. Upendra Razak(B) &
Mr. N. Upendra(C)

HME

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Syllabus

IV B.Tech, II-Sem (ME) T C
3+1* 3

[A0336158] INDUSTRIAL AUTOMATION AND ROBOTICS

OBJECTIVE:

- In the present scenario all the manufacturing industries are automated to improve the productivity as well as the quality of the product.

OUTCOMES:

At the end of the course, the student will be able to:

1. The student should understand the some fundamental aspects and an overview of robotics& automation, including Components of the Industrial Robotics, arms, architecture, end effectors, feedback components etc.
2. Emphasis is placed on understanding motion analysis described mathematically.
3. The Manipulator Kinematics, D-H notation joint coordinates and world coordinates, forward and inverse kinematics are also considered in some detail.
4. Describe construction and working of different types robots

	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PSO1	PSO2	PSO3	PSO4
CO1	3	3	2	2	1	-	-	-	-	-	2	3	2	1	-	1
CO2	2	2	-	2	1	1	-	-	-	-	-	2	2	-	-	1
CO3	3	2	3	-	2	-	2	-	-	-	2	-	2	-	-	-
CO4	3	2	3	2	3	3	-	-	-	-	-	-	2	-	-	1

UNIT – I

INTRODUCTION TO AUTOMATION: Automation - need-types,Basic elements of an automated system, levels of automation- computer process control, Forms of computer process control,sensors,actuators,input/output devices for discrete data, overview of material handling equipment

UNIT – II

NUMERICAL CONTROL: Introduction-NC Procedure, NC Coordinate systems, elements of NC Systems, classification of NC Systems, Advantages and dis-advantages of NC Systems, Applications of NC, NC Manual Part programming, APT Language.

UNIT – III

MANUAL ASSEMBLY LINES AND TRANSFER LINES: Fundamentals of Manual Assembly lines and automated production lines, Alternative assembly systems, Design for Assembly, Applications of Automated production lines, Analysis of Transfer lines with NO Internal storage, Analysis of Transfer lines with storage Buffers.

UNIT – IV

INTRODUCTION TO INDUSTRIAL ROBOTS: Robotics Definition - robot configurations, Work volume, Robot Anatomy, Robot Drive systems, Precision of Movement, End effectors, Robotic sensors and actuators, Grippers.

UNIT – V

MANIPULATOR KINEMATICS: Homogeneous transformations as applicable to rotation and translation - (D-H) notation, Forward and inverse kinematics.

Manipulator Dynamics: differential transformation, Jacobians, Lagrange – Euler and Newton Euler formations.

UNIT – VI

ROBOT ACTUATORS AND FEED BACK COMPONENTS: Actuators- pneumatic-hydraulic actuators, Electric & stepper motors, comparison, Position sensors – potentiometers-resolvers- encoders – velocity sensors-tactile sensors-proximity sensors, Robot applications in Manufacturing.

TEXT BOOKS:

1. Mikell P. Groover, Automation, Production Systems and CIM, Prentice-Hall of India Pvt. Ltd.
2. M.P. Groover, Industrial Robotics, TMH.

REFERENCE BOOKS:

1. K.S.Fu., R.C.Gonzalez, C.S.G. Lee, Robotics: Control Sensing, Vision and Intelligence International Edition, McGraw Hill Book Co.
2. P. Coiffet and M.Chaironze, An Introduction to Robot Technology, Kogam Page Ltd. London.
3. Richard. D.Klafter, Robotics Engineering, Prentice Hall
4. Ashitave Ghosal, Robotics, Fundamental Concepts and analysis, Oxford Press
5. Mittal R.K & Nagrath IJ, Robotics and Control, TMH.
6. John. J. Craig, Introduction to Robotics, Pearson.

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LESSON PLAN

NAME OF THE FACULTY: Dr. MANOJ PANCHAL **ACADEMIC YEAR:** 2020-21

CLASS/SEM: IV B. TECH/II SEM **TOTAL HOURS: 50**

NAME OF THE SUBJECT: [A0336158] INDUSTRIAL AUTOMATION AND ROBOTICS

S.NO	UNIT	TOPIC	Lecture	TOTAL HOURS
1	I	INTRODUCTION TO AUTOMATION: Automation - need-types	L1	8
		Basic elements of an automated system, levels of automation	L2,L3	
		computer process control, Forms of computer process control	L4,L5	
		sensors, actuators, input/output devices for discrete data	L6,L7	
		overview of material handling equipment	L8	
2	II	NUMERICAL CONTROL: Introduction-NC Procedure, NC Coordinate systems	L9,L10	7
		elements of NC Systems, classification of NC Systems, Advantages and dis-advantages of NC Systems, Applications of NC	L11,L12	
		NC Manual Part programming	L13,L14	
		APT Language	L15	
3	III	Fundamentals of Manual Assembly lines and automated production lines	L16	8
		Alternative assembly systems, Design for Assembly, Applications of Automated production lines,	L17,L18,L19	
		Analysis of Transfer lines with NO Internal storage	L20,L21	
		Analysis of Transfer lines with storage Buffers.	L22,L23	
4	IV	INTRODUCTION TO INDUSTRIAL ROBOTS: Robotics Definition - robot configurations	L24,L25	9
		Work volume, Robot Anatomy	L26,L27	
		Robot Drive systems, Precision of Movement	L28,L29	
		End effectors, Robotic sensors and actuators And Grippers	L30,L31,L32	
5	V	MANIPULATOR KINEMATICS: Homogeneous transformations	L33,L34	10
		Applicable to rotation and translation (D-H) notation, Forward and inverse kinematics. Manipulator	L35,L36	
		Dynamics: differential transformation, Jacobians	L37,L38	
		Newton Euler formulation.	L39,L40,	
		Lagrange – Euler formulation,	L41,L42	
6	VI	ROBOT ACTUATORS AND FEED BACK COMPONENTS: Actuators- Pneumatic-Hydraulic Actuators	L43,L44	8
		Electric & Stepper Motors, Comparison	L46	
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Unit:- I : INTRODUCTION TO AUTOMATION

Syllabus | Lectures 8

- Automation Defined
- Need of Automation
- Automation types
- Level of automation
- Computer Process Control
- Forms of Computer Process Control
- Sensors
- Actuators
- Input/output devices for discrete data
- Overview of Material Handling System
- Elements of Automated System

Automation Defined

'Automation' is the technology by which a process or procedure is accomplished without human assistance.

- ✓ It is implemented using a *program of instructions* combined with a *control system* that executes the instructions.
- ✓ To automate a process, power is required, both to drive the process itself and to operate the program and control system. Although automation can be applied in a wide variety of areas, it is most closely associated with the manufacturing industries.
- ✓ It was in the context of manufacturing that the term was originally coined by an engineering manager at Ford Motor Company in 1946.

Industrial perspective:

Automation is key a concept for the 4.0 industry and is a growing value among industrial companies. According to a publication **Fortune Business Insights**, the industrial automation market worldwide reached 157.04 billion dollars in 2018 and is expected to reach 296.70 billion dollars in 2026, almost twice as much as a year ago.

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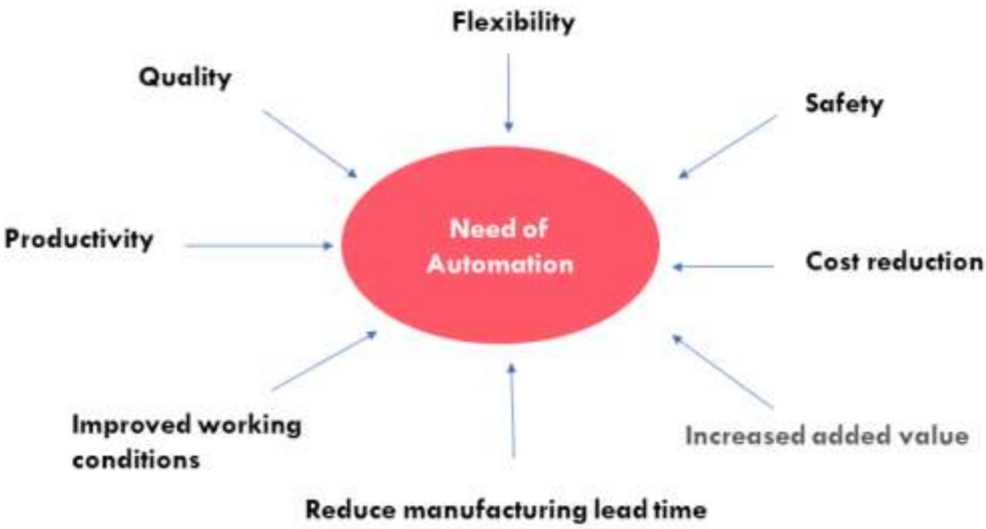
Need Of Automation



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Types of Automation

Fixed Automation: It is used in high volume production with dedicated equipment, which has a fixed set of operation and designed to be efficient for this set.

Continuous flow and Discrete Mass Production systems use this automation.

e.g. Distillation Process, Conveyors, Paint Shops, Transfer lines etc.

Typical features of fixed automation are

(1) high initial investment for custom-engineered equipment,

(2) high production rates, and

(3) inflexibility of the equipment to accommodate product variety.

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Types of Automation: Fixed Automation

Example of Fixed Automation

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Types of Automation: Programmable Automation

- **Programmable Automation**: In programmable automation, the production equipment is designed with the capability to change the sequence of operations to accommodate different product configurations.
- The operation sequence is controlled by a ***program***, which is a set of instructions coded so that they can be read and interpreted by the system.
- New programs can be prepared and entered into the equipment to produce new products.

Types of Automation: Programmable Automation

Ex. A numerical-control machine tool, Industrial robots are another example.

Features that characterize programmable automation include

(1) High investment in general-purpose equipment

(2) Lower production rates than fixed automation

(3) Flexibility to deal with variations and changes in product configuration

(4) High suitability for batch production

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Types of Automation: Flexible Automation

- **Flexible Automation:** Flexible automation is an extension of programmable automation.
- A flexible automated system is capable of producing a variety of parts or products with virtually no time lost for changeovers from one design to the next.
- There is no lost production time while reprogramming the system and altering the physical setup (tooling, fixtures, machine settings).
- Accordingly, the system can produce various mixes and schedules of parts or products instead of requiring that they be made in batches.
- What makes flexible automation possible is that the differences between parts processed by the system are not significant, so the amount of changeover between designs is minimal.

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Types of Automation: Flexible Automation

Features of flexible automation include

(1) High investment for a custom-engineered system

(2) Continuous production of variable mixtures of parts or products

(3) Medium production rates

(4) Flexibility to deal with product design variations.

Ex. A flexible cell is typically a single CNC machine tool possibly with automated materials handling system, and can make many part types at low volumes, sometimes one-off prototypes of products.

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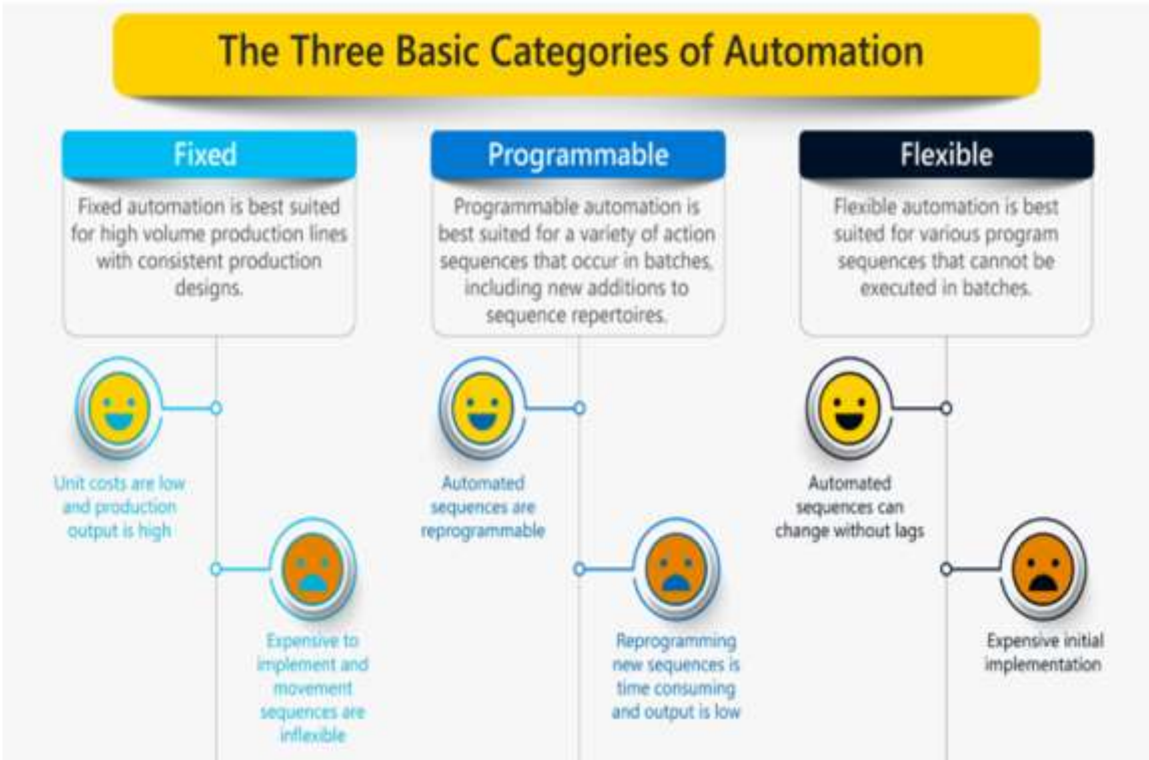
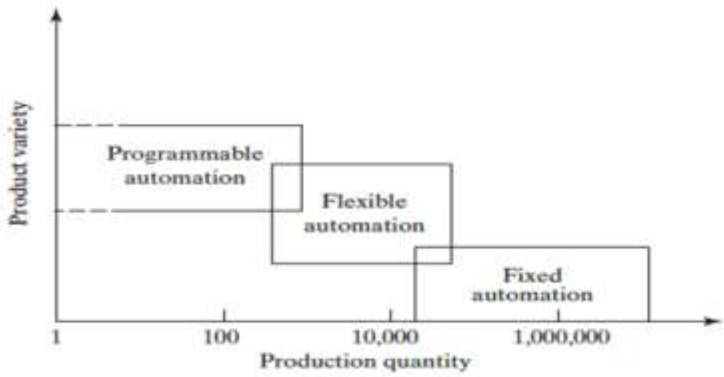
Quick Summary on Types of Automation



Comparison between different Types of Automation



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USA Principle for Automation

The USA Principle is a commonsense approach to automation and process improvement projects. Similar procedures have been suggested in the manufacturing and automation trade literature, but none has a more captivating title than this one.

USA stands for

(1) Understand the existing process,

(2) Simplify the process,

(3) Automate the process.

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Ten Strategies for Automation and Process Improvement

1. *Specialization of operations.* The first strategy involves the use of special-purpose equipment designed to perform one operation with the greatest possible efficiency. This is analogous to the specialization of labor, which is employed to improve labor productivity.

2. *Combined operations.* Production occurs as a sequence of operations. Complex parts may require dozens or even hundreds of processing steps. The strategy of combined operations involves reducing the number of distinct production machines or workstations through which the part must be routed.

3. *Simultaneous operations.* A logical extension of the combined operations strategy is to simultaneously perform the operations that are combined at one workstation. In effect, two or more processing (or assembly) operations are being performed simultaneously on the same work part, thus reducing total processing time.

4. *Integration of operations.* This strategy involves linking several workstations together into a single integrated mechanism, using automated work handling devices to transfer parts between stations. In effect, this reduces the number of separate work centers through which the product must be scheduled. With more than one workstation, several parts can be processed simultaneously, thereby increasing the overall output of the system.

5. *Increased flexibility.* This strategy attempts to achieve maximum utilization of equipment for job shop and medium-volume situations by using the same equipment for a variety of parts or products. It involves the use of programmable or flexible automation Prime objectives are to reduce setup time and programming time for the production machine. This normally translates into lower manufacturing lead time and less work-in-process.

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6. *Improved material handling and storage.* A great opportunity for reducing nonproductive time exists in the use of automated material handling and storage systems. Typical benefits include reduced work-in-process, shorter manufacturing lead times, and lower labor costs.

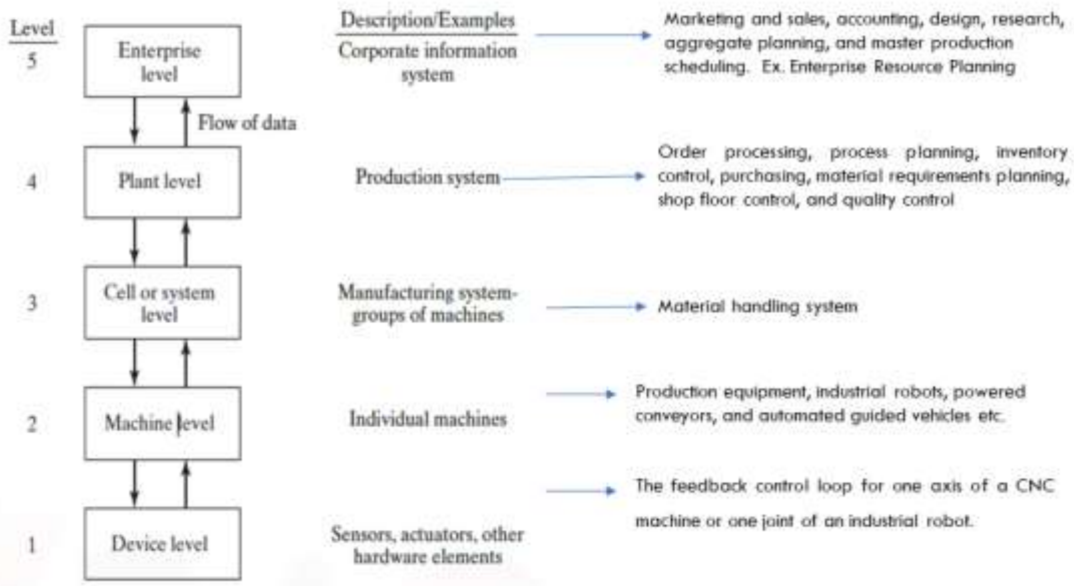
7. *On-line inspection.* Inspection for quality of work is traditionally performed after the process is completed. This means that any poor-quality product has already been produced by the time it is inspected. Incorporating inspection into the manufacturing process permits corrections to the process as the product is being made. This reduces scrap and brings the overall quality of the product closer to the nominal specifications intended by the designer.

8. *Process control and optimization.* This includes a wide range of control schemes intended to operate the individual processes and associated equipment more efficiently. By this strategy, the individual process times can be reduced and product quality can be improved.

9. *Plant operations control.* Whereas the previous strategy is concerned with the control of individual manufacturing processes, this strategy is concerned with control at the plant level. It attempts to manage and coordinate the aggregate operations in the plant more efficiently. Its implementation involves a high level of computer networking within the factory.

10. *Computer-integrated manufacturing (CIM).* Taking the previous strategy one level higher, CIM involves extensive use of computer systems, databases, and networks throughout the enterprise to integrate the factory operations and business functions

Level of Automation



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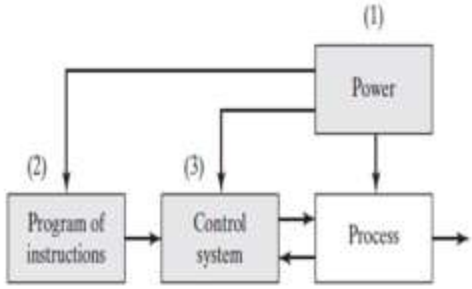
Element of Automated System

An automated system consists of three basic elements:

(1) Power to accomplish the process and operate the system

(2) A program of instructions to direct the process

(3) A control system to actuate the instructions.



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Functions of element of automated system

An automated system consists of three basic elements:

(1) Power: Power or energy is required to operate the system and to do the process.

(2) A program of instructions: It contains instruction or direction to accomplish the process.

(3) A control system or controller: it is required to interpret the program of instruction and convert that into mechanical action of actuator.

A **real-time controller:** is a controller that is able to respond to the process within a short enough time period that process performance is not degraded. Real-time control usually requires the controller to be capable of **multitasking**, which means coping with multiple tasks concurrently without the tasks interfering with one another.

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Industrial Control-Defined

- *Industrial Control* is defined here as the automatic regulation of unit operations and their associated equipment, as well as the integration and coordination of the unit operations in the larger production system. The term *unit operations* usually refers to manufacturing processes.Can also apply to material handling or other equipment

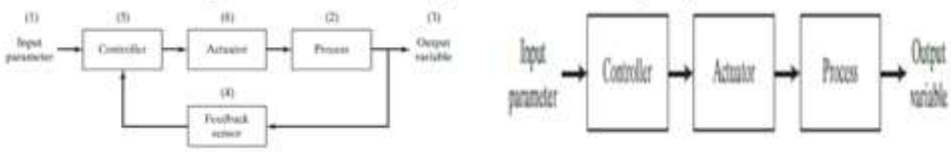
Note: control systems are different for different kind of industry, in order to understand the application of control system, we need to understand kind of operations or processes are performed at industrial level.

(1) Process industries: Process industries perform their production operations on amounts of materials, because the materials tend to be liquids, gases, powders, and similar materials.

(2) Discrete manufacturing industries :whereas discrete manufacturing industries perform their operations on quantiles of materials, because the materials tend to be discrete parts and products.

Control System

- The control element of the automated system executes the program of instructions.
- The control system causes the process to accomplish its defined function, which is to perform some manufacturing operation.
- The control system is an automated system can be either closed loop or open loop.
- A ***closed loop control system***, also known as a *feedback control system*, is one in which the output variable is compared with an input parameter



A ***process parameter*** is an input to the process, whereas a ***process variable*** is the corresponding output of the process.

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Industrial Control

Unit Operations in the Process Industries and Discrete Manufacturing Industries

Process Industries	Discrete Manufacturing Industries
Chemical reactions	Casting
Comminution	Forging
Chemical vapor deposition	Extrusion
Distillation	Machining
Mixing and blending of ingredients	Plastic molding
Separation of ingredients	Sheet metal stamping

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Industrial Control

Levels of Automation in the Process Industries and Discrete Manufacturing Industries

Level	Process Industries	Discrete Manufacturing Industries
5	Enterprise level—management information system, strategic planning, high-level management of enterprise	Enterprise level—management information system, strategic planning, high-level management of enterprise
4	Plant level—scheduling, tracking materials, equipment monitoring	Plant or factory level—scheduling, tracking work-in-process, routing parts through machines, machine utilization
3	Supervisory control level—control and coordination of several interconnected unit operations that make up the total process	Manufacturing cell or system level—control and coordination of groups of machines and supporting equipment working in coordination, including material handling equipment
2	Regulatory control level—control of unit operations	Machine level—production machines and workstations for discrete product manufacture
1	Device level—sensors and actuators comprising the basic control loops for unit operations	Device level—sensors and actuators to accomplish control of machine actions

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Computer Process Control

- Digital computers to control industrial processes had its origins in the continuous process industries in the late 1950s.
- Prior to that time, analog controllers were used to implement continuous control, and relay systems were used to implement discrete control.
- At that time, computer technology was in its infancy, and the only computers available for process control were large, expensive mainframes.
- Compared with today's technology, digital computers of the 1950s were slow, unreliable, and not well suited to process-control applications.

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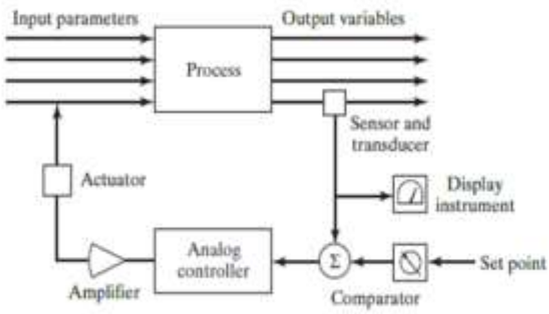
Forms of Computer Process Control

1. Computer process monitoring
2. Direct digital control (DDC)
3. Numerical control and robotics
4. Programmable logic control
5. Supervisory Control and Data Acquisition
6. Distributed control systems
7. PCs in Process Control
8. Enterprise-Wide Integration of Factory Data

Analog Process Control

- Typical hardware components of the analog control loop include
- The sensor and transducer,
- An instrument for displaying the output variable,
- Some means for establishing the set point of the loop (shown as a dial in the figure, suggesting that the setting is determined by a human operator),
- A comparator (to compare set point with measured output variable),
- The analog controller, an amplifier, and
- The actuator that determines the input parameter to the process.



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Computer Process Monitoring

- Computer observes process and associated equipment, collects and records data from the operation
- The computer does not directly control the process
- Types of data collected:
  - Process data – input parameters and output variables
  - Equipment data – machine utilization, tool change scheduling, diagnosis of malfunctions
  - Product data – to satisfy government requirements, e.g., pharmaceutical and medical

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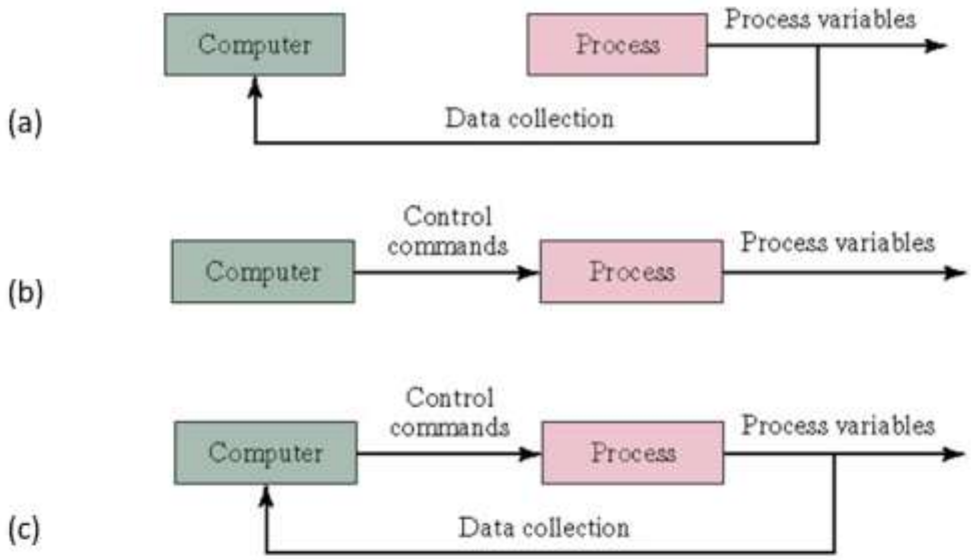
Computer Process Monitoring



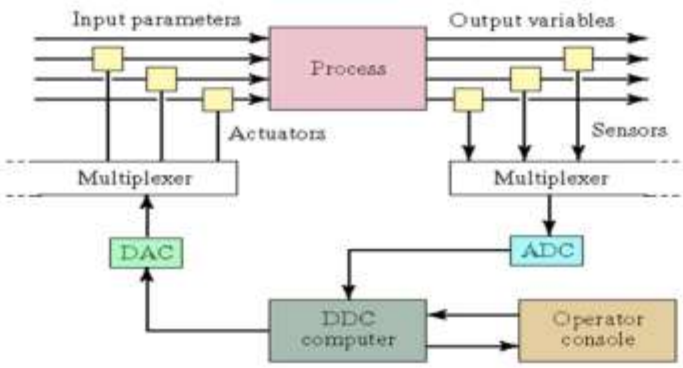
(a) Process Monitoring, (b) Open-Loop Control, and (c) Closed-Loop Control

Direct Digital Control (DDC)

- Form of computer process control in which certain components in a conventional analog control system are replaced by the digital computer
- Circa: 1960s using mainframes
- Applications: process industries
- Accomplished on a time-shared, sampled-data basis rather than continuously by dedicated components
  - Components remaining in DDC: sensors and actuators
  - Components replaced in DDC: analog controllers, recording and display instruments, set point dials

DDC (continued)

- Originally seen as a more efficient means of performing the same functions as analog control
- Additional opportunities became apparent in DDC:
  - More control options than traditional analog control (PID control), e.g., combining discrete and continuous control
  - Integration and optimization of multiple loops
  - Editing of control programs



Numerical Control and Robotics

- Computer numerical control (CNC) – computer directs a machine tool through a sequence of processing steps defined by a program of instructions
  - Distinctive feature of NC – control of the position of a tool relative to the object being processed
  - Computations required to determine tool trajectory
- Industrial robotics – manipulator joints are controlled to move and orient end-of-arm through a sequence of positions in the work cycle

Programmable Logic Controller (PLC)

- Microprocessor-based controller that executes a program of instructions to implement logic, sequencing, counting, and arithmetic functions to control industrial machines and processes
- Introduced around 1970 to replace electromechanical relay controllers in discrete product manufacturing
- Today's PLCs perform both discrete and continuous control in both process industries and discrete product industries

Supervisory Control and Data Acquisition.

The term *supervisory control* is usually associated with the process industries, but the concept applies equally well to discrete manufacturing, where it corresponds to cell- or system-level control.

Supervisory control represents a higher level of control than CNC, PLCs, and other automated processing equipment.

In general, these other control systems are interfaced directly to the process. By contrast, supervisory control is superimposed on these process level control systems.

The term *supervisory control and data acquisition* (SCADA) emphasizes the fact that such control systems also collect data from the process, which often includes multiple sites distributed over large distances. A typical SCADA system consists of the following components:

(1) A central supervisory computer system capable of collecting data from the process and transmitting command signals to the process,

(2) A human-machine interface (HMI) that presents the collected data to the system operator(s) and enables them to As the previous description indicates, SCADA is implemented as a distributed system, in which a central computer communicates with multiple remote devices (e.g., PLCs and RTUs).

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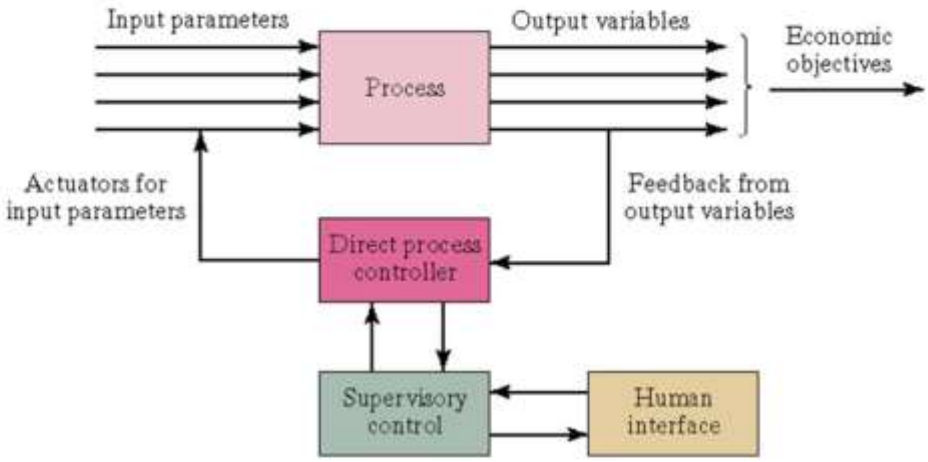
Supervisory Control and Data Acquisition.

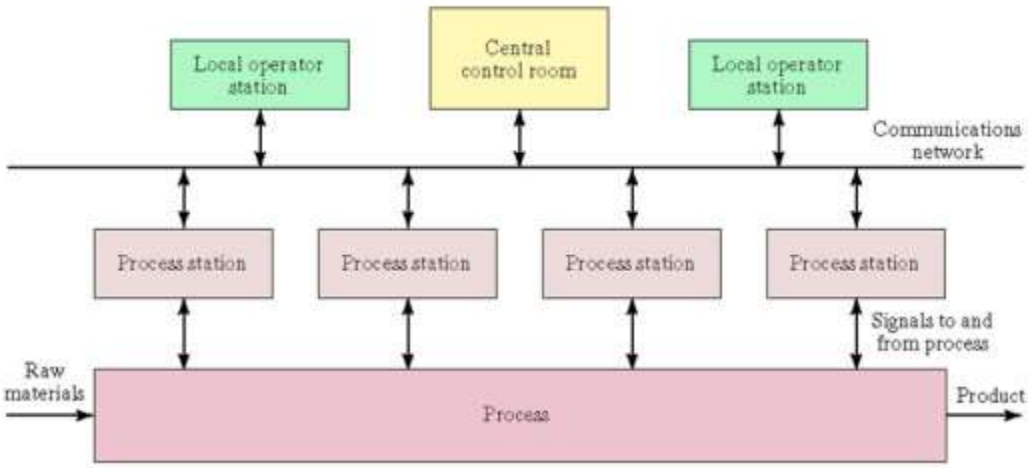


Distributed Control Systems (DCS)

Multiple microcomputers connected together to share and distribute the process control workload

- Features:
  - Multiple process control stations to control individual loops and devices
  - Central control room where supervisory control is accomplished
  - Local operator stations for redundancy
  - Communications network (data highway)

Distributed Control System



DCS Advantages

- Can be installed in a very basic configuration, then expanded and enhanced as needed in the future
- Multiple computers facilitate parallel multitasking
- Redundancy due to multiple computers
- Control cabling is reduced compared to central controller configuration
- Networking provides process information throughout the enterprise for more efficient plant and process management

Distinction Between DCS And SCADA

The distinction between DCS and SCADA is not always clear. Both terms can often be applied to the same system.

The term *distributed system* emphasizes an interconnected collection of computers, whereas *supervisory control* emphasizes the use of a central computer to manage an interconnected collection of remote controller and data acquisition devices.

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PCs in Process Control

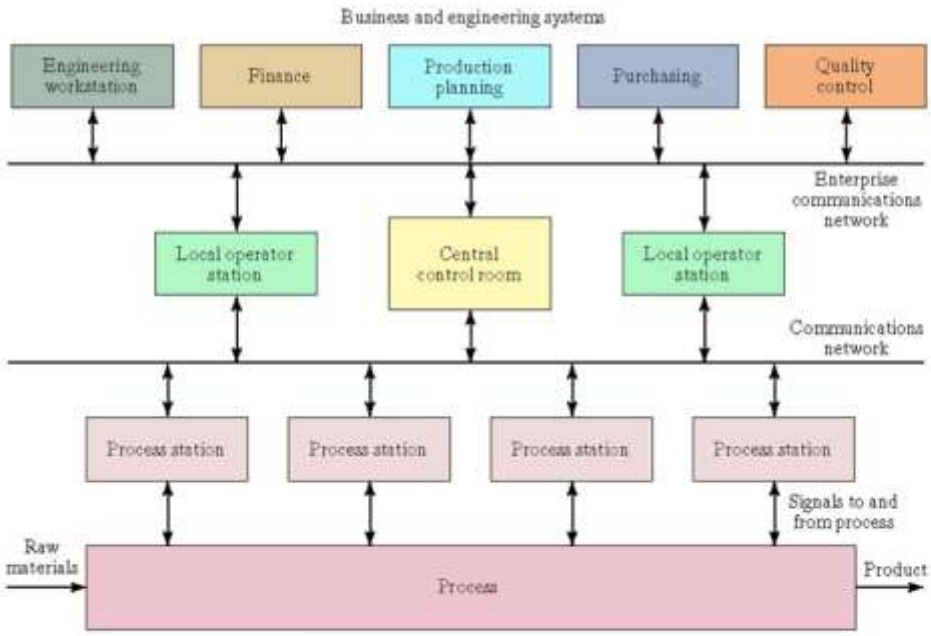
Two categories of personal computer applications in process control:

1. Operator interface – PC is interfaced to one or more PLCs or other devices that directly control the process
   - PC performs certain monitoring and supervisory functions, but does not directly control process
2. Direct control – PC is interfaced directly to the process and controls its operations in real time
   - Traditional thinking is that this is risky

Enterprise-Wide Integration of Factory Data

- Managers have direct access to factory operations
- Planners have most current data on production times and rates for scheduling purposes
- Sales personnel can provide realistic delivery dates to customers, based on current shop loading
- Order trackers can provide current status information to inquiring customers
- QC can access quality issues from previous orders
- Accounting has most recent production cost data
- Production personnel can access product design data to clarify ambiguities

Enterprise-Wide PC-based Distributed Control System



Sensors

- A sensor is a ***Transducer***, which is a device that converts a physical variable of one form into another form that is more useful for the given application.
- In particular, a **Sensor** is a device that converts a physical stimulus or variable of interest (such as temperature, force, pressure, or displacement) into a more convenient form (usually an electrical quantity such as voltage) for the purpose of measuring the stimulus.
- The conversion process quantifies the variable, so that it can be interpreted as a numerical value.

Category	Examples of Physical Variables
Mechanical	Position (displacement, linear and angular), velocity, acceleration, force, torque, pressure, stress, strain, mass, density
Electrical	Voltage, current, charge, resistance, conductivity, capacitance
Thermal	Temperature, heat, heat flow, thermal conductivity, specific heat
Radiation	Type of radiation (e.g., gamma rays, X-rays, visible light), intensity, wavelength
Magnetic	Magnetic field, flux, conductivity, permeability
Chemical	Component identities, concentration, pH levels, presence of toxic ingredients, pollutants

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Sensors

Measuring Device	Description
Accelerometer	Analog device used to measure vibration and shock. Can be based on various physical phenomena (e.g., capacitive, piezoresistive, piezoelectric).
Ammeter	Analog device that measures the strength of an electrical current.
Bimetallic switch	Binary switch that uses a bimetallic coil to open and close electrical contact as a result of temperature change. A bimetallic coil consists of two metal strips of different thermal expansion coefficients bonded together.
Bimetallic thermometer	Analog temperature-measuring device consisting of bimetallic coil (see previous definition) that changes shape in response to temperature change. Shape change of coil can be calibrated to indicate temperature.
Dynamometer	Analog device used to measure force, power, or torque. Can be based on various physical phenomena (e.g., strain gage, piezoelectric effect).
Float transducer	Float attached to lever arm. Pivoting movement of lever arm can be used to measure liquid level in vessel (analog device) or to activate contact switch (binary device).
Fluid flow sensor	Analog measurement of liquid flow rate, usually based on pressure difference between flow in two pipes of different diameter.
Fluid flow switch	Binary switch similar to limit switch but activated by increase in fluid pressure rather than by contacting object.
Limit switch (mechanical)	Binary contact sensor in which lever arm or pushbutton closes (or opens) an electrical contact.
Linear encoder	Digital device used to measure linear position and/or speed using a transducer that reads a stationary linear scale indicating position. Speed can be measured as position divided by time lapse. Transducer technologies include optical, magnetic, and capacitive.
Linear variable differential transformer	Analog position sensor consisting of primary coil opposite two secondary coils separated by a magnetic core. When primary coil is energized, induced voltage in secondary coil is function of core position. Can also be adapted to measure force or pressure.
Manometer	Analog device used to measure pressure of gas or liquid. It is based on comparison of known and unknown pressure forces. A barometer is a specific type of manometer used to measure atmospheric pressure.

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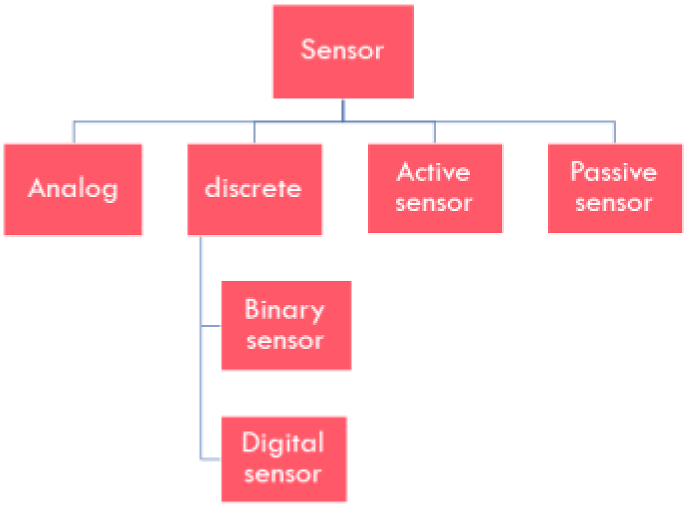
Sensors



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Sensors

- An ***analog sensor*** produces a continuous analog signal such as electrical voltage, whose value varies in an analogous manner with the variable being measured. Examples are thermocouples, strain gages, and potentiometers.
- A ***discrete sensor*** produces an output that can have only certain values. Discrete sensors are often divided into two categories: binary and digital.

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Sensors

- A ***binary sensor*** produces an on/off signal. The most common devices operate by closing an electrical contact from a normally open position. Limit switches operate in this manner.
- A ***digital sensor*** produces a set of parallel status bits (e.g., a photoelectric sensor array) or as a series of pulses that can be counted (e.g., an optical encoder). In either case, the digital signal represents the quantity that is measured.

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Actuator

In industrial control systems, an actuator is a hardware device that converts a controller command signal into a change in a physical parameter. The change in the physical parameter is usually mechanical, velocity or position change

Actuators can be classified into one of three categories (1) electric, (2) hydraulic, and (3) pneumatic

- Electric Actuator : Electric motors of various kinds, solenoids, and electromechanical relays. Electric actuators can be either linear (output is linear displacement) or rotational (output is angular displacement).
- Hydraulic actuators: hydraulic fluid to amplify the controller command signal. The available devices provide either linear or rotational motion. Hydraulic actuators are often specified when large forces are required.
- Pneumatic actuators: uses compressed air (typically "shop air" in the factory) as the driving power. Again, both linear and rotational pneumatic actuators are available. Because of the relatively low air pressures involved, these actuators are usually limited to relatively low- force applications compared with hydraulic actuators.

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Input/Output devices for discrete data

- **Continuous data** is **data** that falls in a **continuous** sequence. **Discrete data** is countable while **continuous data** is measurable. **Discrete data** contains distinct or separate values. On the other hand, **continuous data** includes any value within range

Discrete data can be processed by a digital computer without the kinds of conversion Procedures required for continuous analog signals. discrete data Divide into three categories:

(a) binary data, (b) discrete data other than binary, and (c) pulse data.

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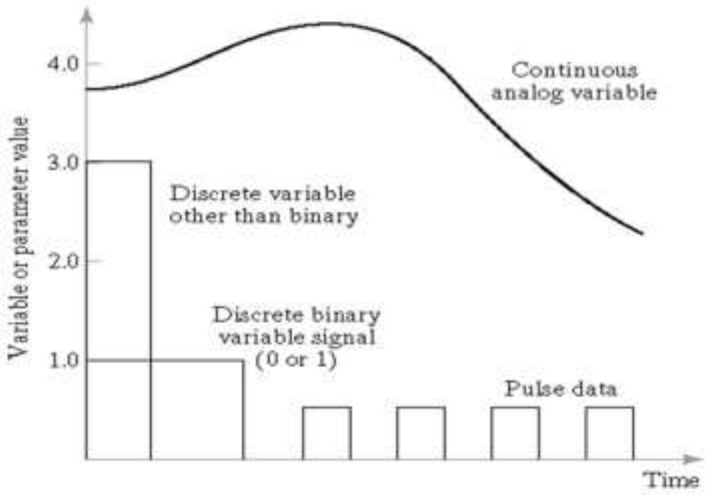
Input/Output devices for discrete data

Categories:

- Binary - they can take on either of two possible values, ON or OFF, 1 or 0, etc.
- Discrete other than binary - they can take on more than two possible values but less than an infinite number of possible values
- Pulse data - a train of pulses that can be counted

Input/Output devices for discrete data



Input/Output devices for discrete data

Contact Input/Output Interfaces

- Contact interfaces are of two types, input and output.
- These interfaces read binary data from the process into the computer and send binary signals from the computer to the process, respectively.
- The terms *input* and *output* are relative to the computer.

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Input/Output devices for discrete data

- A ***contact input interface*** is a device by which binary data are read into the computer from some external source (e.g., a process).
- It consists of a series of simple contacts that can be either closed or open (on or off) to indicate the status of binary devices connected to the process such as limit switches (contact or no contact), valves (open or closed), or motor pushbuttons (on or off).
- The computer periodically scans the actual status of the contacts to update the values stored in memory.
- The contact input interface can also be used to enter discrete data other than binary.
- This type of data is generated by devices such as a photoelectric sensor array

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Input/Output devices for discrete data

The ***contact output interface*** is a device that communicates on/off signals from the computer to the process.

The contact positions are set either on or off. These positions are maintained until changed by the computer, perhaps in response to events in the process.

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Input/Output devices for discrete data

- In computer process-control applications, hardware controlled by the contact output interface include alarms, indicator lights (on control panels), solenoids, and constant-speed motors.
- The computer controls the sequence of on/off activities in a work cycle through this contact output interface.
- The contact output interface can be used to transmit a discrete data value other than binary by assigning an array of contacts in the interface for that purpose.
- The 0 and 1 values of the contacts in the array are evaluated as a group to determine the corresponding discrete number. In effect, this procedure is the reverse of that used by the contact input interface for discrete data other than binary.

Input/Output devices for discrete data

A ***pulse counter*** is a device that converts a series of pulses into a digital value.

The most common type of pulse counter is one that counts electrical pulses. It is constructed using sequential logic gates, called *flip-flops*, which are electronic devices that possess memory capability and that can be used to store the results of the counting procedure.

Pulse counters can be used for both counting and measurement applications. A typical counting application might add up the number of packages moving past a photoelectric sensor along a conveyor in a distribution center.

Input/Output devices for discrete data

- A typical measurement application might indicate the rotational speed of a shaft. One possible method to accomplish the measurement is to connect the shaft to a rotary encoder , which generates a certain number of electrical pulses for each rotation.
- To determine rotational speed, the pulse counter measures the number of pulses received during a certain time period and divides this by the duration of the time period and by the number of pulses in each revolution of the encoder.

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Input/Output devices for discrete data

- A ***pulse generator*** is a device that produces a series of electrical pulses whose total number and frequency are determined and sent by the control computer.
- The total number of pulses might be used to drive a stepper motor in a positioning system. The frequency of the pulse train, or pulse rate, could be used to control the rotational speed of a stepper motor.
- A pulse generator operates by repeatedly closing and opening an electrical contact, thus producing a sequence of discrete electrical pulses.
- The amplitude (voltage level) and frequency are designed to be compatible with the device being controlled.

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Overview of material handling equipment

- *Material handling* is defined by the Material Handling Industry of America as "the movement, protection, storage and control of materials and products throughout the process of manufacture and distribution, consumption and disposal.
- Good material handling system ensures safely, efficiently, at low cost, in a timely manner, accurately (the right materials in the right quantities to the right locations), and without damage to the materials.
- The cost of material handling is a significant portion of total production cost estimates. Material handling: System by which materials, parts, and products are moved, stored, and tracked in the world's commercial infrastructure.

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Overview of material handling equipment

For the larger system the term *logistics is used.*

External logistics is concerned with transportation and related activities that occur outside of a facility. In general, these activities involve the movement of materials between different geographical locations. The five traditional modes of transportation are rail, truck, air, ship, and pipeline.

Internal logistics, more popularly known as material handling, involves the movement and storage of materials inside a given facility. The interest in this book is on internal logistics.

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Overview of material handling equipment

The equipment can be classified as following

(1) Transport equipment

(2) Positioning equipment

(3) Unit load formation equipment

(4) Storage equipment

(5) Identification and control equipment

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Overview of material handling equipment

- **Transport Equipment.** Material transport equipment is used to move materials inside a factory, warehouse, or other facility.

The five main types of equipment are

(1) Industrial trucks

(2) Automated guided vehicles

(3) Rail-guided vehicles

(4) Conveyors

(5) Hoists and cranes.

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Overview of material handling equipment

- Industrial trucks: Industrial trucks divided into two types powered and non-powered. Non-powered trucks are platforms or containers with wheels that are pushed or pulled by human workers to move the materials.

- Powered industrial trucks are steered by human workers. They provide mechanized movement of materials.

Overview of material handling equipment

2. Automated guided vehicles (AGVs): AGVs are battery –powered, automatically steered vehicles that follow defined pathways in the floor. AGVs are used to move unit loads between load and unload stations in the facility. Routing variations are possible (Different loads move between different stations)

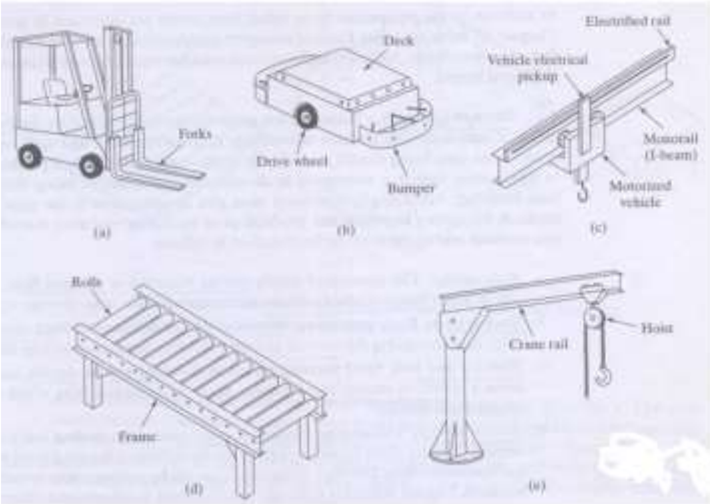
3. Monorails and other rail guided vehicles: These are self-propelled vehicles that ride on a fixed rail system . The vehicles operate independently and are usually driven by electric motors that pick up power from an electrified rail.

Routing variations are possible

4. Conveyors: Conveyors constitute a large family of material Transport equipment that are designed to move materials over fixed paths, generally in large volumes. Powered conveyors roller, belt and tow-line and non-powered by human workers

Overview of material handling equipment

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



a)Fork lift truck, industrial truck
b) Unit load automated guided vehicle
c) Monorail
d) Roller conveyor
e) Jib crane with hoist

Overview of material handling equipment

Positioning Equipment:-

- This category consists of equipment used to handle parts and other materials at a single location: for example, loading and unloading parts from a production machine in a work cell.
- Positioning is accomplished by industrial robots that perform material handling and parts feeders in automated assembly.
- Hoists used at a single location can also be included in this category.

Overview of material handling equipment

Unit Load Formation Equipment:- The term *unitizing equipment* refers to

- Containers used to hold individual items during handling
- Equipment used to load and package the containers. Containers include pallets, boxes, baskets, barrels, and drums.
- The second category of unitizing equipment includes ***palletizers***, which are designed to automatically load cartons onto pallets and shrink-wrap plastic film around them for shipping, and ***depalletizers***, which are designed to unload cartons from pallets. Other wrapping and packaging machines are also included in this equipment category.

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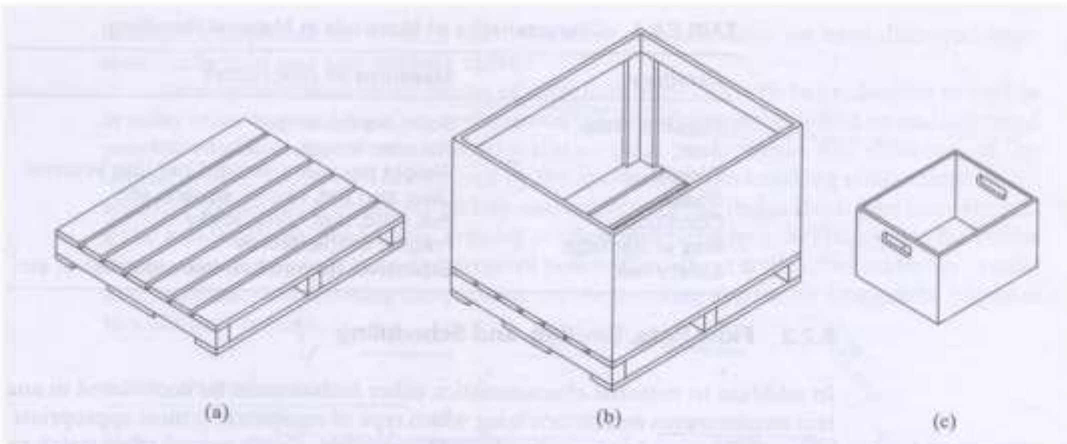
Overview of material handling equipment



Examples of unit load containers for material handling
a) Wooden pallet b) pallet box and c) tote box

Overview of material handling equipment

Storage Equipment. Although it is generally desirable to reduce the storage of materials in manufacturing, it seems unavoidable that raw materials and work-in-process spend some time in storage, even if only temporarily.

Finished products are likely to spend time in a warehouse or distribution center before being delivered to the final customer.

Overview of material handling equipment

Storage methods and equipment can be classified as follows

a) Bulk storage: It consists of simply storing materials in an open floor area, generally in pallets or containers. It requires little or no storage equipment

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

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

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Overview of material handling equipment

d) Drawer storage: This storage medium is more costly than shelves, but is more convenient. Finding items stored in shelves can be difficult if the shelf level is too high or too low or too deep. It is generally used for tools, hardware and other small items.

e) Automated storage systems: Automated and semi automated systems are available to deposit and withdraw items into and from the storage compartments.

There are two basic types: automated storage or retrieval systems: consists of rack and shelf systems 2) Carousel systems that rotate storage bins past a stationary load or unload station.

Overview of material handling equipment

- **Identification and Control Equipment.** The scope of material handling includes keeping track of the materials being moved and stored.
- This is usually done by affixing some kind of label to the item, carton, or unit load that uniquely identifies it.
- The most common label used today is a bar code that can be read quickly and automatically by bar code readers. This is the same basic technology used by grocery stores and retail merchandisers.
- An alternative identification technology that is growing in importance is RFID (for radio frequency identification).

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Old questions paper

- List the various forms of computer process control- 2 marks
- What is function of controller in automation system- 2 mark
- Define material handling – 4 marks
- Explain in detail about input output devices for discrete data- 10 marks
- What is USA principle- 2marks
- Discuss in detail about forms of computer process control- 10 marks
- List out types of automation-2
- What is real- time controller -2
- What is fixed automation and what are some of its features-4
- Discuss in brief about ten strategies for automation process improvement 10

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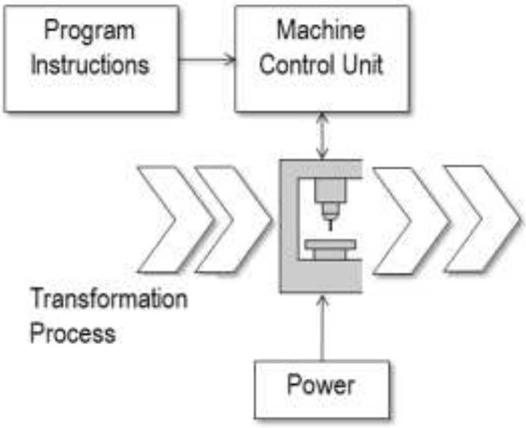
Unit:- II : NUMERICAL CONTROL

Syllabus Lectures 7

- Fundamentals of NC Technology
- Computer Numerical Control
- Distributed Numerical Control
- Applications of NC
- NC Part Programming
- Advantages and disadvantages of NC
- APT Programming

Numerical Control (NC) Defined

- Programmable automation in which the mechanical actions of a 'machine tool' are controlled by a program containing coded alphanumeric data that represents relative positions between a work head (e.g., cutting tool) and a work part.
- The work head is a cutting tool or other processing apparatus, and the work part is the object being processed.



Features Numerical Control (NC)

- When the current job is completed, the program of instructions can be changed to process a new job. The capability to change the program makes NC suitable for low and medium production.
- Numerical control can be applied to a wide variety of processes. The applications
- Categories: (1) machine tool applications, such as drilling, milling, turning, and other metal working; and (2) other applications, such as assembly, rapid prototyping, and inspection.
- The common operating feature of NC in all of these applications is control of the work head movement relative to the work part.
- The concept for NC dates from the late 1940s. The first NC machine was developed in 1952.

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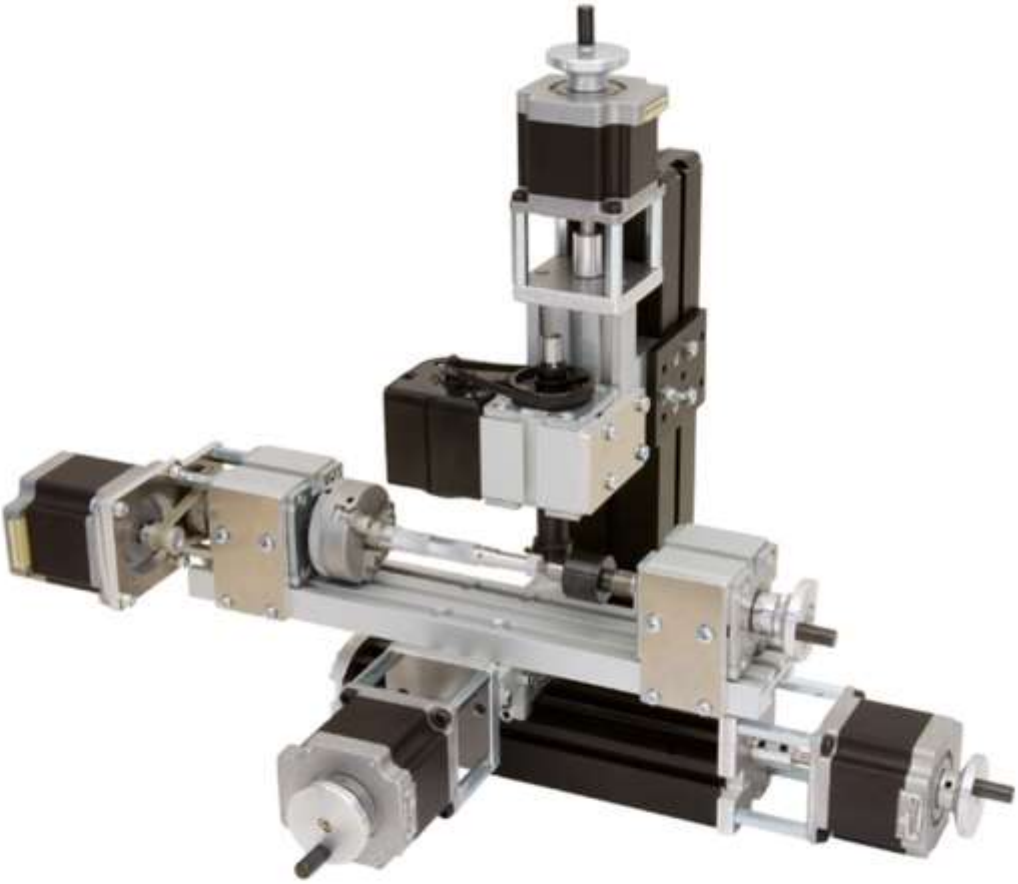

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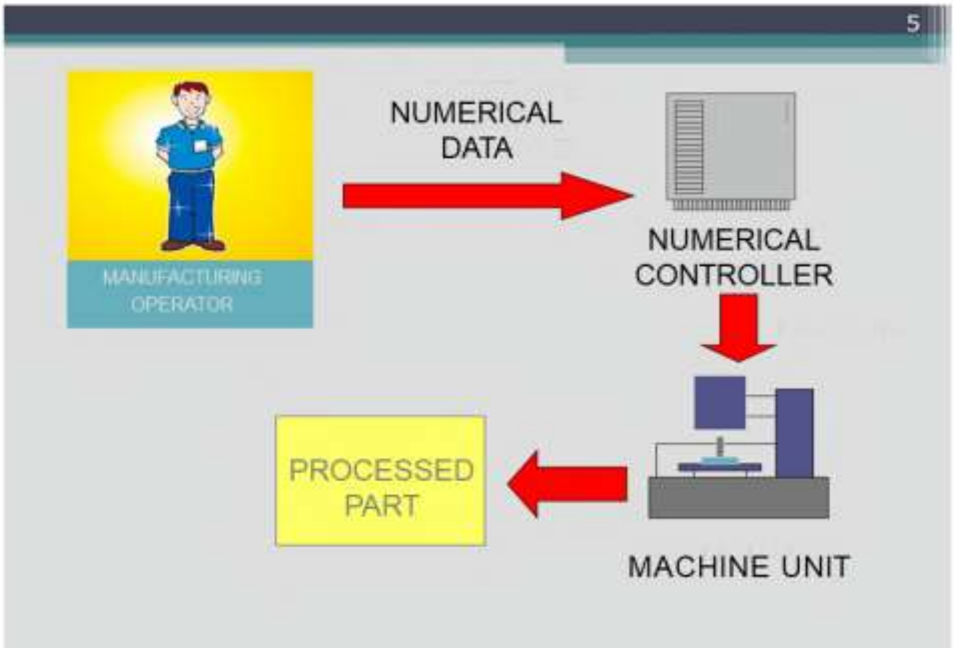
Basic Component of NC



Basic Component of NC

- The Program of Instruction
- Machine Control Unit
- Processing Equipment

Basic Component of NC - Program of Instructions

- The ***part program*** is the set of detailed step-by-step commands that direct the actions of the processing equipment.
- In machine tool applications, the person who prepares the program is called a *part programmer*. In these applications, the individual commands refer to positions of a cutting tool relative to the worktable on which the work part is fixtured. Additional instructions are usually included, such as spindle speed, feed rate, cutting tool selection, and other functions. The program is coded on a suitable medium for submission to the machine control unit.
- Common medium was 1-in wide punched tape, using a standard format that could be interpreted by the machine control unit.
- Today, punched tape has largely been replaced by newer storage technologies in modern machine shops. These technologies include magnetic tape, diskettes, and electronic transfer of part programs from a computer.
-

Basic Component of NC- Machine Control unit

- In modern NC technology, the ***machine control unit*** (MCU) is a microcomputer and related control hardware that stores the program of instructions and executes it by converting each command into mechanical actions of the processing equipment, one command at a time.
- The related hardware of the MCU includes components to interface with the processing equipment and feedback control elements.
- The MCU also includes one or more reading devices for entering part programs into memory.
- Software residing in the MCU includes control system software, calculation algorithms, and translation software to convert the NC part program into a usable format for the MCU.
- The MCU is a computer, the term *computer numerical control* (CNC) is used to distinguish this type of NC from its technological ancestors that were based entirely on hardwired electronics. Today, virtually all new MCUs are based on computer technology.

Basic Component of NC- Processing equipment

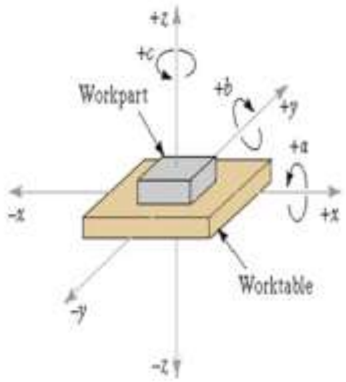
- The third basic component of an NC system is the processing equipment that performs the actual productive work (e.g., machining). It accomplishes the processing steps to transform the starting workpiece into a completed part.
- Its operation is directed by the MCU, which in turn is driven by instructions contained in the part program.
- In the most common example of NC, machining, the processing equipment consists of the worktable and spindle as well as the motors and controls to drive them.

NC Coordinate Systems

- To program the NC processing equipment, a part programmer must define a standard axis system by which the position of the work head relative to the work part can be specified.
- There are two axis systems used in NC, one for flat and prismatic work parts and other is or rotational parts.

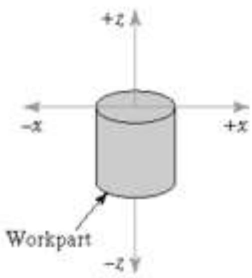
NC Coordinate Systems

- The axis system for flat and block-like parts consists of the three linear axes (*x*, *y*, *z*) in the Cartesian coordinate system, plus three rotational axes (*a*, *b*, *c*), as shown in Fig.
- In most machine tool applications, the *x*- and *y*-axes are used to move and position the worktable to which the part is attached, and the *z*-axis is used to control the vertical position of the cutting tool.
- Such a positioning scheme is adequate for simple NC applications such as drilling and punching of flat sheet metal.
- The *a*-, *b*-, and *c*-rotational axes specify angular positions about the *x*-, *y*-, and *z*- axes, respectively



NC Coordinate Systems

- Machine tools with rotational axis capability generally have either four or five axes: three linear axes plus one or two rotational axes.
- The coordinate axes for a rotational NC system are illustrated in Figure. These systems are associated with NC lathes and turning machines. Although the workpiece rotates, this is not one of the controlled axes on most turning machines. Consequently, the *y*-axis is not used.
- The path of the cutting tool relative to the rotating workpiece is defined in the *x*–*z* plane, where the *x*-axis is the radial location of the tool and the *z*-axis is parallel to the axis of rotation of the part.
- Some machine tools are equipped with more than the number of axes described above. The additional axes are usually included to control more than one tool or spindle



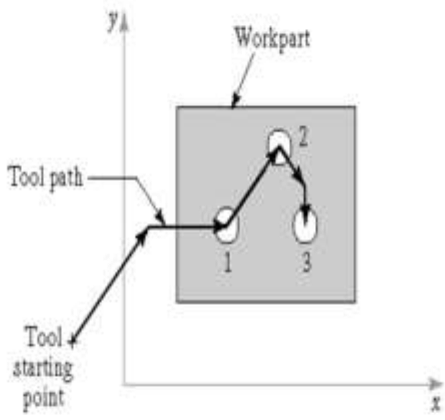
Motion Control Systems

- Some NC processes are performed at discrete locations on the work part (e.g., drilling and spot welding). Others are carried out while the work head is moving (e.g., turning, milling, and continuous arc welding).
- If the work head is moving, it may be necessary to follow a straight line path or a circular or other curvilinear path. These different types of movement are accomplished by the motion control system, whose features are explained below

Motion Control Systems

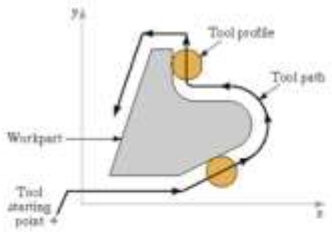
Point-to-Point systems

- ***Point-to-point*** systems, also called *positioning systems*, move the worktable to a programmed location without regard for the path taken to get to that location.
- Once the move has been completed, some processing action is accomplished by the work head at the location, such as drilling or punching a hole. Thus, the program consists of a series of point locations at which operations are performed, as depicted in Figure



Continuous path systems

- are capable of continuous simultaneous control of two or more axes.
- This provides control of the tool trajectory relative to the work part. In this case, the tool performs the process while the worktable is moving, thus enabling the system to generate angular surfaces, two-dimensional curves, or three-dimensional contours in the work part. This control mode is required in many milling and turning operations.
- When continuous path control is utilized to move the tool parallel to only one of the major axes of the machine tool worktable, this is called *straight-cut NC*. When continuous path control is used for simultaneous control of two or more axes in machining operations, the term *contouring* is used.

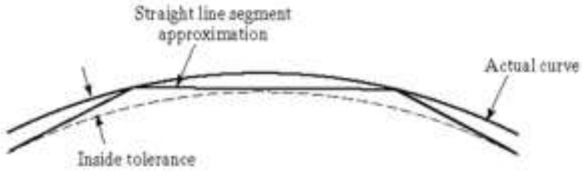


A simple two-dimensional profile milling operation to illustrate continuous path control

Motion Control Systems

One of the important aspects of contouring is interpolation. The paths that a contouring-type NC system is required to generate often consist of circular arcs and other smooth nonlinear shapes

1. Linear interpolation
   - Straight line between two points in space
2. Circular interpolation
   - Circular arc defined by starting point, end point, center or radius, and direction
3. Helical interpolation
   - Circular plus linear motion
4. Parabolic and cubic interpolation
   - Free form curves using higher order equations



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Absolute vs. Incremental Positioning

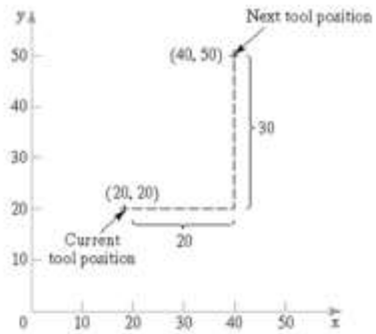
Another aspect of motion control is concerned with whether positions are defined relative to the origin of the coordinate system (absolute positioning) or relative to the previous location of the tool (incremental positioning).

Absolute positioning

Move is: $x = 40, y = 50$

Incremental positioning

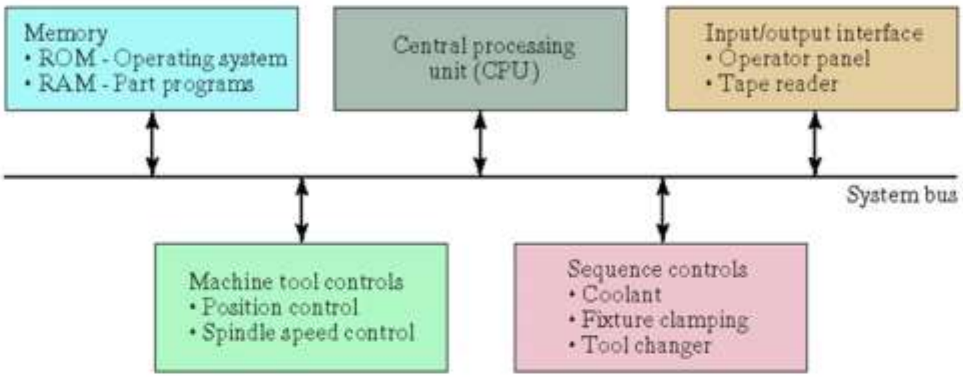
Move is: $x = 20, y = 30$.



CNC- Computer Numerical Control

- *Computer numerical control* (CNC), which is defined as an NC system whose MCU consists of a dedicated microcomputer rather than a hardwired controller.
- The latest computer controllers for CNC feature highspeed processors, large memories, solid-state memory, improved servos, and bus architectures

(CNC)-Machine Control Unit



(CNC)-Machine Control Unit

The MCU consists of the following components and subsystems:

(1) central processing unit,

(2) memory,

(3) I/O interface,

(4) controls for machine tool axes and spindle speed, and

(5) sequence controls for other machine tool functions.

These subsystems are interconnected by means of a system bus, which communicates data and signals among the components of the network.

Feature that distinguish NC and CNC

- ***Storage of more than one part program:*** With improvements in storage technology, newer CNC controllers have sufficient capacity to store multiple programs.
- ***Program editing at the machine tool:*** CNC permits a part program to be edited while it resides in the MCU computer memory. Hence, a program can be tested and corrected entirely at the machine site. Editing also permits cutting conditions in the machining cycle to be optimized. After the program has been corrected and optimized, the revised version can be stored for future use.
- *Fixed cycles and programming subroutines:* The increased memory capacity and the ability to program the control computer provide the opportunity to store frequently used machining cycles as *macros* that can be called by the part program. Instead of writing the full instructions for the particular cycle into every program, a programmer includes a call statement in the part program to indicate that the macro cycle should be executed.

- *Adaptive control:* In this feature, the MCU measures and analyses machining variables, such as spindle torque, power, and tool-tip temperature, and adjusts cutting speed and/or feed rate to maximize machining performance. Benefits include reduced cycle time and improved surface finish.
- ***Interpolation:*** Some of the interpolation schemes are normally executed on a CNC System because of the computational requirements. Linear and circular interpolations are sometimes hardwired into the control unit, but helical, parabolic, and cubic interpolations are usually executed by a stored program algorithm.
- ***Positioning features for setup:*** Setting up the machine tool for a given work part involves installing and aligning a fixture on the machine tool table. This must be accomplished so that the machine axes are established with respect to the work part. The alignment task can be facilitated using certain features made possible by software options in a CNC system, such as *position set*.

- ***Acceleration and deceleration calculations:*** This feature is applicable when the cutter moves at high feed rates. It is designed to avoid tool marks on the work surface that would be generated due to machine tool dynamics when the cutter path changes abruptly
- ***Communications interface:*** With the trend toward interfacing and networking in plants today, modern CNC controllers are equipped with a standard communications interface to link the machine to other computers and computer-driven devices. This is useful for applications such as (1) downloading part programs from a central data file; (2) collecting operational data such as workpiece counts, cycle times, and machine utilization; and (3) interfacing with peripheral equipment, such as robots that load and unload parts.
- *Diagnostics:* Many modern CNC systems possess a diagnostics capability that monitors certain aspects of the machine tool to detect malfunctions or signs of impending malfunctions

DNC

- There are two ways in which digital computers have been used to implement NC. This section describes two approaches:

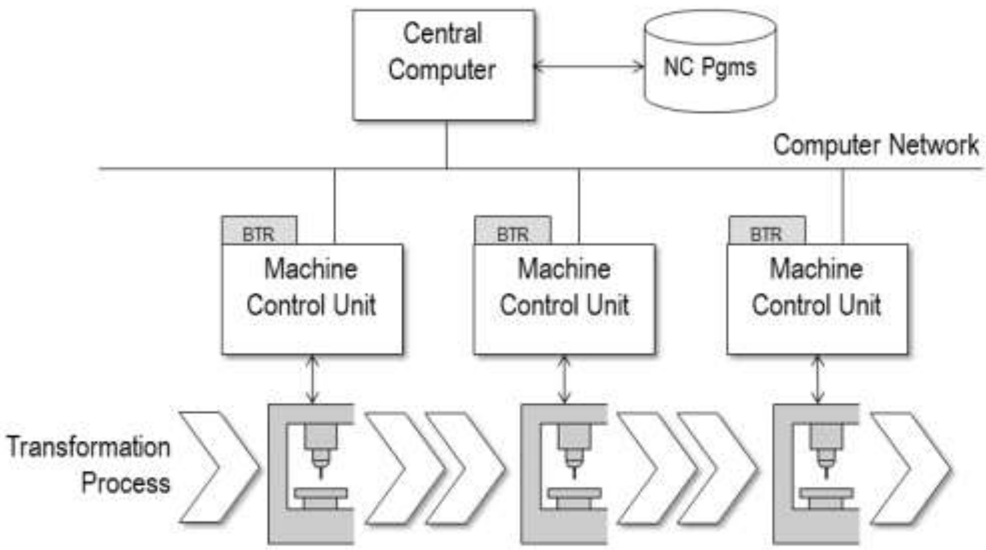
(1) direct numerical control and

(2) distributed numerical control.

DNC

- Direct numerical control (DNC) – control of multiple machine tools by a single (mainframe) computer through direct connection and in real time
  - 1960s technology
  - Two way communication
- Distributed numerical control (DNC) – network consisting of central computer connected to machine tool MCUs, which are CNC
  - Present technology
  - Two way communication

Distributed Numerical Control

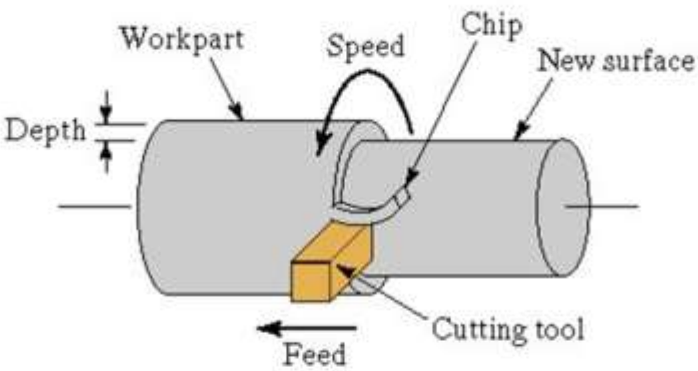


Applications of NC

Applications of NC

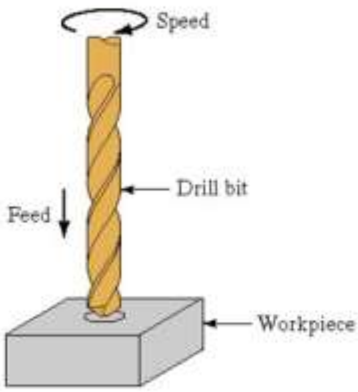
- Machine tool applications:
  - Milling, drilling, turning, boring, grinding
  - Machining centers, turning centers, mill-turn centers
  - Punch presses, thermal cutting machines, etc.
- Other NC applications:
  - Component insertion machines
  - Drafting machines
  - Electrical wire wrap machines
  - Tape laying machines
  - Filament winding machines

Common NC Machining Operations

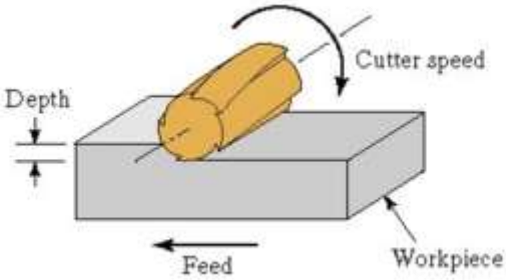


Turning

Common NC Machining Operations

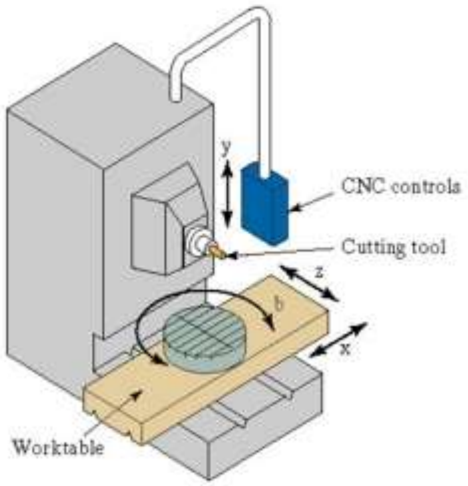


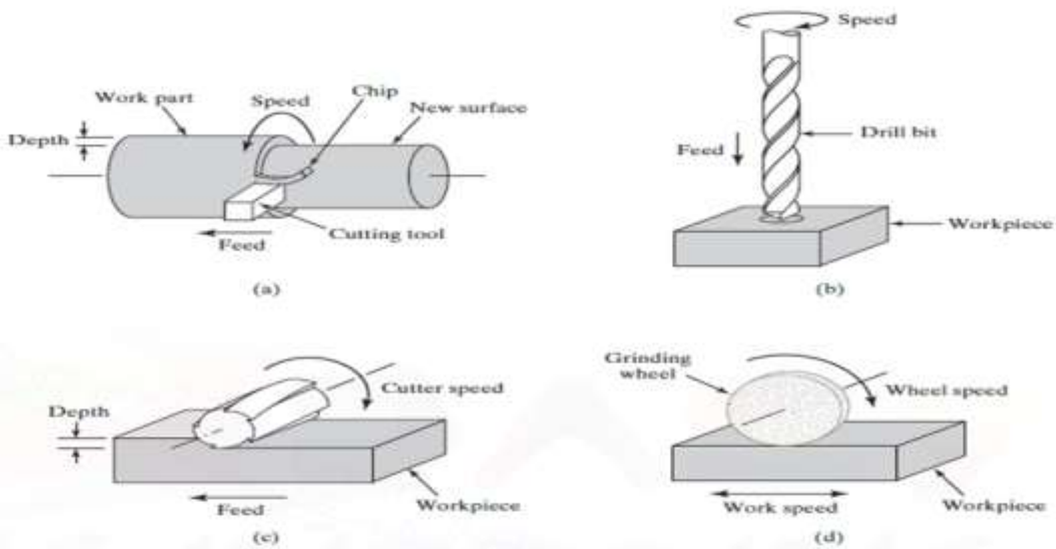
Drilling



Milling

CNC Horizontal Milling Machine





Analysis of milling

$$N = v/pi*D$$

where N = spindle rotation speed, rev/min; v = cutting speed, m/min (ft/min); and D = milling cutter diameter, m (ft).

$$f_r = N n_t f$$

where f_r = feed rate, mm/min (in/min); N = spindle rotational speed, rev/min; n_t = number of teeth on the milling cutter; and f = feed, mm/tooth (in/tooth).

The following is a list of the common material-removal CNC machine tools along with their typical features:

• *NC lathe*, either horizontal or vertical axis. Turning requires two-axis, continuous path control, either to produce a straight cylindrical geometry (straight turning) or to create a profile (contour turning).

• *NC boring mill*, horizontal or vertical spindle. Boring is similar to turning, except that an internal cylinder is created instead of an external cylinder. The operation requires continuous path, two-axis control.

• *NC drill press*. This machine uses point-to-point control of a work head (spindle containing the drill bit) and two axis (x–y) control of a worktable. Some NC drill presses have turrets containing six or eight drill bits. The turret position is programmed under NC control, allowing different drill bits to be applied to the same work part during the machine cycle without requiring the machine operator to manually change the tool.

• *NC milling machine*. A milling machine requires continuous path control to perform straight cut or contouring operations. Figure 7.10 illustrates the features of a CNC four-axis milling machine.

• *NC cylindrical grinder*. This machine operates like a turning machine, except that the tool is a grinding wheel. It has continuous path two-axis control, similar to anNC lathe.

Other application of NC

Rapid prototyping and additive manufacturing. These include a number of processes that add material, one thin layer at a time, to construct a part. Many of them operate by means of a work head that is manipulated by NC over the partially constructed part. Some processes use lasers to cure photosensitive liquid polymers (stereolithography) or fuse solid powders (selective laser sintering); others use extruder heads that add material (fused deposition modelling).

Water jet cutters and abrasive water jet cutters. These machines are used to cut various materials, including metals and nonmetals (e.g., plastic, cloth), by means of a fine, high-pressure, high-velocity stream of water. Abrasive particles are added to the stream in the case of abrasive water jet cutting to facilitate cutting of more difficult materials (e.g., metals). The work head is manipulated relative to the work material by means of numerical control.

- ***Component placement machines.*** This equipment is used to position components on an *x*–*y* plane, usually a printed circuit board. The program specifies the *x*- and *y*-axis positions in the plane where the components are to be located. Component placement machines find extensive applications for placing electronic components on printed circuit boards. Machines are available for either through-hole or surface mount applications as well as similar insertion-type mechanical assembly operations.
- ***Coordinate measuring machines***. A coordinate measuring machine (CMM) is an inspection machine used for measuring or checking dimensions of a part. A CMM has a probe that can be manipulated in three axes and that identifies when contact is made against a part surface. The location of the probe tip is determined by the CMM control unit, thereby indicating some dimension on the part. Many coordinate measuring machines are programmed to perform automated inspections under NC.

- ***Wood routers and granite cutters***. These machines perform operations similar to NC milling for metal machining, except the work materials are not metals. Many wood cutting lathes are also NC machines.
- ***Tape laying machines for polymer composites***. The work head of this machine is a dispenser of uncured polymer matrix composite tape. The machine is programmed to lay the tape onto the surface of a contoured mould, following a back-and-forth and crisscross pattern to build up a required thickness. The result is a multi layered panel of the same shape as the mould.
- ***Filament winding machines for polymer composites***. These are similar to the preceding machine except that a filament is dipped in uncured polymer and wrapped around a rotating pattern of roughly cylindrical shape

NC Application Characteristics (of Machining Applications)

- Batch and High Volume production
- Repeat and/or Repetitive orders
- Complex part geometries
- Mundane operations
- Many separate operations on one part

Advantages of NC

The advantages generally attributed to NC are the following:

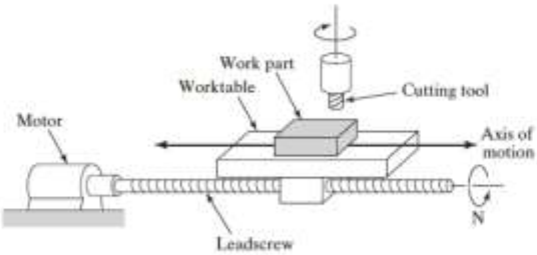
- *Nonproductive time is reduced.*
- *Greater accuracy and repeatability*
- *Lower scrap rates.*
- *Inspection requirements are reduced.*
- *More complex part geometries are possible*
- *Engineering changes can be accommodated more gracefully*
- *Simpler fixtures.*
- *Shorter manufacturing lead times.*
- *Reduced parts inventory.*
- *Less floor space*
- *Operator skill requirements are reduced.*

Disadvantages of NC

- *Higher investment cost*. An NC machine tool has a higher first cost than a comparable conventional machine tool.
- *Higher maintenance effort.*
- *Part programming.*
- *Higher utilization of NC equipment*. To maximize the economic benefits of NC, some companies operate multiple shifts. This might mean adding one or two extra shifts to the plant's normal operations, with the requirement for supervision and other staff support.

NC positioning System

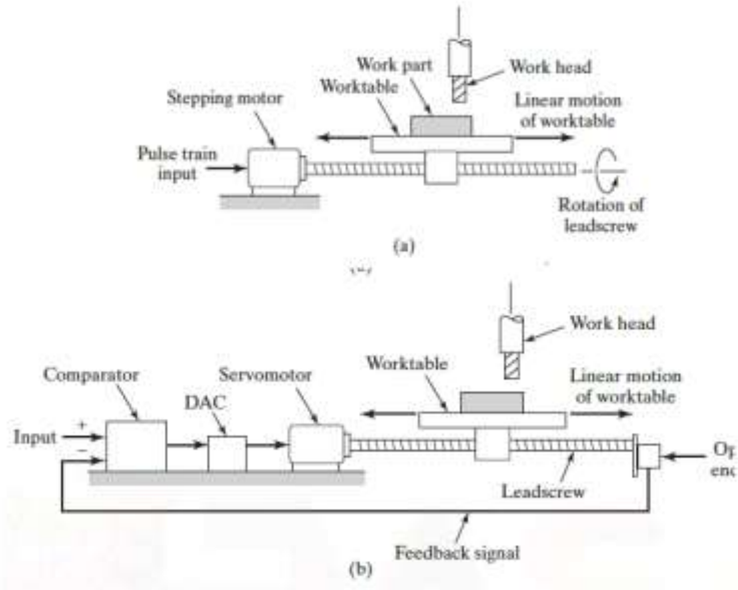
- An NC positioning system converts the coordinate axis values in the NC part program into relative positions of the tool and work part during processing. Consider the simple positioning system shown in Figure.
- The system consists of a cutting tool and a worktable on which a work part is fixtured.
- The table is designed to move the part relative to the tool. The worktable moves linearly by means of a rotating leadscrew or ball screw, which is driven by a stepper motor or servomotor



Two types of control systems are used in positioning systems: (a) open loop and

(b) closed loop,

- An open-loop system operates without verifying that the actual position achieved in the move is the same as the desired position.
- A closed-loop system uses feedback measurements to confirm that the final position of the worktable is the location specified in the program. Open-loop systems cost less than
- closed-loop systems and are appropriate when the force resisting the actuating motion is minimal. Closed-loop systems are normally specified for machines that perform continuous path operations such as milling or turning.



Two Types of motion control system in NC (a) open loop and (b) closed loop

Cost-Benefits of NC

Costs

- High investment cost
- High maintenance effort
- Need for skilled programmers
- High utilization required

Benefits

- Cycle time reduction
- Nonproductive time reduction
- Greater accuracy and repeatability
- Lower scrap rates
- Reduced parts inventory and floor space
- Operator skill-level reduced

NC Part Programming

1. Manual part programming
2. Manual data input
3. Computer-assisted part programming
4. Part programming using CAD/CAM

Manual Part Programming

Binary Coded Decimal System

- Each of the ten digits in decimal system (0-9) is coded with four-digit binary number
- The binary numbers are added to give the value
- BCD is compatible with 8 bits across tape format, the original storage medium for NC part programs
- Eight bits can also be used for letters and symbols

Manual Part Programming

Creating Instructions for NC

- Bit - 0 or 1 = absence or presence of hole in the tape
- Character - row of bits across the tape
- Word - sequence of characters (e.g., y-axis position)
- Block - collection of words to form one complete instruction
- Part program - sequence of instructions (blocks)

Manual Part Programming

- In manual part programming, the programmer prepares the NC code using a low level machine language.
- The coding system is based on binary numbers. This coding is the low-level machine language that can be understood by the MCU. When higher level languages are used, such as APT and CAD/CAM ,the statements in these respective programs are converted to this basic code.
- NC uses a combination of the binary and decimal number systems, called the *binary-coded decimal* (BCD) system. In this coding scheme, each of the ten digits (0–9) in the decimal system is coded as a four digit binary number, and these binary numbers are added in sequence as in the decimal

Manual Part Programming

Decimal digit	BCD			
	8	4	2	1
0	0	0	0	0
1	0	0	0	1
2	0	0	1	0
3	0	0	1	1
4	0	1	0	0
5	0	1	0	1
6	0	1	1	0
7	0	1	1	1
8	1	0	0	0
9	1	0	0	1

Manual Part Programming-Block Format

Organization of words within a block in NC part program

- Also known as tape format because the original formats were designed for punched tape
- Word address format - used on all modern CNC controllers
  - Uses a letter prefix to identify each type of word
  - Spaces to separate words within the block
  - Allows any order of words in a block
  - Words can be omitted if their values do not change from the previous block

Manual Part Programming

Types of Words

N - sequence number prefix

G - preparatory words

- Example: G00 = PTP rapid traverse move

Block Format

X, Y, Z - prefixes for *x*, *y*, and *z*-axes

F - feed rate prefix

S - spindle speed

T - tool selection

M - miscellaneous command

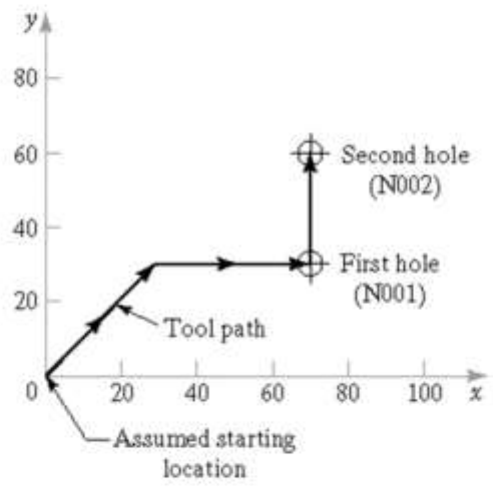
- Example: M07 = turn cutting fluid on

Manual Part Programming

Example: Word Address Format

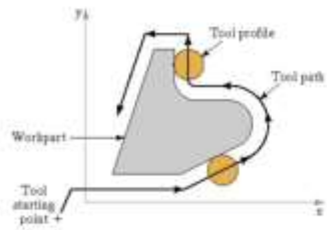
N001 G00 X07000 Y03000 M03

N002 Y06000



Cutter Offset

Cutter path must be offset from actual part outline by a distance equal to the cutter radius



Manual Part Programming

Issues in Manual Part Programming

- Adequate for simple jobs, e.g., PTP drilling
- Linear interpolation
  G01 G94 X050.0 Y086.5 Z100.0 F40 S800
- Circular interpolation
  G02 G17 X088.0 Y040.0 R028.0 F30
- Cutter offset
  G42 G01 X100.0 Y040.0 D05

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Manual Part Programming

Example

NC part program code	Comments
N001 G21 G90 G92 X-050.0 Y-050.0 Z010.0;	Define origin of axes.
N002 G00 Z-020.0 S1989 M03;	Rapid to cutter depth, turn spindle on.
N003 G01 G94 G42 Y0 D05 F398;	Bring tool to starting y-value, start cutter offset.
N004 G01 X075.0;	Mill lower horizontal edge of part.
N005 G01 X150.0 Y043.02;	Mill angled edge at 35 degrees.
N006 G01 Y070.0;	Mill vertical edge at right of part.
N007 G01 X080.0;	Mill horizontal edge leading to arc.
N008 G17 G02 X050.0 Y100.0 R030.0;	Circular interpolation around arc.
N009 G01 Y125.0;	Mill vertical step above arc.
N010 G01 X0;	Mill top part edge.
N011 G01 Y0	Mill vertical edge at left of part.
N012 G40 G00 X-050.0 Y-050.0 Z010.0 M05;	Rapid move to target point, cancel offset, spindle stop.
N013 M30;	End of program, stop machine.

Manual Data Input

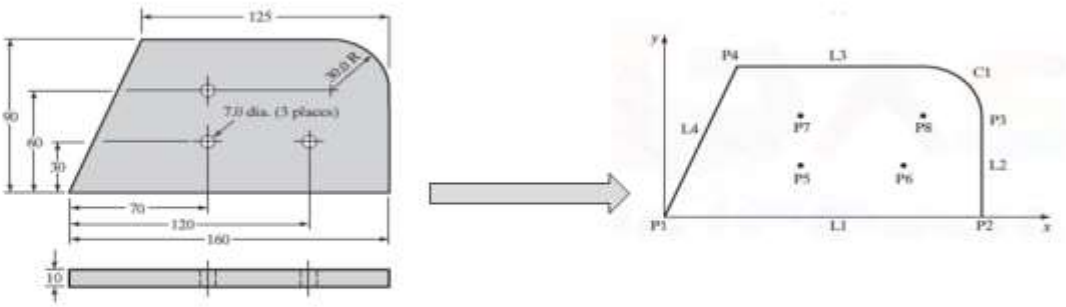
- Machine operator does part programming at machine
  - Operator enters program by responding to prompts and questions by system
  - Monitor with graphics verifies tool path
  - Usually for relatively simple parts
- Ideal for small shop that cannot afford a part programming staff
- To minimize changeover time, system should allow programming of next job while current job is running

Computer-Assisted Part Programming

- Write machine instructions using natural language type statements
- Statements translated into machine code of the MCU
- APT (Automatically Programmed Tool) Language

Computer-Assisted Part Programming

APT Part Programming



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Computer-Assisted Part Programming

APT Part Programming

The part programmer enters the program using APT or some other high-level part programming language. The input translation module converts the coded instructions contained in the program into computer-usable form, preparatory to further processing. In APT, input translation accomplishes the following tasks:

(1) syntax check of the input code to identify errors in format, punctuation, spelling, and statement sequence;

(2) assigning a sequence number to each APT statement in the program;

(3) converting geometry elements into a suitable form for computer processing; an

(4) generating an intermediate file called PROFIL that is utilized in subsequent arithmetic calculations. The arithmetic module consists of a set of subroutines to perform the

APT Part Programming

Sample Statements

- Part is composed of basic geometric elements and mathematically defined surfaces
- Examples of statements:

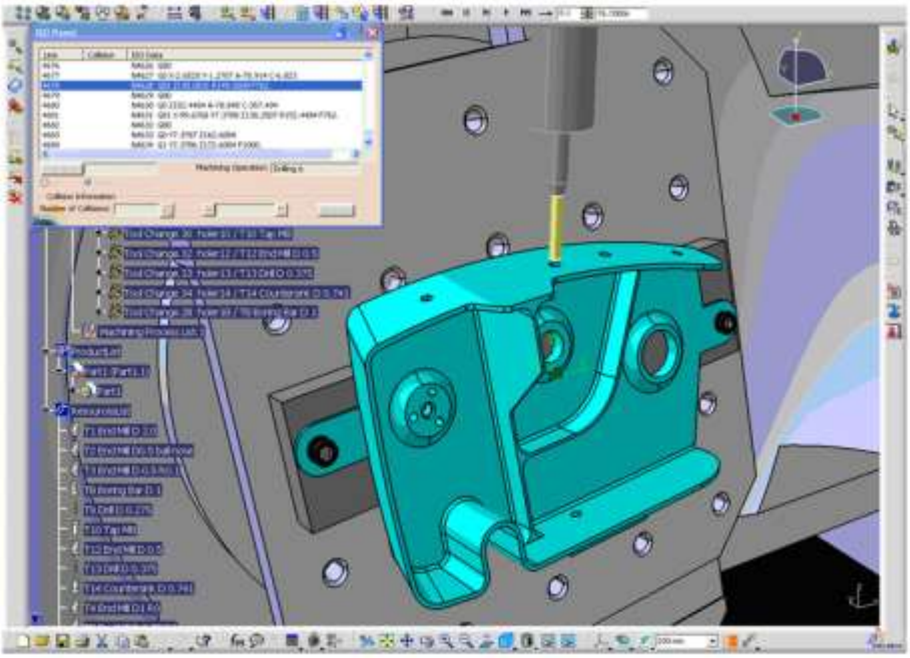
  P4 = POINT/35,90,0

  L1 = LINE/P1,P2

  C1 = CIRCLE/CENTER,P8,RADIUS,30

- Tool path is sequence of points or connected line and arc segments
- Point-to-Point command: GOTO/P4
- Continuous path command: GOLFT/L1,TANTO,C1

NC Part Programming Using CAD/CAM



Questions

1. Type three of the NC advantages?
2. What are the Basic Components of an NC System?
3. What are The NC programming methods?
4. What is the Computer Numerical Control (CNC)?

Answers

Type three of the NC advantages?

- Simpler fixtures
- Shorter lead times
- Reduce parts inventory
-

What are the Basic Components of an NC System?

- Program of instructions
- Machine control unit
- Processing equipment
-

What are The NC programming methods?

- Manual part programming
- Computer-assisted part programming
- Part programming using CAD/CAM
- Manual data input
-

What is the Computer Numerical Control (CNC)?

- Is defined as an NC system whose MCU is based on a dedicated microcomputer rather than on a hard-wired controller

Old question paper

- What are Parameters considered while Preparing a Manual Part Programming- 2 Marks
- A Cast Iron Work Piece is to be faced milled on a NC Machines using Cemented carbide Inserts. The cutter has 16 teeth and is 120mm in diameter. Cutting speed=200m/min and feed=0.005mm/tooth. Convert these value to rev/min and mm/rev respectively.- 7 marks.
- Explain the type of coordinate system used in NC machines.- 7 marks
- What are three advantage of NC- 2 marks
- Write the applications of NC and discuss them in detail.-10 marks
- What is the difference between open loop and closed loop control system in NC- 4marks

$$f_r = N n_t f$$

where f_r = feed rate, mm/min (in/min); N = spindle rotational speed, rev/min; n_t = number of teeth on the milling cutter; and f = feed, mm/tooth (in/tooth).

- Parameters that are considered while preparing a manual part program

1. Spindle speed
2. Feed rate
3. Coordinate axis

Unit-III Assembly Lines

Fundamentals of Manual Assembly Lines

Manual Assembly Lines

- production line that consists of a sequence of workstations where assembly tasks are performed by human workers. Products are assembled as they move along the line. At each station, a worker performs a portion of the total work on the unit.
- Assembly workers perform tasks at workstations located along the line-of-flow of the product
- Usually a powered conveyor is used Some of the workstations may be equipped with portable powered tools

Factors favoring the use of assembly lines:

- High or medium demand for product
- Products are similar or identical
- Total work content can be divided into work elements
- To automate assembly tasks is impossible

Fundamentals of Manual Assembly Lines

Manual Assembly Line

- ❑ A production line that consists of a sequence of workstations where assembly tasks are performed by human workers
- ❑ Products are assembled as they move along the line
- ❑ At each station a portion of the total work content is performed on each unit
- ❑ Base parts are launched onto the beginning of the line at regular intervals (cycle time)
- ❑ Workers add components to progressively build the product

Fundamentals of Manual Assembly Lines

Why Assembly Lines are Productive

- **Specialization of labour:**
- When a large job is divided into small tasks and each task is assigned to one worker, the worker becomes highly proficient at performing the single task (Learning curve)

- **Interchangeable parts:**
- Each component is manufactured to sufficiently close tolerances that any part of a certain type can be selected at random for assembly with its mating component.

Fundamentals of Manual Assembly Lines

Some Definitions

- **Work flow:**

Each work unit should move steadily along the line

- **Line pacing**

Workers must complete their tasks within a certain cycle time, which will be the pace of the whole line

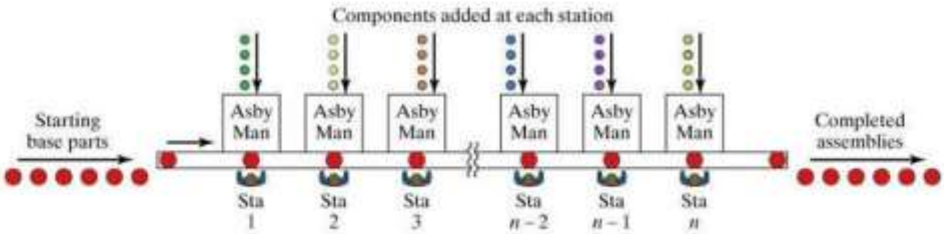
Fundamentals of Manual Assembly Lines

Origin of Manual Assembly Line

Two assembly operators working on an engine assembly line (photo courtesy of Ford Motor Company)

Fundamentals of Manual Assembly Lines

•Configuration of an *n*-workstation manual assembly line



•The production rate of an assembly line is determinedby its slowest station

Assembly workstation: A designated location along the work flow path which one or more work elements are performed by one or more workers The work elements represent small portions of the total work that must be accomplished to assemble the product.

Fundamentals of Manual Assembly Lines

Assembly Workstation

A designated location along the work flow path at which one or more work elements are performed by one or more workers

Typical operations performed at manual assembly stations

Adhesive application	Electrical connections	Snap fitting
Sealant application	Component insertion	Soldering
Arc welding	Press fitting	Stitching/stapling
Spot welding	Riveting	Threaded fasteners

Fundamentals of Manual Assembly Lines

Work Transport Systems-Manual Methods

- Manual methods: Work units are moved between stations by the workers without powered conveyor

Problems:

Starving of stations

Blocking of stations

Fundamentals of Manual Assembly Lines

Work Transport Systems-Manual Methods

- To reduce starving,
  - use buffers
- To prevent blocking,
  - provide space between upstream and downstream stations.
- But both solutions can result in higher WIP,
  - which is economically undesirable.

Fundamentals of Manual Assembly Lines

Work Transport Systems-Mechanized Methods

- **Continuously moving conveyor:** operates at constant velocity
  - Work units are fixed to the conveyor
    - Worker moves alongside the line and back
  - Work units are removable from the conveyor
- **Synchronous transport (intermittent transport – stop-and-go line):** all work units are moved simultaneously between stations.
  - Problem: Incomplete units; excessive stress. Not common for manual lines (variability).
- **Asynchronous transport :** a work unit leaves a given station when the assigned task is completed.
  - Variations in worker task times: small queues in front of each station.

Fundamentals of Manual Assembly Lines

Coping with Product Variety

- **Single model assembly line (SMAL)**
  - Every work unit is the same
- **Batch model assembly line (BMAL) – multiple model line**
  - Two or more different products
  - Products are so different that they must be made in batches with setup between
- **Mixed model assembly line (MMAL)**
  - Two or more different models
  - Differences are slight so models can be made simultaneously with no downtime

Fundamentals of Manual Assembly Lines

Coping with Product Variety

- Advantages of mixed models over batch order models
  - No production time is lost during changeovers
  - High inventories due to batch ordering are avoided
  - Production rates of different models can be adjusted as product demand changes.
- Disadvantages of mixed models over batch order models
  - Each station is equipped to perform variety of tasks (costly)
  - Scheduling and logistic activities are more difficult in this type of lines.

Alternative Assembly Systems:

- Assembly line workers often complain about the monotony of the repetitive tasks they must perform and the unrelenting pace they must maintain when a moving conveyor is used.
- Poor quality workmanship, sabotage of the line equipment, and other problems have occurred on high production assembly lines.
- To address these issues, alternative assembly systems are available in which the work is made less monotonous and repetitious by enlarging the scope of the tasks performed, or the work is automated.

Alternative Assembly Systems

A single station manual assembly cell

- It consists of a single workplace in which the assembly work is accomplished
- on the product or some major sub assembly of the product.

Assembly cells based on worker teams

- It involves the use of multiple workers assigned to a common assembly task.

Automated assembly systems

- Use automated methods at workstations rather than humans. These can be type IA or type IIIA manufacturing systems.

Alternative Assembly Systems

- **Single-station manual assembly cell**
  - A single workstation in which all of the assembly work is accomplished on the product or on some major subassembly
  - Common for complex products produced in small quantities, sometimes one of a kind
- **Assembly by worker teams**
  - Multiple workers assigned to a common assembly task
  - Advantage: greater worker satisfaction
  - Disadvantage: slower than line production

Automated Production Lines- Defined

- An Automated Production line is comprised of series of a series of workstations linked by a transfer system and an electrical control system.
- Each station perform a specific operation (preferably machining operations)and the product is processed step by step as it moves along the line in a pre-defined production sequence.

Automated Production Lines

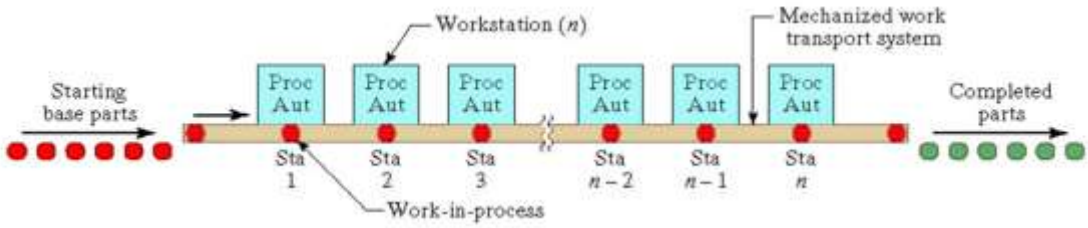
- High product demand
  - Requires large production quantities
- Stable product design
  - Difficult to change the sequence and content of processing operations once the line is built
- Long product life
  - At least several years
- Multiple operations required on product
  - The different operations are assigned to different workstations in the line

Benefits of Automated Production Lines

- Low direct labor content
- Low product cost
- High production rates
- Production lead time and work-in-process are minimized
- Factory floor space is minimized

Automated Production Lines-configuration

Configuration



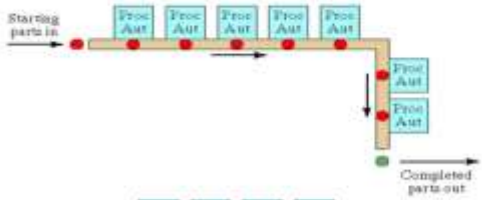
General configuration of an automated production line consisting of *n* automated workstations that perform processing operations

Automated Production Lines System Configurations

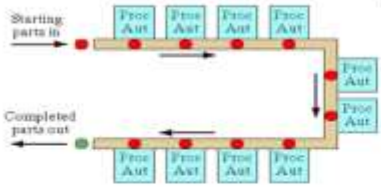
- In-line - straight line arrangement of workstations
- Segmented in-line – two or more straight line segments, usually perpendicular to each other
- Rotary indexing machine (e.g., dial indexing machine)

Segmented In-Line Configurations

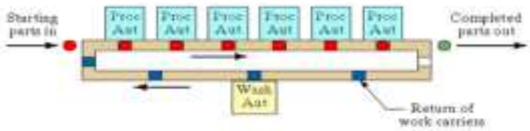
L-shaped layout



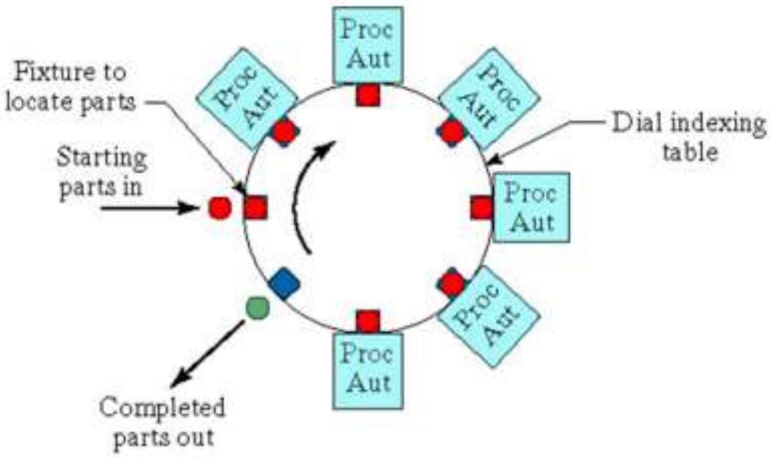
U-shaped layout



Rectangular configuration



Rotary Configuration

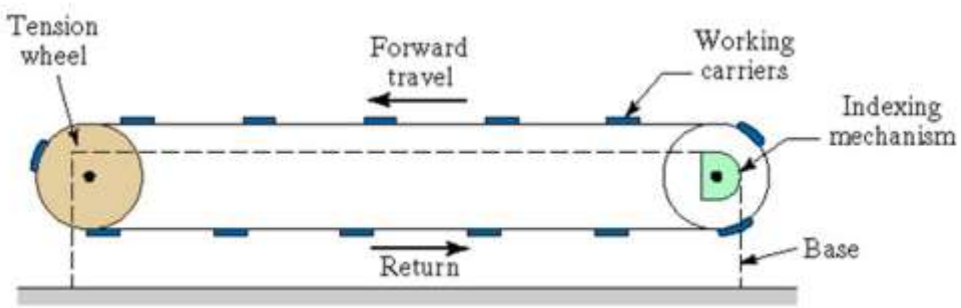


Work part Transfer Mechanisms

- Linear transfer systems:
  - Continuous motion – not common for automated systems
  - Synchronous motion – intermittent motion, all parts move simultaneously
  - Asynchronous motion – intermittent motion, parts move independently
- Rotary indexing mechanisms:
  - Geneva mechanism
  - Others

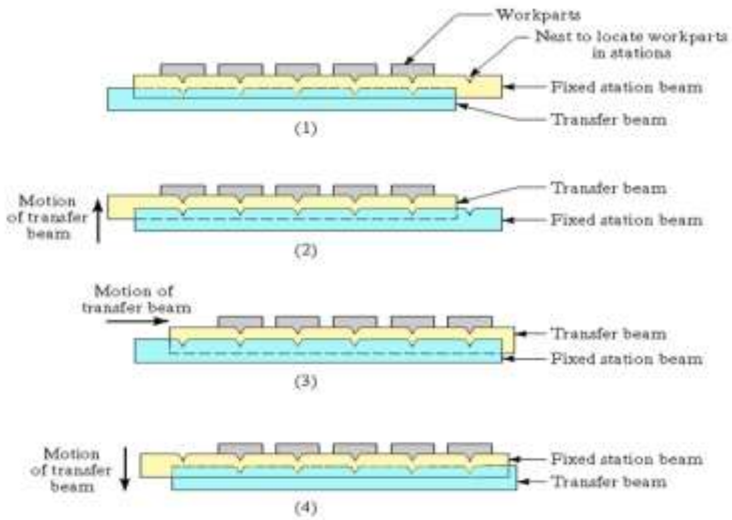
Work part Transfer Mechanisms

Belt-Driven Linear Transfer System



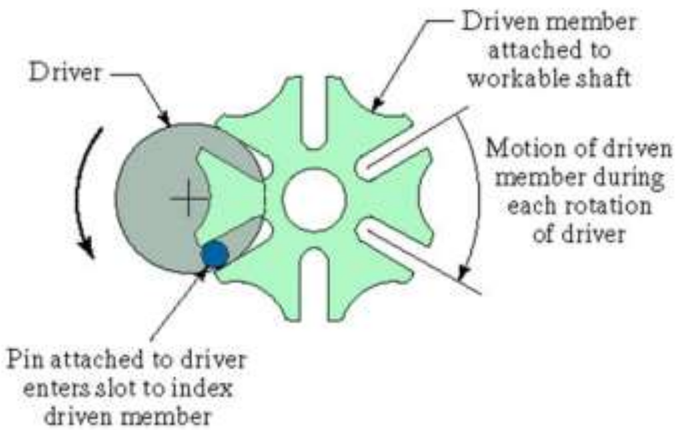
Side view of chain or steel belt-driven conveyor (over and under type) for linear transfer using work carriers

Work part Transfer Mechanisms



Walking Beam Transport System

Work part Transfer Mechanisms-Geneva Mechanism with Six Slots



Geneva Mechanism with Six Slots

Work part Transfer Mechanisms-Geneva Mechanism with Six Slots

- A representative type is the ***Geneva mechanism***, which uses a continuously rotating driver to index the table through a partial rotation,
- If the driven member has six slots for a six-station dial-indexing table, each turn of the driver results in a 1/6th rotation of the worktable, or 60°.
- The driver only causes motion of the table through a portion of its own rotation.

Work part Transfer Mechanisms-Geneva Mechanism with Six Slots

- A representative type is the ***Geneva mechanism***, which uses a continuously rotating driver to index the table through a partial rotation,
- If the driven member has six slots for a six-station dial-indexing table, each turn of the driver results in a 1/6th rotation of the worktable, or 60°.
- The driver only causes motion of the table through a portion of its own rotation.

For a six slotted Geneva, 120° of driver rotation is used to index the table. The remaining 240° of driver rotation is dwell time for the table, during which the operation must be completed on the work unit. In general,

where θ = angle of rotation of worktable during indexing (degrees of rotation), and n_s = number of equally spaced slots in the Geneva. The angle of driver rotation during indexing = 2θ,

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

Establish the maximum number of workstation positions that can be placed around the periphery of the table. Given the rotational speed of the driver, total cycle

$$T_c = \frac{1}{N}$$

$$T_s = \frac{(180 + \theta)}{360N}$$

$$T_r = \frac{(180 - \theta)}{360N}$$

Example

A rotary worktable is driven by a Geneva mechanism with six slots, as in Figure 16.7. The driver rotates at 30 rev/min. Determine the cycle time, available processing time, and the lost time each cycle to index the table.

Solution: With a driver speed of 30 rev/min, the total cycle time is given by Equation (16.2):

$$T_c = (30)^{-1} = 0.0333 \text{ min} = \mathbf{2.0 \text{ sec}}$$

The angle of rotation of the worktable during indexing for a six-slotted Geneva is given by Equation (16.1):

$$\theta = \frac{360}{6} = 60^\circ$$

Q. A rotary worktable is driven by a Geneva mechanism with six slots, The driver rotates at 30 rev/min. Determine the cycle time, available processing time, and the lost time each cycle to index the table.

Solution: With a driver speed of 30 rev/min, the total cycle time is given $T_c = 30^{-1}$ = 0.0333 min = **2.0 sec**

The angle of rotation of the worktable during indexing for a six-slotted Geneva

$$\theta = 360/6 = 60^\circ$$

Service time

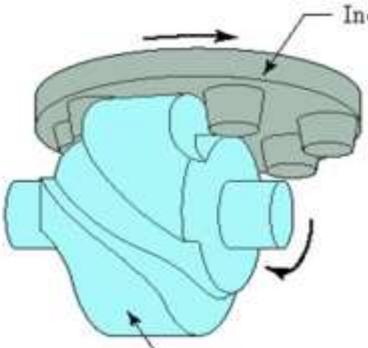
$$T_s = \frac{(180+60)}{360(30)} = 0.0222 \text{ min} = \mathbf{1.333\ sec}$$

Repositioning time

$$T_r = \frac{(180-60)}{360(30)} = 0.0111 \text{ min} = \mathbf{0.667\ sec}$$

(A) A rotary worktable is driven by a Geneva mechanism with five slots. The driver rotates at 24 rev/min. Determine (a) the cycle time, (b) available process time, and (c) indexing time each cycle.

Cam Mechanism to Drive Dial Indexing Table



CAM Mechanisms

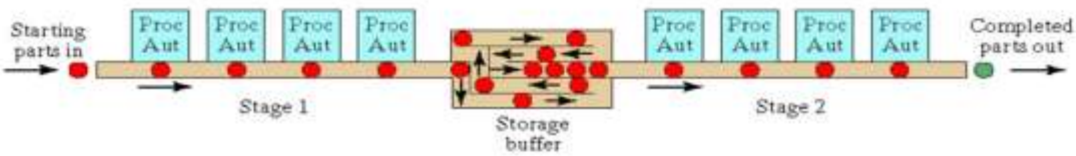
- CAM Mechanism provide probably the most accurate and reliable method of indexing the dial.
- They are in widespread use in industry despite the fact that the cost is relatively high compared to alternative mechanisms.
- The cam can be designed to give a variety of Velocity and dwell characteristics.

Storage Buffers in Production Lines

A location in the sequence of workstations where parts can be collected and temporarily stored before proceeding to subsequent downstream stations

- Reasons for using storage buffers:
  - To reduce effect of station breakdowns
  - To provide a bank of parts to supply the line
  - To provide a place to put the output of the line
  - To allow curing time or other required delay
  - To smooth cycle time variations
  - To store parts between stages with different production rates

Storage Buffers in Production Lines



Storage buffer between two stages of a production line

Control Functions in an automated Production Line

- Sequence control
  - To coordinate the sequence of actions of the transfer system and workstations
- Safety monitoring
  - To avoid hazardous operation for workers and equipment
- Quality control
  - To detect and possibly reject defective work units produced on the line

Applications of Automated Production Lines

- Transfer lines for machining
  - Synchronous or asynchronous workpart transport
  - Transport with or without pallet fixtures, depending on part geometry
  - Various monitoring and control features available
- Rotary transfer machines for machining
  - Variations include center column machine and trunnion machine

Transfer Lines

- In a transfer line, the workstations containing machining work heads are arranged in an in-line or segmented in-line configuration and the parts are moved between stations by transfer mechanisms such as the walking-beam system.
- The transfer line is the most highly automated and productive system in terms of the number of operations that can be performed to accommodate complex work geometries.
- It is manufacturing system which consist of number of workstations connected by automated material handling system

Transfer Lines

The transfer line can include a large number of workstations, but reliability of the system decreases as the number of stations is increased.

Today, many transfer lines are being designed for flexibility and ease of changeover so that

(1) different but similar work parts can be produced on the same system and

(2) workstations from obsolete lines can be used on new lines

Thus, there is a trend in transfer lines in the direction of flexible manufacturing systems Indeed, the term *flexible transfer line* is sometimes applied to these systems.

The workstations in these lines consist of both fixed tooling and CNC

Transfer lines- System Design Considerations

- Most companies that use automated production lines and related systems turn the design of the system over to a machine tool builder that specializes in this type of equipment.
- The customer (company purchasing the equipment) must develop specifications that include design drawings of the part and the required production rate. Typically, several machine tool builders are invited to submit the proposal
- The proposed line consists of standard work heads, spindles, feed units, drive motors, transfer mechanisms, bases, and other standard modules, all assembled into a special configuration to match the machining requirements of the particular part.

System Design Considerations

- Building block approach: machine tool companies specialize in transfer lines and indexing machines
  - User contracts for custom-engineered line
  - Standard modules such as workheads, feed units, transfer mechanisms, and bases
  - Called a unitized production line
- Link line: uses standard machine tools connected by specialized handling system
- Specialized processes often engineered by the user company

System Design Considerations

- Examples of these standard modules are illustrated in Figures. The controls for the system are either designed by the machine builder or sublet as a separate contract to a controls specialist.
- Transfer lines and indexing machines constructed using this building-block approach are sometimes referred to as *unitized production lines*.

System Design Considerations

- An alternative approach in designing an automated line is to use standard machine tools and to connect them with standard or special material handling devices.
- The material handling hardware serves as the transfer system that moves work between the standard machines.
- The term *link line* is sometimes used in connection with this type of construction.
- In some cases, the individual machines are manually operated if there are fixturing and location problems that are difficult to solve without human assistance.

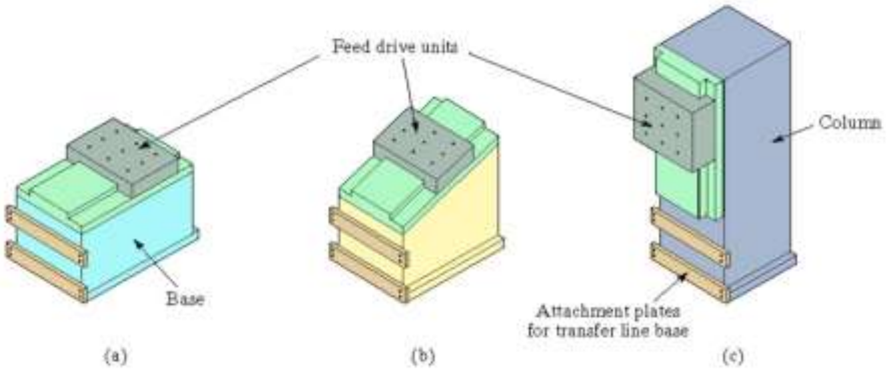
System Design Considerations

- A Company often prefers to develop a link line rather than a unitized production line because it can utilize existing equipment in the plant. This usually means the production line can be installed sooner and at lower cost.
- Since the machine tools in the system are standard, they can be reused when the production run is finished. Also, the lines
- can be engineered by personnel within the company rather than outside contractors.

System Design Considerations

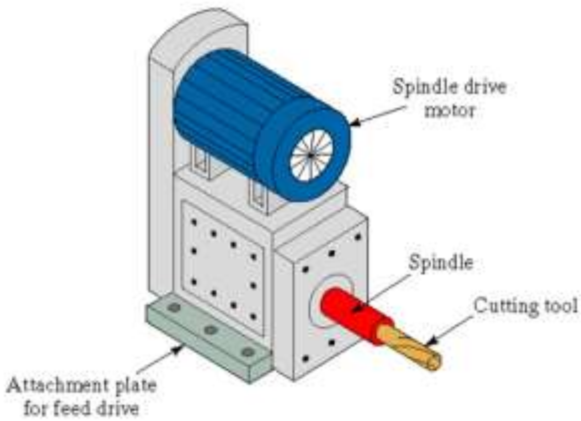
The limitation of the link line is that it tends to favor simpler part shapes and therefore fewer operations and workstations. Unitized lines are generally capable of higher production rates and require less floor space. However, their high cost makes them suitable only for very long production runs on products that are not subject to frequent design changes.

Standard Feed Units used with In-Line or Rotary Transfer Machines



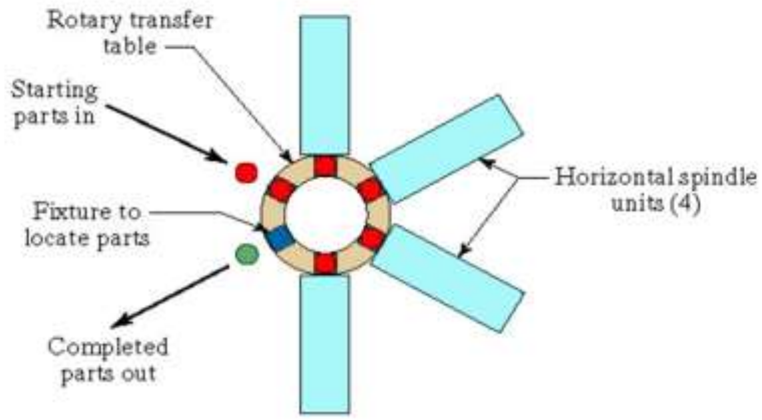
(a) Horizontal feed drive unit, (b) angular feed drive unit, and (c) vertical column feed drive unit

Standard Milling Head



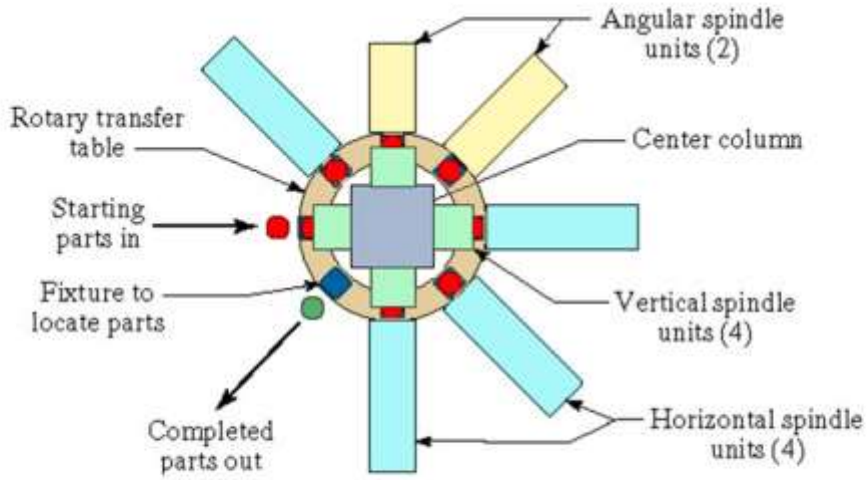
Milling head unit that attaches to one of the feed drive units in the previous slide

Rotary Transfer Machine (Plan View)



Plan view of a rotary transfer machine.

Center Column Machine (Plan View)



Plan view of the center-column machine

Analysis of Transfer Lines

In the analysis and design of automated production lines

- Three problem areas must be considered:
  1. Line balancing
     - To divide the total work load among workstations as evenly as possible
  2. Processing technology
     - Theory and principles about the manufacturing or assembly processes used on the line
  3. System reliability - two cases:
     - Transfer lines with no internal parts storage
     - Transfer lines with internal storage buffers

Analysis of Transfer lines with no internal storage buffers

There are a few assumptions that we will have to make about The operation of the Transfer line & rotary machines indexing

- The workstations perform operations such as
- machining & not assembly.
- Processing times at each station are constant
- though they may not be equal.
- There is synchronous transfer of parts.
- No internal storage of buffers.

Analysis of Transfer lines with no internal storage buffers

Analysis of Cycle time

In the operation of an automated production line, parts are introduced into the first workstation & are processed and transported at regular intervals to the succeeding stations. This interval defines the ideal cycle time, *Tc* of the production line

Tc, Is The Summation Of Is The processing Time For The Slowest Station Plus Transfer Times

$$T_c = \text{Max}\{T_{si}\} + T_r$$

Tc= Ideal cycle on the line (min)

Tsi = Processing time at station (min)

Tr= Repositioning time, called the transfer time (min)

In above eq. we use the max (Tsi) because the longest service time establishes the pace of the production line. The remaining stations with smaller service times will have to wait for the slowest station.

- In the operation of a transfer line, random breakdowns & planned stoppages cause downtime on the line.

Common reasons for downtime on an Automated Production line:

1. Tool failures at workstations.
2. Tool adjustments at workstations
3. Scheduled tool charges
4. Limit switch or other electrical malfunctions.
5. Mechanical failure of a workstation.
6. Mechanical failure of a transfer line.
7. Stock outs of starting work parts.
8. Insufficient space for completed parts.
9. Preventive maintenance on the line worker breaks.

- In the operation of a transfer line, random breakdowns and planned stoppages cause downtime on the line. Although the breakdowns and line stoppages occur randomly, their

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

These downtime occurrences cause the actual average production cycle time of the line to be longer than the ideal cycle time.

$$T_p = T_c + FT_d$$

where *F* = downtime frequency, line stops/cycle; and *Td* = average downtime per line stop, min. The downtime *Td* includes the time for the repair crew to swing into action, diagnose the cause of the failure, fix it, and restart the line. Thus, *FTd* = downtime averaged on a per cycle basis.

Line downtime is usually associated with failures at individual workstations. represent malfunctions that cause a single station to stop production.

Since all workstations on an automated production line with no internal storage are interdependent, the failure of one station causes the entire line to stop.

Let *pi* = probability or frequency of a failure at station *i*, where *i* = 1, 2,c, *n*, and *n* = the number of workstations on the line. The frequency of line stops per cycle is obtained by merely summing the frequencies *pi* over the *n* stations, that is,

$$F = \sum_{i=1}^{n} p_i$$

Where F= expected frequency line stops per cycle, from Equation, *pi* = frequency of station breakdown per cycle at station *i*, causing a line stop; and *n* = number of workstations on the line. If all *pi* are assumed equal, which is unlikely but useful for approximation and computation purposes, then

$$F = np$$

Performance Measures

One of the important measures of performance on an automated transfer line is production rate, which is the reciprocal of *Tp*:

$$Rp = 1/Tp,$$

where *Rp* = actual average production rate, pc/min; and *Tp* is the actual average production time. It is of interest to compare this rate with the ideal production rate given by

$$Rc = 1/Tc$$

where *Rc* = ideal production rate, pc/min. It is customary to express production rates on automated production lines as hourly rates, so the rates in Equations (16.9) and (16.10) must be multiplied by 60.

In the context of automated production lines, line efficiency refers to the proportion of uptime on the line and is really a measure of reliability, more than efficiency. Nevertheless, this is the terminology of production lines. Line efficiency can be calculated as

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

where *E* = the proportion of uptime on the production line, and the other terms are as previously defined. An alternative measure of performance is the proportion of downtime on the line *D*, which is given by

$$D = FTd / Tp = FTd/(Tc + FTd)$$

It is obvious that

$$E + D = 1.0$$

Another important performance measure of an automated production line is the cost per unit produced. This piece cost includes the cost of the starting material that is to be processed on the line, the cost of time on the production line, and the cost of any tooling that is consumed (e.g., cutting tools on a machining line). The piece cost can be expressed

$$C_{pc} = C_m + C_o T_p + C_t$$

where *Cpc* = cost per piece, \$/pc;
Cm = cost of starting material, \$/pc;
Co = cost per minute to operate the line, \$/min;
Tp = average production time per piece, min/pc; and
Ct = cost of tooling per piece, \$/pc.
Co = the allocation of capital cost of the equipment over the service life, labour to perate the line, applicable overheads, maintenance, & other relevant costs all reduced to cost per min.

Q. A machine tool builder submits a proposal for a 20-station transfer line to machine a certain component currently produced by conventional methods. The proposal states that the line will operate at a production rate of 50 pc/hr at 100% efficiency. On similar transfer lines, the probability of station breakdowns per cycle is equal for all stations: p = 0.005 breakdowns/cycle. It is also estimated that the average downtime per line stop will be 8.0 min. The starting casting that is to be machined on the line costs $3.00 per part. The line operates at a cost of $75.00/hr. The 20 cutting tools (one tool per station) last for 50 parts each, and average cost per tool is $2.00 per cutting edge. Determine (a) production rate, (b) line efficiency, and (c) cost per piece produced on the line.

Solution: (a) At 100% efficiency, the line produces 50 pc/hr. The reciprocal gives the unit time, or ideal cycle time per piece:

$$T_c = 1/50 = 0.02 \text{ hr/pc} = 1.2 \text{ min}$$

With a station breakdown frequency p = 0.005, the frequency of line stops is

$$F = 20 * 005 = 0.10 \text{ breakdowns per cycle}$$

Given an average downtime of 8.0 min, the average production time per piece is

$$T_p = T_c + FT_d = 1.2 + 0.10*8 = 1.2 + 0.8 = 2.0 \text{ min/pc}$$

Actual average production rate is the reciprocal of average production time per piece:

$$R_p = 1/2.0 = 0.500 \text{ pc/min} = \mathbf{30.0 \text{ pc/hr}}$$

(b) Line efficiency is the ratio of ideal cycle time to actual average production time:

***E* = 1.2/ 2.0 = 0.60 = 60%**

(c) Tooling cost per piece is *Ct* = 20 tools*($2/tool)/ (50 parts)= $0.80/pc

Now the unit cost can be calculated by Equation given in earlier slide

The hourly rate of $75/hr to operate the line is equivalent to $1.25/min

Cpc = 3.00 + 1.25*(2.0) + 0.80 = $**6.30/pc**

Problem on Transfer line performance:

A 30 station Transfer line is being proposed to machine a certain component currently produced by conventional methods. The proposal received from the machine tool builder states that the line will operate at a production rate of 100 pc/ hr at 100% efficiency. From a similar transfer line it is estimated that breakdowns of all types will occur at a frequency of F =0.20 breakdowns per cycle & that the average downtime per line stop will be 8.0 minutes. The starting blank that is machined on the line costs Rs. 5.00 per part. The line operates at a cost for 100 parts each & the average cost per tool = Rs. 20 per cutting edge.

Compute the following:

1. Production rate
2. Line efficiency

Solution: (a) At 100% efficiency, the line produces 100 pc/hr. The reciprocal gives the unit time, or ideal cycle time per piece:

$$T_c = 1/100 = 0.01 \text{ hr/pc} = 0.6 \text{ min/pc}$$

the frequency of line stops is

$$F = 0.2 \text{ breakdowns per cycle}$$

Given an average downtime of 8.0 min, the average production time per piece is

$$T_p = T_c + FT_d = 0.6 + 0.2*8 = 0.6 + 1.6 = 2.2 \text{ min/pc}$$

Actual average production rate is the reciprocal of average production time per piece:

$$R_p = 1/2.2 = 0.4545 \text{ pc/min} = 27 \text{ pc/hr}$$

(b) Line efficiency is the ratio of ideal cycle time to actual average production time:

$$E = 0.6/2.2 = 27\%$$

What the Equations Tell Us – Lines with No Storage Buffers

- As the number of workstations increases
  - Line efficiency and production rate are adversely affected
- As reliability of individual workstations decreases
  - Line efficiency and production rate are adversely affected

Analysis of Transfer lines with internal storage buffers

The workstations are interdependent in an automated Production line with no internal parts storage. When one station breaks down, all other stations on the line are affected, either immediately or by the end of a few cycles of operation, due to starving or blocking.

Starving on an automated production line means that a workstation is prevented from performing its cycle because it has no part to work on. When a breakdown occurs at any workstation on the line, the downstream stations will either immediately or eventually become starved for parts.

Blocking means that a station is prevented from performing its work cycle because it cannot pass the part just completed to the neighboring downstream station. When a breakdown occurs at a station on the line, the upstream stations become blocked because the broken-down station cannot accept the next part for processing from its upstream neighbor. Therefore, none of the upstream stations can pass its completed part forward.

- If one storage buffer is used, the line is divided into two stages. If two buffers are used at two different locations along the line, then a three stage line is formed, and so forth. The upper limit is to have storage buffers between every pair of adjacent stations. The number of stages will then equal the number of workstations.
- For an *n*-stage line, there will be *n* - 1 storage buffers, not including the raw parts inventory at the front of the line or the finished parts inventory at the end of the line.
- Consider a two-stage transfer line, with a storage buffer separating the stages. Suppose that, on average, the storage buffer is half full.
- If the first stage breaks down, the second stage can continue to operate (avoid starving) using parts that have been collected in the buffer. And if the second stage breaks down, the first stage can continue to operate (avoid blocking) because it has the buffer to receive its output.
- The reasoning for a two stage line can be extended to production lines with more than two stages. upstream and downstream buffers.

Limits of Storage Buffer Effectiveness. Two extreme cases of storage buffer effectiveness can be identified: (1) no buffer storage capacity at all, and (2) infinite capacity storage buffers. In the analysis that follows, it is assumed that the ideal cycle time *Tc* is the same for all stages considered. This is generally desirable in practice because it helps to balance production rates among stages.

In the case of no storage capacity, the production line acts as one stage. When a station breaks down, the entire line stops. This is the case of a production line with no internal storage analyzed earlier . The efficiency of the line is given by Equation given below It is rewritten here as the line efficiency of a zero capacity storage buffer,

$$E_0 = \frac{T_c}{T_c + FT_d}$$

Where E_0 is zero storage buffer capacity, and the other terms have the same meanings as before.

The opposite extreme is the theoretical case where buffer zones of infinite capacity are installed between every pair of stages. If it is assumed that each buffer zone is half full (in other words, each buffer zone has an infinite supply of parts as well as the capacity to accept an infinite number of additional parts), then each stage is independent of the rest. The presence of infinite storage buffers means that no stage will ever be blocked or starved because of a breakdown at some other stage. Of course, an infinite capacity storage buffer cannot be realized in practice

$$E_k = \frac{T_c}{T_c + F_k T_{dk}}$$

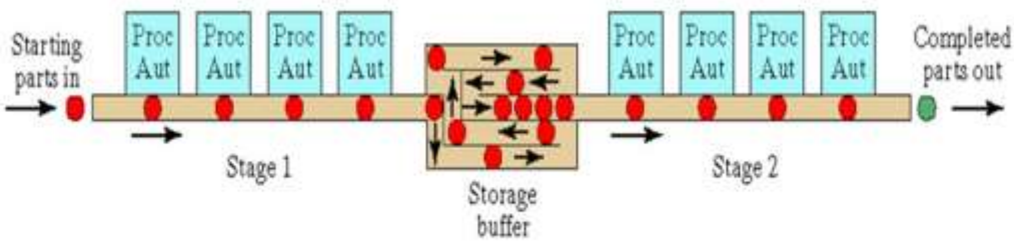
where the subscript k is used to identify the stage. According to the preceding logic, the
overall line efficiency is given by

$$E_\infty = \text{Minimum}\{E_k\} \quad \text{for } k = 1, 2, \ldots, K$$

where the subscript identifies E as the efficiency of a line whose storage buffers all have infinite capacity

By including one or more storage buffers in an automated production line, one expects the line efficiency to be greater than $E0$ but E cannot be achieved because buffer zones of infinite capacity are not possible. Hence, the actual value of line efficiency for a given buffer capacity b will fall somewhere between these extremes:

$$E_0 < E_b < E_\infty$$



Analysis of a Two-Stage Transfer Line

Most of the discussion in this section is based on the work of Buzacott, who pioneered the analytical research on production lines with buffer stocks

The two-stage line is divided by a storage buffer of capacity *b*, which is the number of work parts it can store. The buffer receives the output of stage 1 and forwards it to stage 2, temporarily storing any parts up to its capacity *b* when stage 2 experiences a line stop. The ideal cycle time *Tc* is the same for both stages. It is assumed that the downtime distributions of each stage are the same with mean downtime = *Td*. Let *F*1 and *F*2 = the breakdown rates of stages 1 and 2, respectively; *F*1 and *F*2 are not necessarily equal.

Accordingly, the efficiencies in the two stages would tend to equalize over time. The overall line efficiency for the two-stage line can be expressed as

$$E_b = E_0 + D_1' h(b) E_2$$

where *Eb* = overall line efficiency for a two-stage line with buffer capacity *b*; *E*0 = line efficiency for the same line with no internal storage; and the second term on the righthand side $(D_1' h(b) E_2)$ represents the improvement in efficiency that results from having a storage buffer with *b* >0. Consider the terms on the right-hand side in Equation

The value of *E*0 was given by Equation, but it is rewritten here to explicitly
define the two-stage efficiency when *b* = 0:

$$E_0 = \frac{T_c}{T_c + (F_1 + F_2)T_d}$$

The term *D*1 can be thought of as the proportion of total time that stage 1 is down, defined as follows:

$$D_1' = \frac{F_1 T_d}{T_c + (F_1 + F_2) T_d}$$

The term *h*(*b*) is the proportion of the downtime *D*1 (when stage 1 is down) that stage 2 could be up and operating within the limits of storage buffer capacity *b*. Buzacott presents equations for evaluating *h*(*b*) using Markov chain analysis.

Assumptions and definitions: Assume that the two stages have equal downtime distributions *Td*1 = *Td*2 = *Td*2 and equal cycle times *Tc*1 = *Tc*2 = *Tc*2. Let *F*1 = downtime frequency for stage 1 and *F*2 = downtime frequency for stage 2. Define *r* to be the ratio of breakdown frequencies as follows:

$$r = \frac{F_1}{F_2}$$

With these definitions and assumptions, the relationships for *h*(*b*) can be expressed for two theoretical downtime distributions as derived by Buzacott

Constant downtime: Each downtime occurrence is assumed to be of constant duration *Td*. This is a case of no downtime variation. Given buffer capacity *b*, define *B* and *L* as

$$b = B\frac{T_d}{T_c} + L$$

where B = *Maximum* Intege $b\frac{T_c}{T_d}$ and L represents the leftover units, the amount by which $B\frac{T_d}{T_c}$ exceeds

There are two cases:

$$\text{Case 1: } r = 1.0.\ h(b) = \frac{B}{B+1} + L\frac{T_c}{T_d}\frac{1}{(B+1)(B+2)}$$

$$\text{Case 2: } r \neq 1.0.\ h(b) = r\frac{1-r^B}{1-r^{B+1}} + L\frac{T_c}{T_d}\frac{r^{B+1}(1-r)^2}{(1-r^{B+1})(1-r^{B+2})}$$

Geometric downtime distribution: In this downtime distribution, the probability that repairs are completed during any cycle duration T_c is independent of the time since repairs began. This is a case of maximum downtime variation. There are two cases

$$\text{Case 1: } r = 1.0.\ h(b) = \frac{b\frac{T_c}{T_d}}{2 + (b-1)\frac{T_c}{T_d}}$$

$$\text{Case 2: } r \neq 1.0.\ \text{Define } K = \frac{1 + r - \frac{T_c}{T_d}}{1 + r - r\frac{T_c}{T_d}} \text{ then } h(b) = \frac{r(1-K^b)}{1-rK^b}$$

Finally, E_2 corrects for the unrealistic assumption in the calculation of $h(b)$ that both stages are never down at the same time. What is more realistic is that when stage 1 is down but stage 2 is producing using parts stored in the buffer, occasionally stage 2 itself will break down. E_2 is calculated as

$$E_2 = \frac{T_c}{T_c + F_2 T_d}$$

A 20-station transfer line is divided into two stages of 10 stations each. The ideal cycle time of each stage is $T_c = 1.2$ min. All of the stations in the line have the same probability of stopping, $p = 0.005$. The downtime is assumed constant when a breakdown occurs, $T_d = 8.0$ min. Compute the line efficiency for the following buffer capacities: (a) $b = 0$, (b) $b = \infty$, (c) $b = 10$, and (d) $b = 100$.

(a) A two-stage line with 20 stations and $b = 0$ turns out to be the same case
as in Example

$$F = np = 20(0.005) = 0.10 \text{ and } T_p = T_c + FT_d = 1.2 + 0.1(8) = 2.0 \text{ min}$$

$$E_0 = \frac{1.2}{2.0} = \mathbf{0.60}$$

(b) For a two-stage line with 20 stations (each stage has 10 stations) and $b = \infty$,

$$F_1 = F_2 = 10(0.005) = 0.05 \text{ and } T_p = 1.2 + 0.05(8) = 1.6 \text{ min}$$

$$E_\infty = E_1 = E_2 = \frac{1.2}{1.6} = \mathbf{0.75}$$

(c) For a two-stage line with $b = 10$, each of the terms in Equation

$$D_1' = \frac{0.05(8)}{1.2 + (0.05 + 0.05)(8)} = \frac{0.40}{2.0} = 0.20$$

Evaluation of $h(b)$ is from Equation given in earlier slide for a constant downtime distribution.

$$\frac{T_d}{T_c} = \frac{8.0}{1.2} = 6.667. \quad \text{For } b = 10, B = 1 \text{ and } L = 3.333. \text{ Thus,}$$

$$h(b) = h(10) = \frac{1}{1+1} + 3.333\left(\frac{1.2}{8.0}\right)\frac{1}{(1+1)(1+2)} = 0.50 + 0.0833 = 0.5833$$

Now to calculate E10

$$E_{10} = 0.600 + 0.20(0.5833)(0.75) = 0.600 + 0.0875 = \mathbf{0.6875}$$

(d) For b = 100, the only parameter in Equation that is different from
part (c) is $h(b)$. For b = 100, B = 15 and L = 0 in Equation Thus,

$$h(b) = h(100) = \frac{15}{15+1} = 0.9375$$

Using this value, $E_{100} = 0.600 + 0.20(0.9375)(0.75) = 0.600 + 0.1406 = \mathbf{0.7406}$

Production Rates on the Two-Stage Line of earlier Example

(a) For $b = 0$, $E_0 = 0.60$. Applying Equation

$$R_p = 0.60/1.2 = 0.5 \text{ pc/min} = \mathbf{30 \text{ pc/hr}}$$

(b) For $b = \infty$, $E_\infty = 0.75$, and $R_p = 0.75/1.2 = 0.625$ pc/min = **37.5 pc/hr**

(c) For $b = 10$, $E_{10} = 0.6875$, and $R_p = 0.6875/1.2 = 0.5729$ pc/min = **34.375 pc/hr**

(d) For $b = 100$, $E_{100} = 0.7406$, and $R_p = 0.7406/1.2 = 0.6172$ pc/min = **37.03 pc/hr**

Old question paper

1. List out the types rotary indexing mechanism -2 marks
2. What is storage buffer- 2 marks
3. Explain the following Assembly lines - 4 marks
    a. Batch modal assembly line
    b. Mixed modal assembly line
4. Discuss in detail about rotary indexing mechanisms – 7marks
5. A rotary worktable is driven by a Geneva mechanism with six slots. Driver rotates at 30 rev/min. determine the cycle time, available process time and the lost time each cycle indexing the table- 7 marks
6. Discuss in detail about application of automated production line- 10 marks
7. What is starving in work transport systems- 2 marks
8. What are three basic control functions that are distinguished in operation of an automated transfer machine- 7 marks
9. A rotary worktable is driven by a Geneva mechanism with five slots. Driver rotates at 48 rev/min. determine the cycle time, available process time and the lost time each cycle indexing the table- 7 marks

Unit 4:-Introduction to industrial robotics

Syllabus   Lectures 9

- Robot anatomy and related attributes
- Robot drive systems
- Robot control systems
- Precision movements
- Work volume
- Robot sensors
- End effector

Industrial Robot Defined

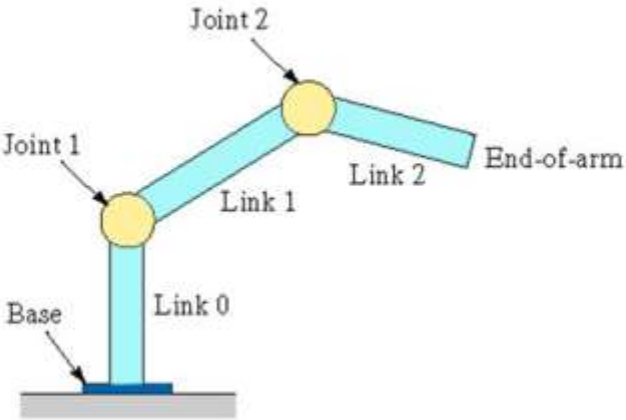
- An ***industrial robot*** is defined as "an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications
- A general-purpose, programmable machine possessing certain anthropomorphic characteristics
- Why industrial robots are important:
  - Robots can substitute for humans in hazardous work environments
  - Consistency and accuracy not attainable by humans
  - Can be reprogrammed
  - Most robots are controlled by computers and can therefore be interfaced to other computer systems

Robot Anatomy

Robot manipulator - a series of joint-link combinations, the purpose of manipulator is to orient or place the material

- Manipulator consists of joints and links
  - Joints provide relative motion
  - Links are rigid members between joints
  - Various joint types: linear and rotary
  - Each joint provides a "degree-of-freedom"
  - Most robots possess five or six degrees-of-freedom
- Robot manipulator consists of two sections:
  - Body-and-arm – for positioning of objects in the robot's work volume
  - Wrist assembly – for orientation of objects

Robot Anatomy



Robot manipulator - a series of joint-link combinations

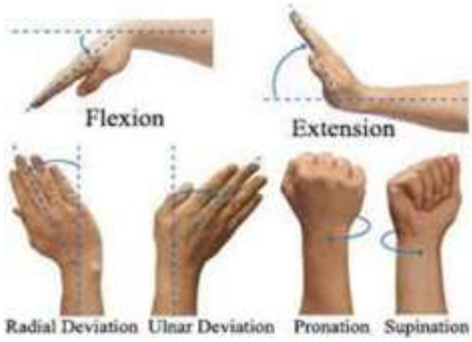
Manipulator

- A robot manipulator can be divided into two sections: a body-and-arm assembly and a wrist assembly. There are usually three axes associated with the body-and-arm, and either two or three axes associated with the wrist.
- At the end of the manipulator's wrist is a device related to the task that must be accomplished by the robot.
- The device, called an *end effector*, is usually either (1) a gripper for holding a work part or (2) a tool for performing some process.
- The body-and-arm of the robot is used to position the end effector, and the robot's wrist is used to orient the end effector.

Manipulator

- Body and arm

Wrist



Types of Manipulator Joints

- Translational motion
  - Linear joint (type L)
  - Orthogonal joint (type O)
- Rotary motion
  - Rotational joint (type R)
  - Twisting joint (type T)
  - Revolving joint (type V)

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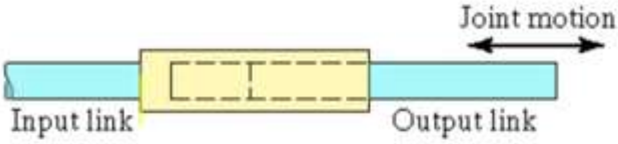
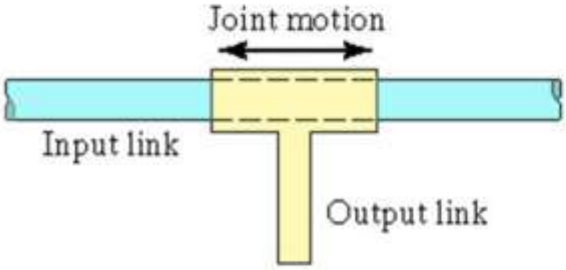
Types of joints commonly used in industrial robot construction

Translational Motion Joints

Linear joint
(type L)

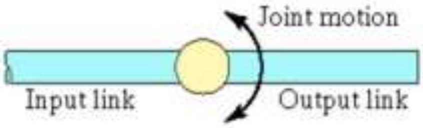


Orthogonal joint
(type O)

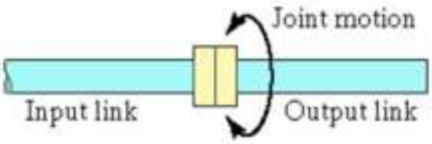


Types of joints commonly used in industrial robot construction

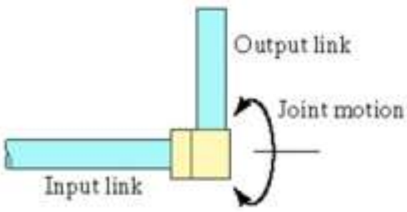
Rotational joint
(type R)



Twisting joint
(type T)



Revolving joint
(type V)



Rotary Motion Joints

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Joint Notation Scheme

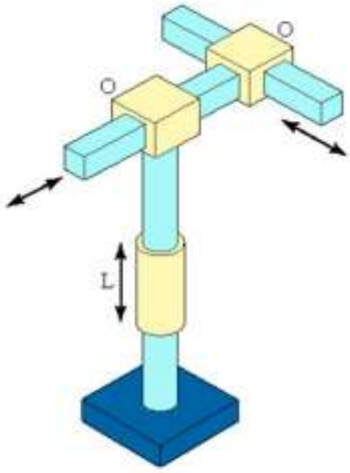
- Uses the joint symbols (L, O, R, T, V) to designate joint types used to construct robot manipulator
- Separates body-and-arm assembly from wrist assembly using a colon (:)
- Example: TLR : TR

Kinematic Configurations of body and arm

- Five common body-and-arm configurations for industrial robots:
  1. Cartesian coordinate body-and-arm assembly
  2. Articulated
  3. Polar (Spherical)coordinate body-and-arm assembly
  4. Cylindrical body-and-arm assembly
  5. Selective Compliance Assembly Robot Arm (SCARA)
- Function of body-and-arm assembly is to position an end effector (e.g., gripper, tool) in space

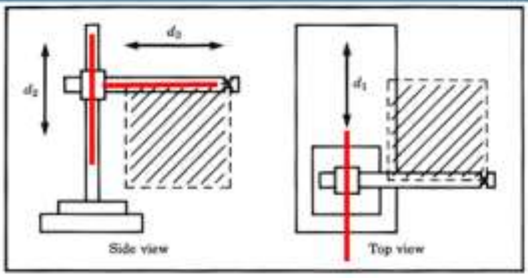
Cartesian Coordinate Body-and-Arm Assembly

- Notation LOO:
- it consists of three orthogonal joints (type O) to achieve linear motions in a three-dimensional rectangular
- Consists of three sliding joints, two of which are orthogonal
- Other names include rectilinear robot and x-y-z robot, *gantry robot*, *rectilinear robot*, and *x–y–z robot*.
- It is commonly used for overhead access to load and unload production machines.



Kinematic Configuration - Cartesian

- **Joints**
  - Joint 1 - Prismatic
  - Joint 2 - Prismatic
  - Joint 3 - Prismatic
- **Inverse Kinematics** - Trivial
- **Structure -**
  - Stiff Structure -> Big Robot
  - Decoupled Joints - No singularities
- **Disadvantage**
  - All feeder and fixtures must lie "inside" the robot



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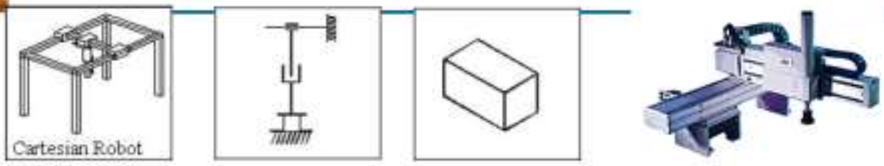
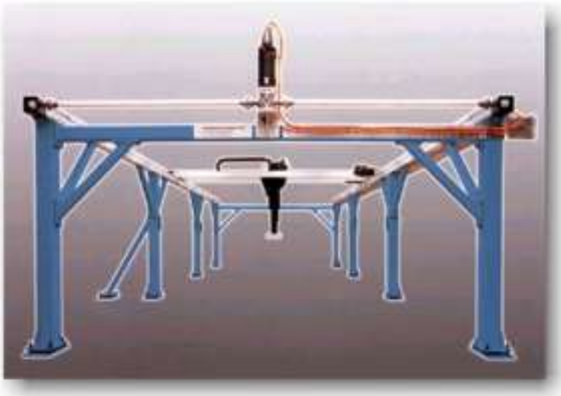
Kinematic Configuration - Cartesian





Gantry

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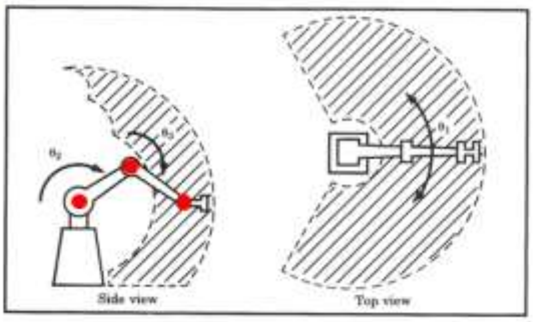
Kinematic Configuration - Articulated

- **Joints**
  - Joint 1 - Revolute -Shoulder
  - Joint 2 - Revolute - Elbow
  - Joint 3 - Revolute - Wrist
- **Workspace**
  - Minimal intrusion
  - Reaching into confine spaces
  - Cost effective for small workspace
- **Examples**
  - PUMA
  - MOTOMAN



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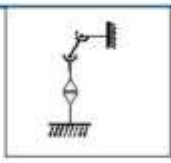
Kinematic Configuration - Articulated



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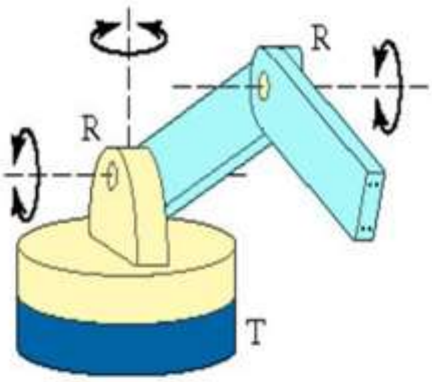
Video Clip

Jointed-Arm Robot (Articulated)

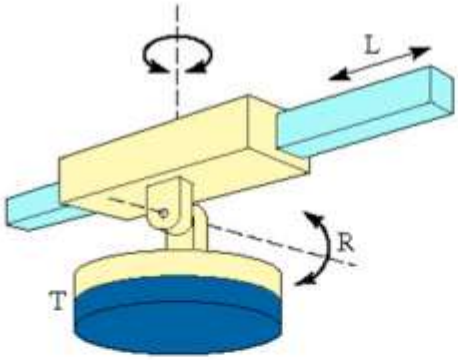
- It has the general configuration of a human shoulder and arm.
- It consists of an upright body that swivels about the base using a T joint. At the top of the body is a shoulder joint (shown as an R joint in the figure), whose output link connects to an elbow joint (another R joint).



TRR

Spherical Coordinate Body-and-Arm Assembly

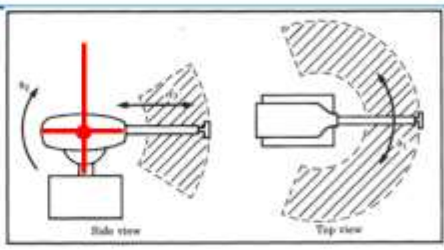
- Notation TRL:



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

Kinematic Configuration - Spherical

- **Joints**
  - Joint 1 - Revolute (Intersect with 2)
  - Joint 2 - Revolute (Intersect with 1)
  - Joint 3 - Prismatic

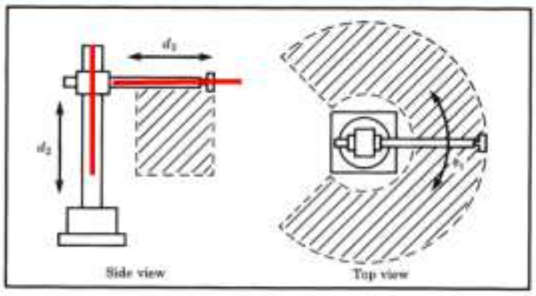


- **Structure**
  - The elbow joint is replaced with prismatic joint
  - Telescope

Kinematic Configuration - Spherical

Kinematic Configuration - Cylindrical

- **Joints**
  - Joint 1 - Revolute
  - Joint 2 - Prismatic
  - Joint 3 - Prismatic



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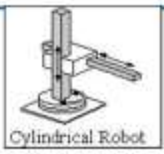
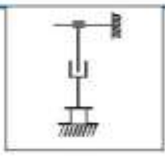
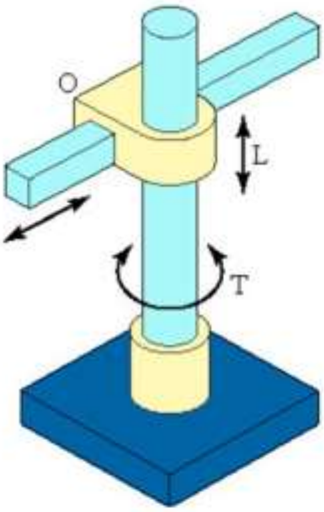
Kinematic Configuration - Cylindrical





Cylindrical Body-and-Arm Assembly

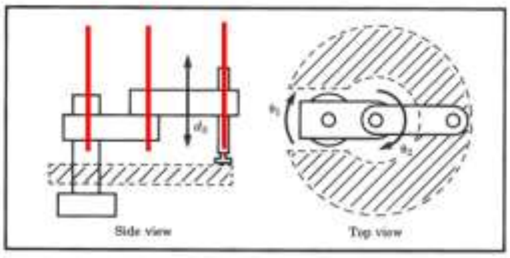
- Notation TLO:



- Consists of a vertical column, relative to which an arm assembly is moved up or down
- The arm can be moved in or out relative to the column

Kinematic Configuration - SCARA

- **Joints**
  - Joint 1 - Revolute
  - Joint 2 - Revolute
  - Joint 3 - Revolute
  - Joint 4 - Prismatic
  - Joint 1,2,3 - In plane



- **Structure**
  - Joint 1,2,3, do not support weight (manipulator or weight)
  - Link 0 (base) can house the actuators of joint 1 and 2
- **Speed**
  - High speed (10 m/s), 10 times faster then the most articulated industrial robots
- **Example** - SCARA (Selective Compliant Assembly Robot Arm)

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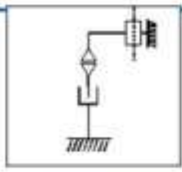
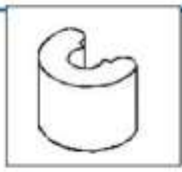
Kinematic Configuration - SCARA





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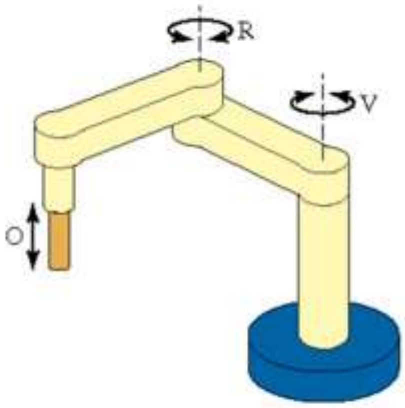
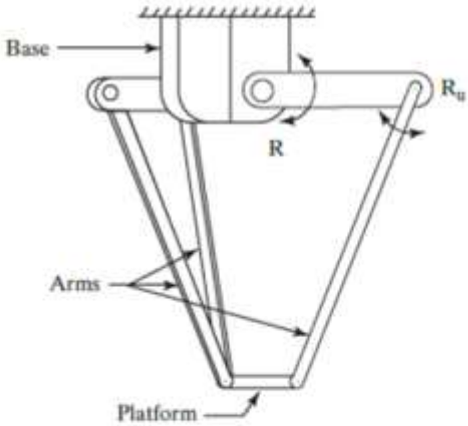
SCARA Robot

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



Delta

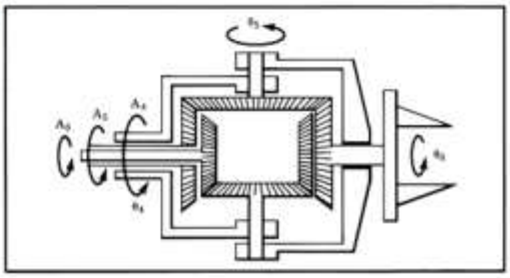
- This unusual design, depicted in Figure consists of three arms attached to an overhead base. Each arm is articulated and consists of two rotational
- Joints (type R), the first of which is powered and the second is unpowered. All three arms are connected to a small platform below, to which the end effector is attached.
- The platform and end effector can be manipulated in three dimensions. The delta
- Robot is used for high-speed movement of small objects, as in product packaging.



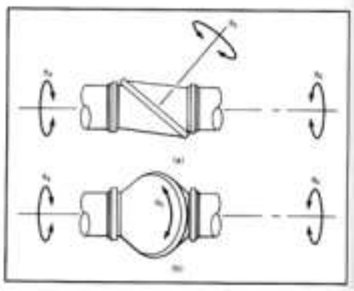
Kinematic Configuration - Wrist

- **Joints**
  - Three (or two) joints with orthogonal axes
- **Workspace**
  - Theoretically - Any orientation could be achieved (Assuming no joint limits)
  - Practically - Severe joint angle limitations
- **Kinematics**
  - Closed form kinematic equations

Kinematic Configuration - Wrist



- Three intersecting orthogonal Axes
  Bevel Gears Wrist
- Limited Rotations



- Three Roll Wrist (Cincinatti Milacron)
- Three intersecting non-orthogonal Axes
- Continues joint rotations (no limits)
- Sets of orientations which are impossible to reach

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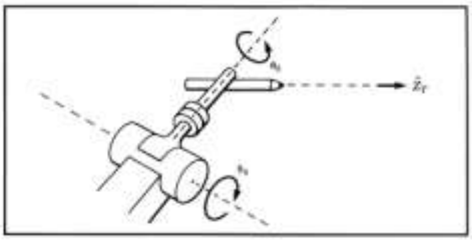
Kinematic Configuration - Wrist

- 5 DOF Welding robot (2 DOF wrist) - Symmetric tool
- The tool axis $\hat{Z}_T$ is mounted orthogonal to axis 5 in order to reach all possible orientations



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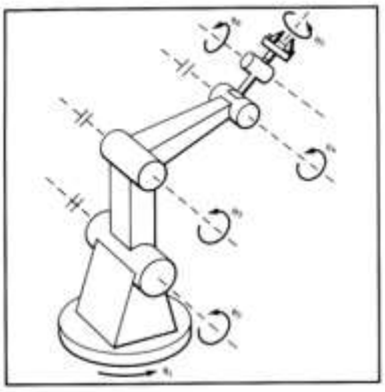
Kinematic Configuration - Wrist

- **Non intersecting axes wrist**
- A closed form inverse kinematic solution may not exist
- **Special Cases** (Existing Solution)
  - Articulated configuration
    Joint axes 2,3,4 are parallel
  - Cartesian configuration
    Joint axes 4,5,6 do not intersect



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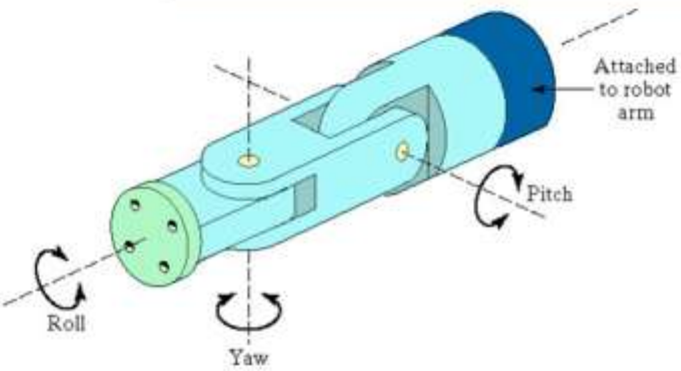
Wrist Configurations

- Wrist assembly is attached to end-of-arm
- End effector is attached to wrist assembly
- Function of wrist assembly is to orient end effector
  - Body-and-arm determines global position of end effector
- Two or three degrees of freedom:
  - Roll
  - Pitch
  - Yaw

Wrist Configuration



- Typical wrist assembly has two or three degrees-of-freedom (shown is a three degree-of freedom wrist)
- Notation :RRT

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Work Volume

- The work volume (also known as *work envelope*) of the manipulator is defined as the three-dimensional space within which the robot can manipulate the end of its wrist.
- Work volume is determined by the number and types of joints in the manipulator (body-and-arm and wrist), the ranges of the various joints, and the physical sizes of the links.
- The shape of the work volume depends largely on the robot's configuration, as indicated in Table in next slide

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Work Volume

Body-and-Arm Joint	Notation	Work Volume
Articulated	TRR	Partial sphere
Polar	TRL	Partial sphere
SCARA	VRO	Cylindrical
Cartesian coordinate	LOO	Rectangular solid
Delta	RRu	Hemisphere

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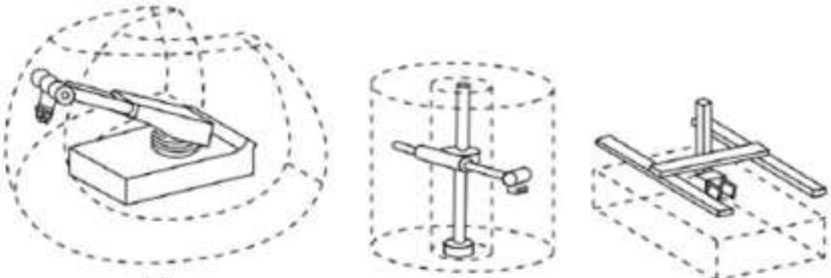
Work volume



(a) (b) (c)

Work volumes for different types of robots: (a) Polar, (b) Cylindrical, (c) Cartesian.

Joint Drive Systems

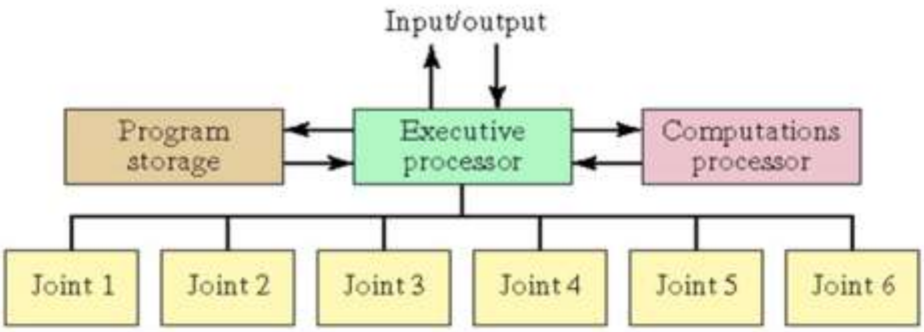
- Electric
  - Uses electric motors to actuate individual joints
  - Preferred drive system in today's robots
- Hydraulic
  - Uses hydraulic pistons and rotary vane actuators
  - Noted for their high power and lift capacity
- Pneumatic
  - Typically limited to smaller robots and simple material transfer applications.

Robot Control Systems

- With respect to robotics, the motion control system used to control the movement of the end-effector or tool.
- The actuations of the individual joints must be controlled in a coordinated fashion for the manipulator to perform a desired motion cycle.
- Microprocessor-based controllers are commonly used today in robotics as the control system hardware.

Robot Control System

- The controller is organized in a hierarchical structure so that each joint has its own feedback control system, and a supervisory controller coordinates the combined actuations of the joints according to the sequence of the robot program.



- Hierarchical control structure of a robot microcomputer controller

Robot Control Systems

Different types of control are required for different applications. Robot controllers can be classified into four categories:

- Limited sequence control – pick-and-place operations using mechanical stops to set positions
- Playback with point-to-point control – records work cycle as a sequence of points, then plays back the sequence during program execution
- Playback with continuous path control – greater memory capacity and/or interpolation capability to execute paths (in addition to points)
- Intelligent control – exhibits behavior that makes it seem intelligent, e.g., responds to sensor inputs, makes decisions, communicates with humans

Robot Control Systems

- Limited sequence control

- 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.

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Robot Control Systems

- Playback with point-to-point control

- 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.

Dr. Manoj Panchal

Robot Control Systems

- Playback with continuous path control

- In these robots are capable of performing motion cycle in which the path followed by the robot in controlled.
- The robot moves through a series of closely space point which describe the desired path.
- Ex: - Spray painting, arc welding & complicate assembly operations.

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Robot Control Systems

- Intelligent control

- This type of robots not only programmable motion cycle but also interact with its environment in a way that years intelligent.
- It can 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.

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Precision of movement

- 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 donned 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.

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Precision of movement

- Repeatability

- 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.

End Effectors

- An end effector is usually attached to the robot's wrist. The end effector enables the robot to accomplish a specific task. Because there is a wide variety of tasks performed by industrial robots, the end effector is usually custom-engineered and fabricated for each different application.
- Two types:
  - Grippers – to grasp and manipulate objects (e.g., parts) during work cycle
  - Tools – to perform a process, e.g., spot welding, spray painting

End Effector (EE)

At the free end of the chain of links which make up the manipulator is the end effector. Depending on the intended application of the robot the end effector may be a gripper welding torch, electromagnet or other tool.

ROBONAUT - Hand (NASA)

Stanford / JPL- Hand (Salsilbury)

Utha / MIT Hand

NIST - Advanced Welding Manufacturing System

Gripper

Grippers are end effectors used to grasp and manipulate objects during the work cycle.

The objects are usually work parts that are moved from one location to another in the cell.

Machine loading and unloading applications fall into this category. Owing to the variety of part shapes, sizes, and weights, most grippers must be custom designed.

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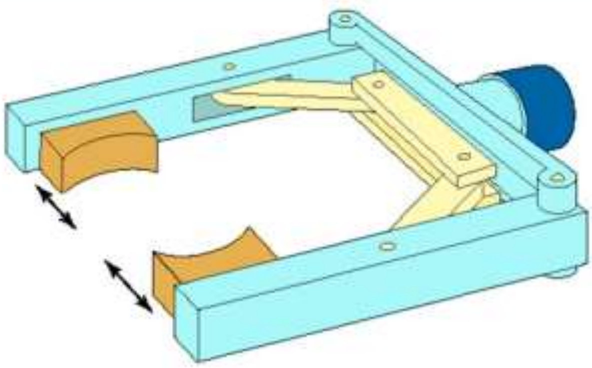
Gripper

Types of grippers used in industrial robot applications include the following:

- *Mechanical grippers*, consisting of two or more fingers that can be actuated by the robot controller to open and close on the work part
- *Vacuum grippers*, in which suction cups are used to hold flat objects
- *Magnetized devices*, for holding ferrous parts
- *Adhesive devices*, which use an adhesive substance to hold a flexible material such as a fabric
- *Simple mechanical devices*, such as hooks and scoops.

Robot Mechanical Gripper



- A two-finger mechanical gripper for grasping rotational parts

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Advances in Mechanical Grippers

- Dual grippers
- Interchangeable fingers
- Sensory feedback
  - To sense presence of object
  - To apply a specified force on the object
- Multiple fingered gripper (similar to human hand)
- Standard gripper products to reduce the amount of custom design required

Tools

- The robot uses tools to perform processing operations on the work part. The robot manipulates the tool relative to a stationary or slowly moving object (e.g., work part or subassembly).
- Examples of tools used as end effectors by robots to perform processing applications include spot welding gun, arc welding tool; spray painting gun; rotating spindle for drilling, routing, grinding, and similar operations; assembly tool (e.g., automatic screwdriver); heating torch; ladle (for metal die casting); and water jet cutting tool.
- In each case, the robot must not only control the relative position of the tool with respect to the work as a function of time, it must also control the operation of the tool. For this purpose, the robot must be able to transmit control signals to the tool for starting, stopping, and otherwise regulating its actions.

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- In some applications, the robot may use multiple tools during the work cycle. For example, several sizes of routing or drilling bits must be applied to the work part. Thus,
- the robot must have a means of rapidly changing the tools. The end effector in this case
- takes the form of a fast-change tool holder for quickly fastening and unfastening the various
- tools used during the work cycle.

Sensors in Robotics

Two basic categories of sensors used in industrial robots:

1. Internal - used to control position and velocity of the manipulator joints
2. External - used to coordinate the operation of the robot with other equipment in the work cell
    - Tactile - touch sensors and force sensors
    - Proximity - when an object is close to the sensor
    - Optical -
    - Machine vision
    - Other sensors - temperature, voltage, etc.

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Robot Application Characteristics

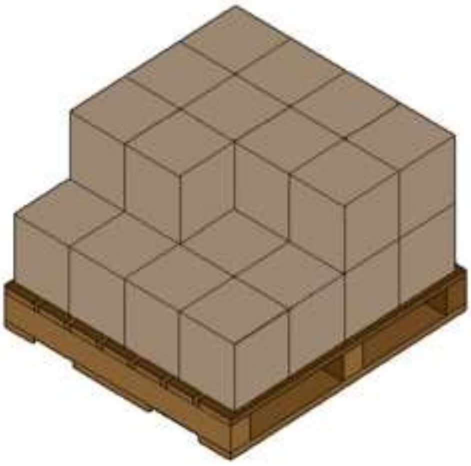
General characteristics of industrial work situations that promote the use of industrial robots

1. Hazardous work environment for humans
2. Repetitive work cycle
3. Difficult handling task for humans
4. Multishift operations
5. Infrequent changeovers
6. Part position and orientation are established in the work cell

Industrial Robot Applications

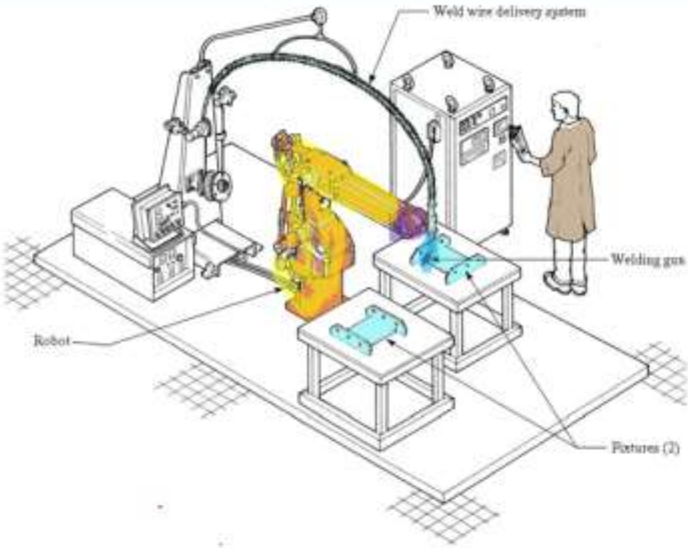
1. Material handling applications
   - Material transfer – pick-and-place, palletizing
   - Machine loading and/or unloading
2. Processing operations
   - Spot welding and continuous arc welding
   - Spray coating
   - Other – waterjet cutting, laser cutting, grinding
3. Assembly and inspection

Arrangement of Cartons on Pallet



Robotic Arc-Welding Cell

- Robot performs flux-cored arc welding (FCAW) operation at one workstation while fitter changes parts at the other workstation



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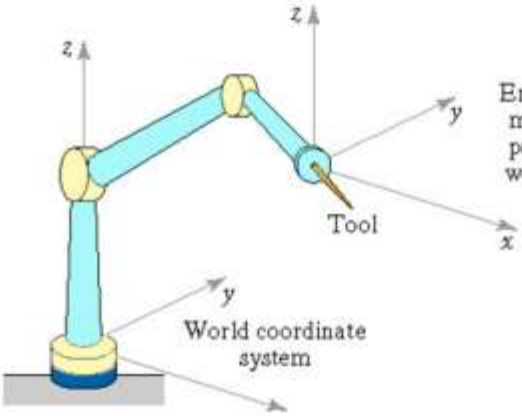
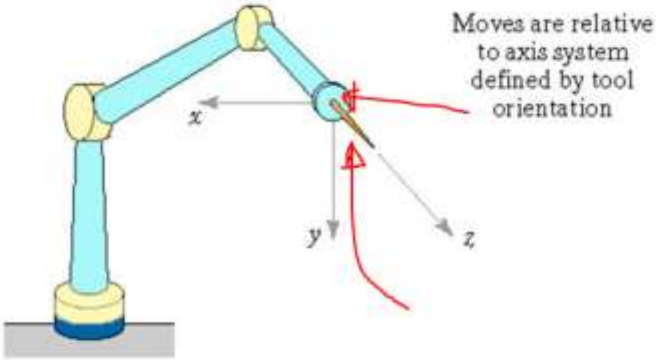
World Coordinate System



- Origin and axes of robot manipulator are defined relative to the robot base

Tool Coordinate System



- Alignment of the axis system is defined relative to the orientation of the wrist faceplate (to which the end effector is attached)

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Old question paper

- List out different types of gripper for robot- 2 marks
- Discuss in detail about robot configuration along with necessary sketches-10 marks
- Draw the sketch of work volume for cylindrical and cartesian robot- 4 marks
- Explain following terms: (i) Spatial Resolution (ii) Accuracy(iii) Repeatability- 7 marks

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Unit:-5- Manipulator Kinematics and Dynamics

Syllabus **Lectures 10**

- **Introduction**
- **Rigid body Transformations**
- **Homogeneous Transformations**
- **Forward Kinematics**
- **D-H Notation**
- **Inverse Kinematics**
- Differential transformation
- Jacobians
- Lagrange – Euler and
- Newton Euler formations

Introduction

INTRODUCTION:

- A Robot manipulator is designed to perform a task in the 3-D space.
- The tool or end effector is required to follow a planned trajectory to manipulate objects or carry out the task in the workspace.
- Kinematic model describes the spatial position of joints and links, position and orientation of end effector .
- The motion can be either unconstrained, if there is no physical interaction between the end- effector and the environment.
- The motion can be constrained if contact forces arise between the end-effector and the environment.

Introduction

KINEMATIC ANALYSIS:

- Kinematic analysis of a manipulator structure concerns the description of the manipulator motion with respect to a fixed reference.
- Cartesian frame by ignoring the forces and moments that cause the motion of the structure.
- Kinematics describes the analytical relationship between the joint positions and the end effector position and orientation.
- The formulation of the kinematics relationship allows studying two key problems of robotics.

1. The direct kinematics problem which is concerned with the determination of a systematic, general method to describe the end- effector position and orientation as a function of the joint values by means of linear algebra tools.

Introduction

2. The inverse kinematics problem which is concerned to transform a desired position and orientation of the end-effector in the workspace into the corresponding joint values.

❑ Differential kinematics describes the analytical relationship between the joint motion and the end-effector motion in terms of velocities.

1.Statics: The availability of a manipulator's kinematic model . To determine the relationship between the forces and torques applied to the joints and the forces and moments applied to the end-effector in static equilibrium configurations.

2.Dynamics: The equation of motion of the manipulator as a function of the forces and moments acting on it. The availability of the dynamic model is very useful for mechanical design of the structure, choice of actuators, determination of control strategies, and computer simulation of manipulator motion.

Introduction

Object Location:

❑ Robotic manipulation, by definition, implies that parts and tools will be moved around in space by some sort of mechanism.

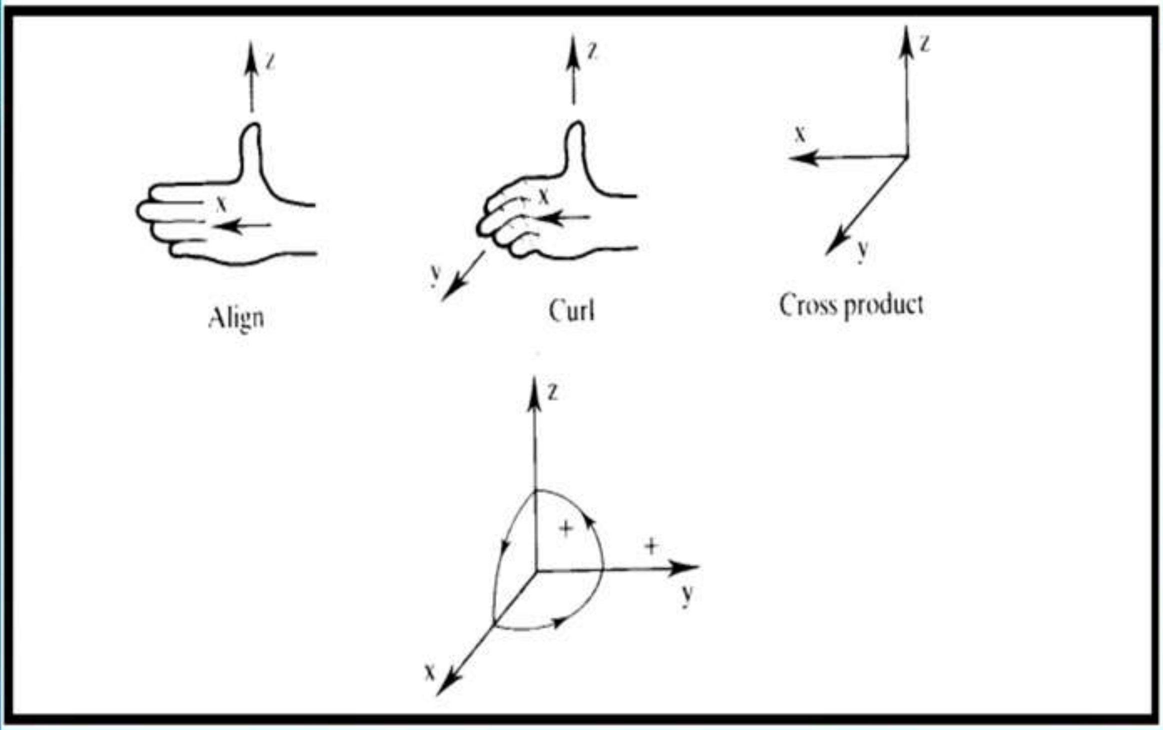
❑ This naturally leads to the need of representing positions and orientations i.e. the location of the parts, tools, and of the mechanism itself.

❑ To define and manipulate mathematical quantities which represent position and orientation we must define co-ordinate systems and develop conventions for representation.

Position Analysis

Cartesian Co-ordinates:

- The position of an object in space is described with Cartesian-coordinates.
- In robotics, the chosen co-ordinate frame forms a right-handed set of vectors.
- The positive direction of rotation is chosen in accordance with the right hand-role, see details in figure



Co-ordinate frame showing positive directions of axes according to the right hand rule

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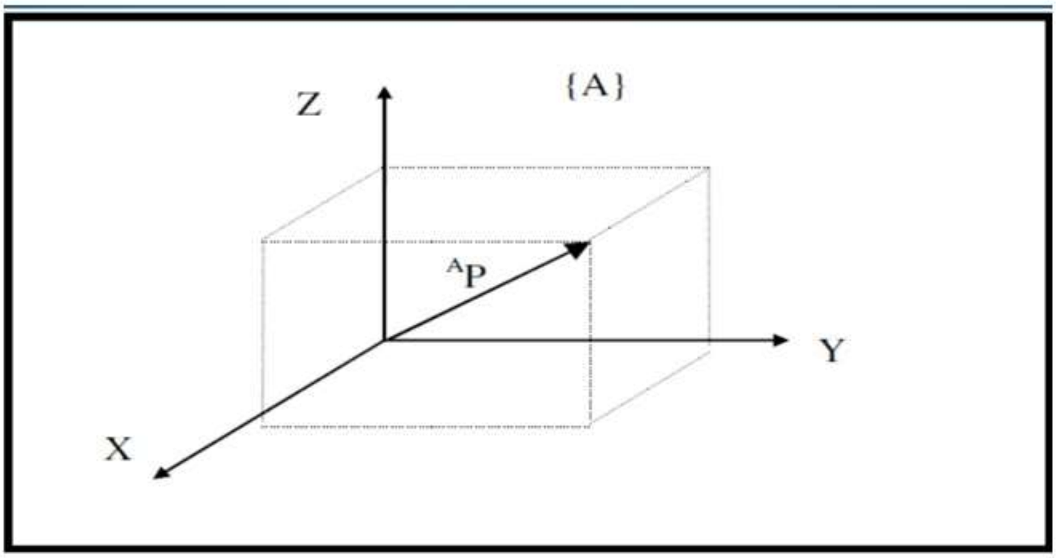
Position Analysis

A point in Space can be described within a coordinate system by its position vector



Position Analysis

- In above figure , the position of the point AP is a vector from the origin of the co-ordinate system {A}.

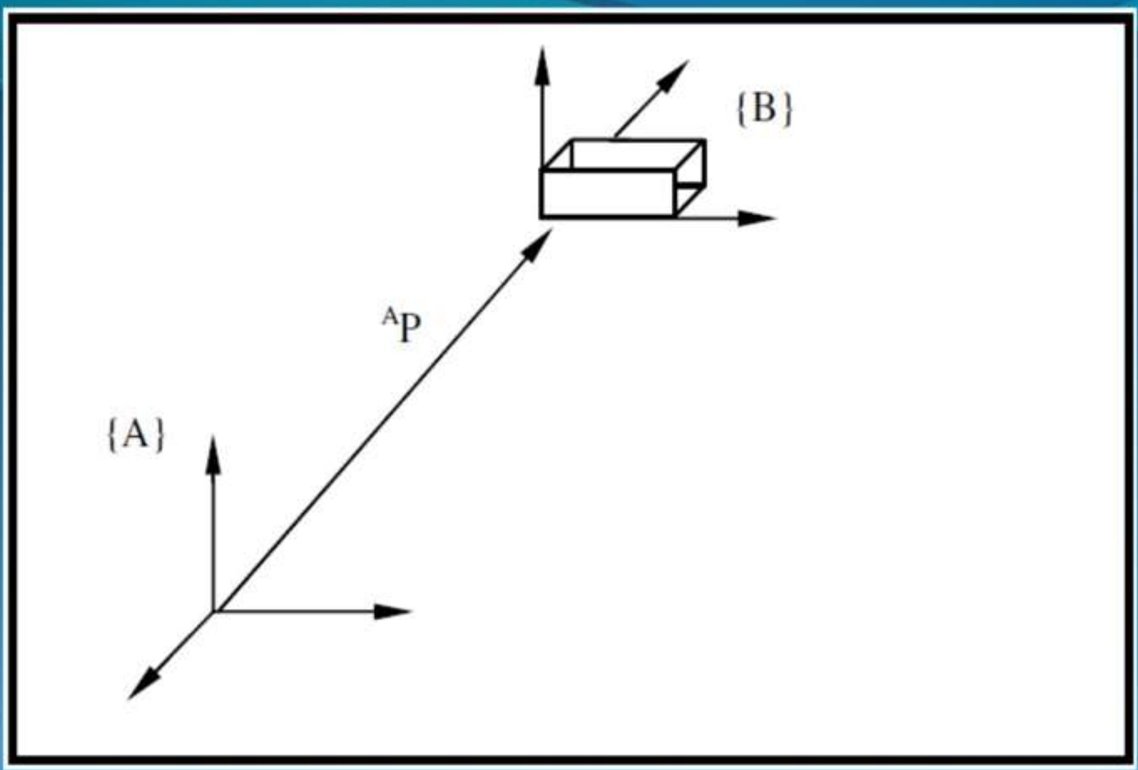
- The position vector can then be represented in homogeneous co-ordinates as a vector where the terms of its components along the co-ordinate axes is given by,

$$^{A}P = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} \quad \text{------------------------(1)}$$

Orientation of Rigid body

Description of An Orientation:

- We will find not only to represent a point in the space but also to describe the orientation of a body in space.
- For an example, the box can be oriented arbitrarily while keeping the corner in the same position in space.
- In order to describe the orientation of a body we will attach a co-ordinate system to the body and then give a description of this co-ordinate system relative to the reference system.



Position & Orientation of a Box

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Orientation of Rigid body

- In the above figure, co-ordinate system {B} has been attached to one of the corners of the box.
- A description of {B} relative to {A} now suffices to give the orientation of the body.
- Thus, positions of points are described with vectors and orientations of bodies are described with an attached co-ordinate system.
- One way to describe the body-attached system, {B}, is to write the unit vectors of its three principal axes in terms of the co-ordinate system {A}.
- This 3 x 3 matrix, described below, is called a rotation matrix, and because this particular describes {B} relative to {A}, the notation

Orientation of Rigid body

$$ {}^{A}_{B}R = \begin{bmatrix} {}^{A}X_{B} & {}^{A}Y_{B} & {}^{A}Z_{B} \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} $$

- In summary, a set of three vectors may be used to specify an orientation.
- For convenience we will construct a 3 x 3 matrix which has these three vectors as its columns. Hence,
  1. The position of a point is represented by a vector.
  2. The orientation of a body is represented with a matrix.

Orientation of Rigid body

- Hence, the frame {B} relative to {A}, the description of frame {A} relative to {B} is given by the transpose of ;that is,

$${}^{B}_{A}R = {}^{A}_{B}R^{T} \quad \text{------------------------(2)}$$

- This suggests, from linear algebra, that the inverse of a rotation matrix is equal to its transpose, a fact which can be easily verified as

$${}^{A}_{B}R^{T}\,{}^{A}_{B}R = \begin{bmatrix} {}^{A}X_B^T \\ {}^{A}Y_B^T \\ {}^{A}Z_B^T \end{bmatrix} \begin{bmatrix} {}^{A}X_B & {}^{A}Y_B & {}^{A}Z_B \end{bmatrix} = I_3 \quad \text{-------------------(3)}$$

Where I_3 is the 3X3 identity matrix, hence

$${}^{A}_{B}R = {}^{B}_{A}R^{-1} = {}^{B}_{A}R^{T} \quad \text{----------------------(4)}$$

- There are three rotation transforms corresponding to rotation about the X, Y, and Z axes by an angle
  - a) Rotation about Z-axis.
  - b) Rotation about X-axis.
  - c) Rotation about Y-axis.

Note:- An axis that's pointing out of the paper is denoted by ⊙ , and an axis that's pointing into the paper is denoted by ⊗.

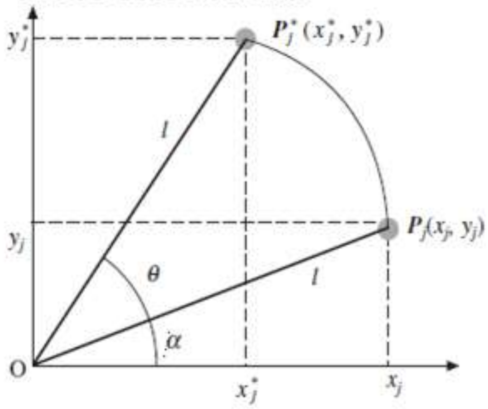
Rigid body Transformation

For a rigid body *S* to be translated along a vector **v** such that each point of *S* shifts by (*p*, *q*),

$$x_j^* = x_j + p,\ \ y_j^* = y_j + q \Rightarrow \begin{bmatrix} x_j^* \\ y_j^* \end{bmatrix} = \begin{bmatrix} x_j \\ y_j \end{bmatrix} + \begin{bmatrix} p \\ q \end{bmatrix} \Rightarrow \mathbf{P}_j^* = \mathbf{P}_j + \mathbf{v}$$

Rigid body Transformation

Consider a rigid body *S* packed with points ***Pi*** ($i = 1, \ldots, n$) and let a point ***Pj*** (x_j, y_j) on *S* be rotated about the *z*-axis to ***Pj**** (x_j^* , y_j^*) by an angle. From, it can be observed that



$$x_j^* = l\cos(\theta + \alpha) = l\cos\alpha\cos\theta - l\sin\alpha\sin\theta$$

$$= x_j\cos\theta - y_j\sin\theta$$

and $y_j^* = l\sin(\theta + \alpha) = l\cos\alpha\sin\theta + l\sin\alpha\cos\theta$

$$= x_j\sin\theta + y_j\cos\theta$$

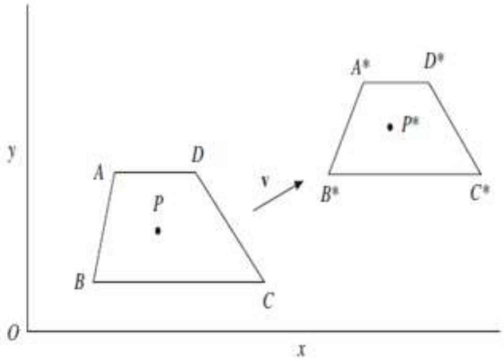
Or in matrix form

$$\begin{bmatrix} x_j^* \\ y_j^* \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x_j \\ y_j \end{bmatrix} \Rightarrow \mathbf{P}_j^* = \mathbf{R}\mathbf{P}_j$$

where $\mathbf{R} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$

Rigid body Transformation

For a planar lamina *ABCD* with *A* (3, 5), *B* (2, 2), *C* (8, 2) and *D* (4, 5) in *x-y* plane and *P* (4, 3) a point in the interior, the lamina is to be translated through $\mathbf{v} = \begin{bmatrix} 8 \\ 5 \end{bmatrix}$.



$$\begin{bmatrix} A* \\ B* \\ C* \\ D* \\ P* \end{bmatrix}^T = \begin{bmatrix} 3 & 5 \\ 2 & 2 \\ 8 & 2 \\ 4 & 5 \\ 4 & 3 \end{bmatrix}^T + \begin{bmatrix} 8 & 5 \\ 8 & 5 \\ 8 & 5 \\ 8 & 5 \\ 8 & 5 \end{bmatrix}^T = \begin{bmatrix} 11 & 10 \\ 10 & 7 \\ 16 & 7 \\ 12 & 10 \\ 12 & 8 \end{bmatrix}^T$$

Rigid body Transformation

$$\begin{bmatrix} x_j^* \\ y_j^* \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & p \\ 0 & 1 & q \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_j \\ y_j \\ 1 \end{bmatrix} = \begin{bmatrix} x_j + p \\ y_j + q \\ 1 \end{bmatrix}$$

$$\mathbf{P}_j^* = \mathbf{R}\mathbf{P}_j \Rightarrow \begin{bmatrix} x_j^* \\ y_j^* \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_j \\ y_j \\ 1 \end{bmatrix}$$

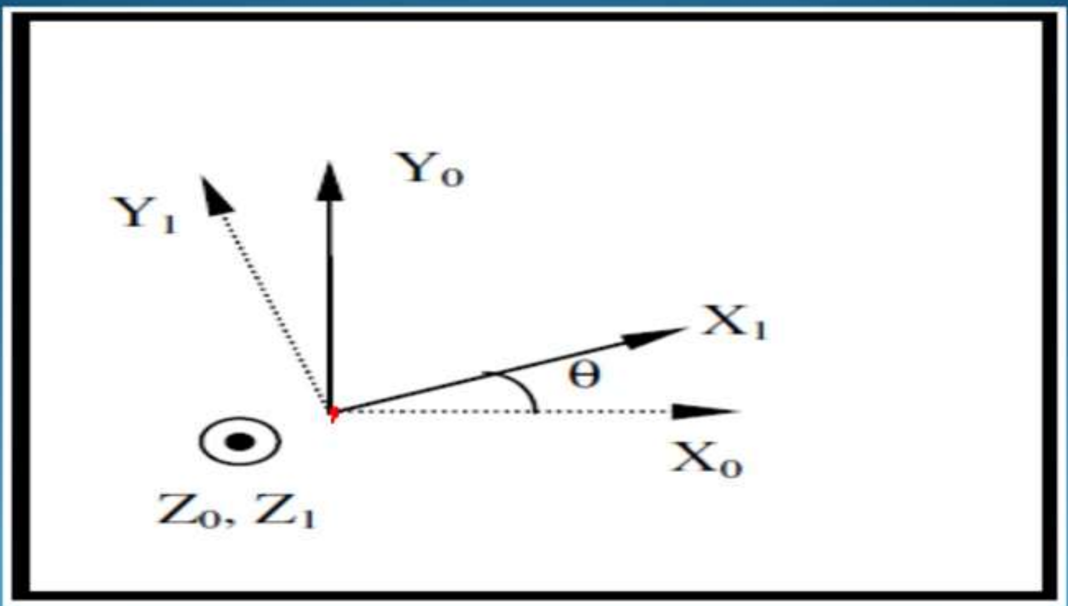
Rigid body Transformation

the rotation matrices about Z-axis:

$$ {}^{0}_{1}R = \begin{bmatrix} cos\theta & -sin\theta & 0 \\ sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{--------------(5)} $$

Rigid body Transformation

a) Rotation about Z-axis:



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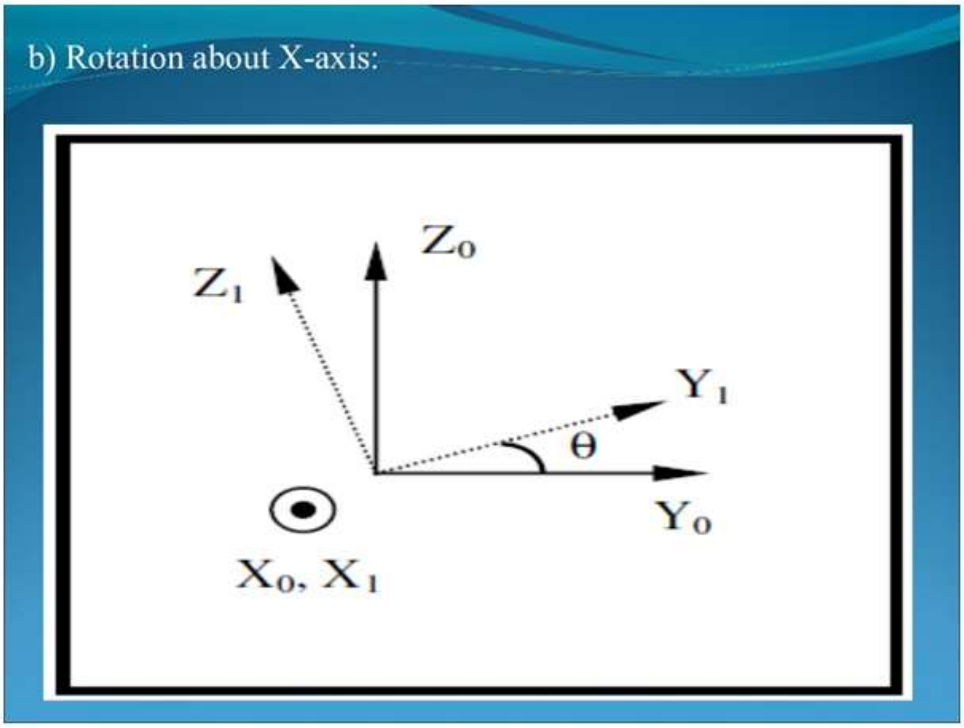
Rigid body Transformation



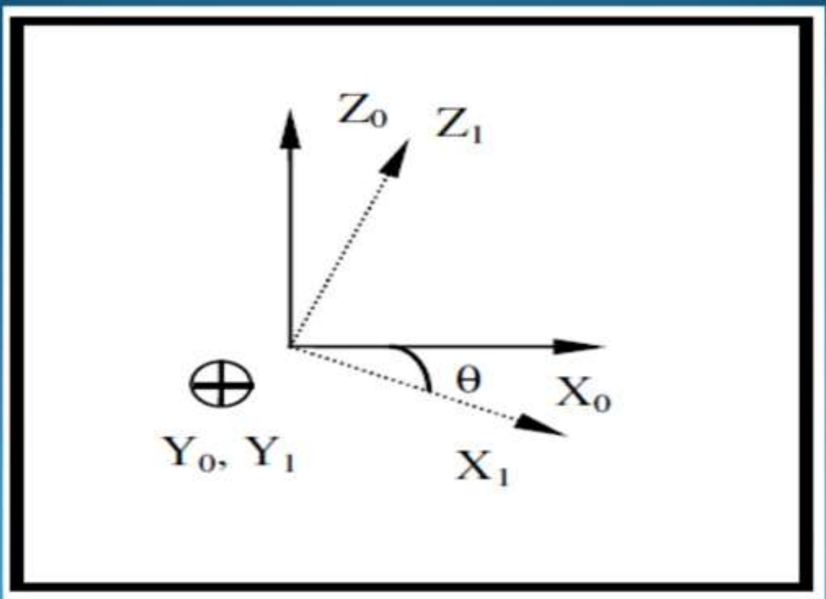
Rigid body Transformation

the rotation matrices about X-axis:

$$ {}^{0}_{1}R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \quad \text{--------------(6)} $$

Rigid body Transformation

c) Rotation about Y-axis:



Rigid body Transformation

the rotation matrices about Y-axis:

$$ {}^{0}_{1}R = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \quad \text{-----------------(7)} $$

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Rigid body Transformation

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & p \\ 0 & 1 & 0 & q \\ 0 & 0 & 1 & r \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{R}_z = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

H=RT → Homogeneous Transformation matrix

Mapping:

Mapping refer to changing the description of a point (or vector) in space from one frame to another frame. The second frame has three possibilities in relation to the first frame.

a) Second frame is rotated w.r.t the first ; the origin of both the frames is same.

b). Second frame is moved away from the first, the axes of both the frames remain parallel, respectively.

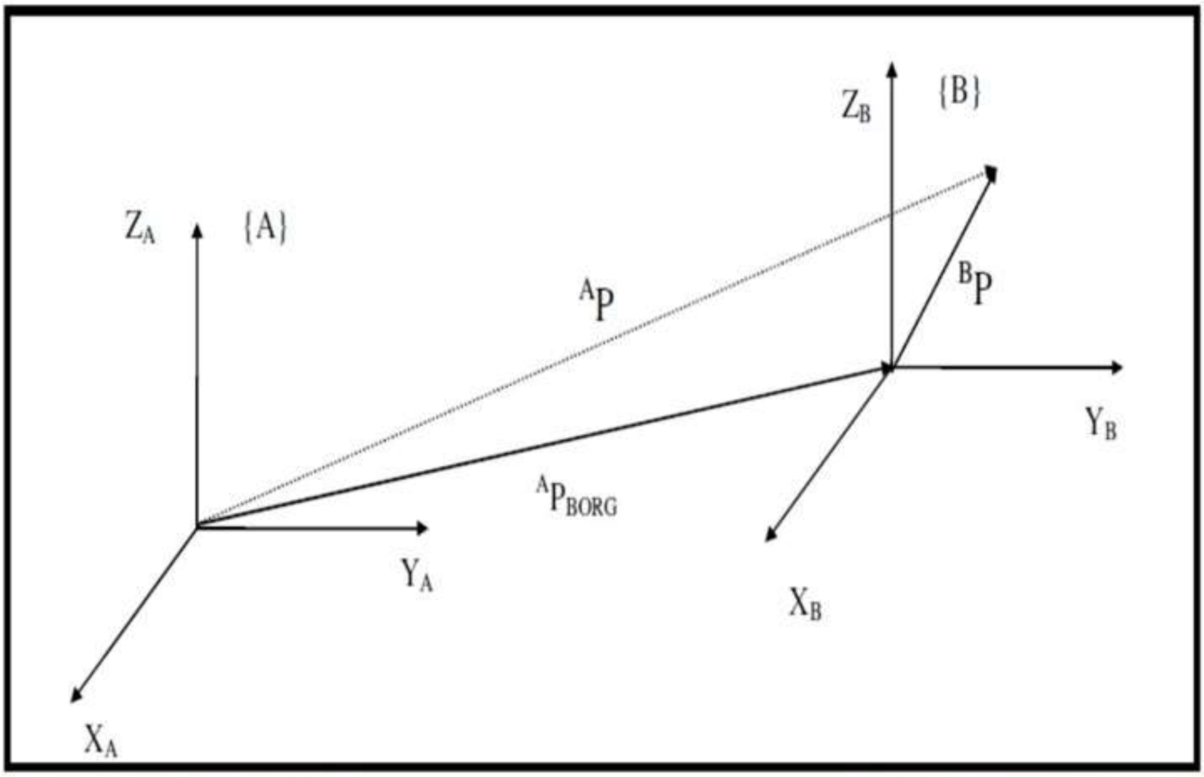
c). Second frame is rotated w.r.t the first and moved away from it , i.e., the second frame is translated and its orientation is also changed.

These situations are modeled in the following sections . It is important to note that mapping changes the description of the point and not the point itself.

Mappings Involving Translated Frames:

- We have a position defined by the vector ${}^{B}P$ (a point P described in co-ordinate frame {B}).
- To express this point in space in terms of frame {A}, when {A} has the same orientation as {B}.
- In this case, {B} differs from {A} only by a translation which is given by ${}^{A}P_{BORG}$ vector which locates the origin of {B} relative to {A}.
- The description of point P relative to co-ordinate system {A}, ${}^{A}P$, is determined by simple vector addition:

$$ {}^{A}P = {}^{B}P + {}^{A}P_{BORG} \qquad \text{---------------------------(10)} $$



Mapping involving translated frames

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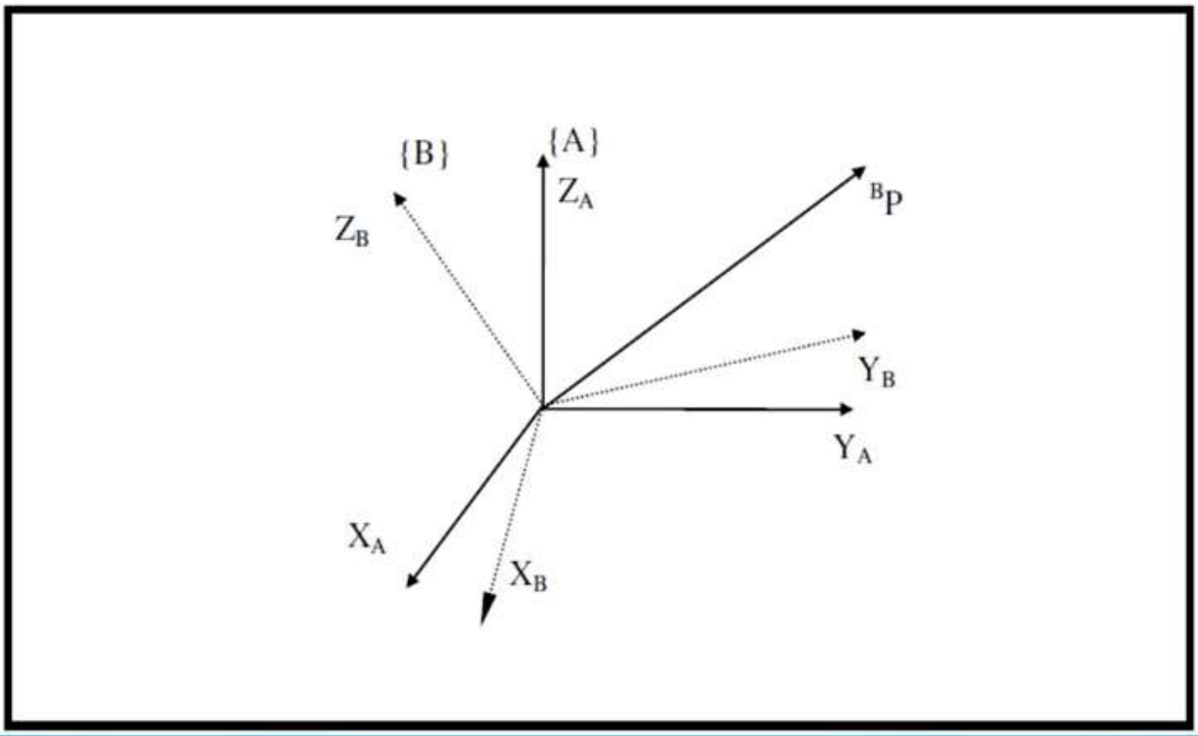
Mappings Involving Rotated Frames:

- The origins of the two frames {A} and {B} are coincident but they have different orientation.
- A point P that is described in co-ordinate system {B}, ^{B}P , and we wish to know its definition with respect to frame {A}, ^{A}P .

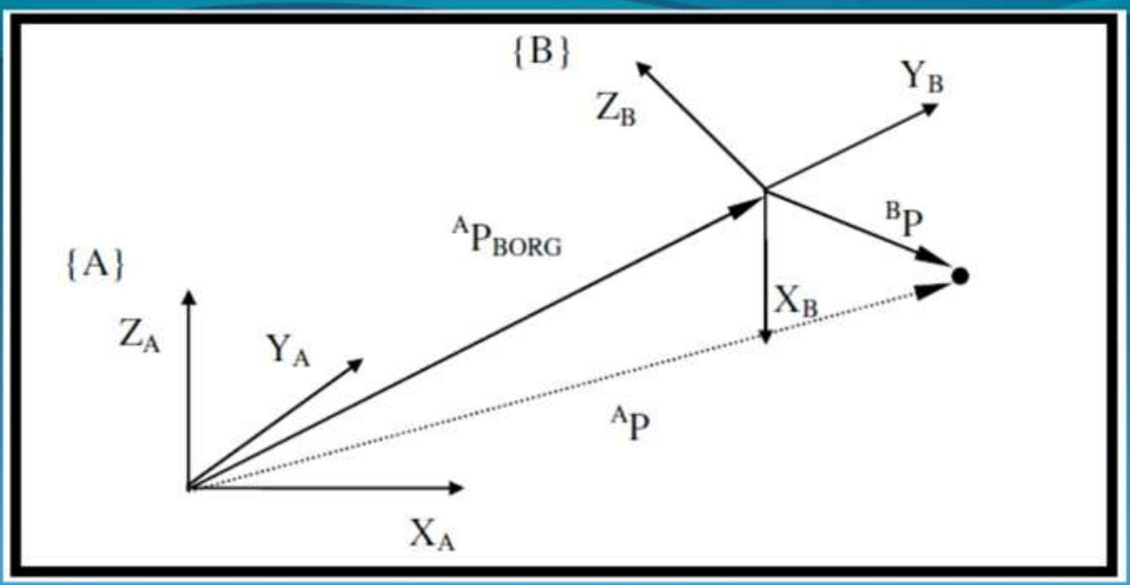
$$^{A}P = {}^{A}_{B}R \, {}^{B}P \qquad \text{-------------------------(11)}$$



Mappings involving rotated frames

Mappings Involving General Frames:

- The description of a vector with respect to some frame {B}, and we would like to know its description with respect to another frame {A}.
- Consider the example the below figure , where the origin of frame {B} is located with a distance from frame {A} with a vector called ${}^{A}P_{BORG}$.
- Also {B} is rotated with respect to {A} as described by ${}^{A}_{B}R$.
- First change ${}^{B}P$ to its description relative to an intermediate frame which has the same orientation as {A}, but whose origin is coincident with the origin of {B}.
- This is done by pre multiplying by ${}^{A}_{B}R$. We then account for the translation between origins by simple vector additions as:



General transform of a vector

$$^{A}P = {}^{A}_{B}R\,{}^{B}P + {}^{A}P_{BORG} \quad \text{------------------------------(12)}$$

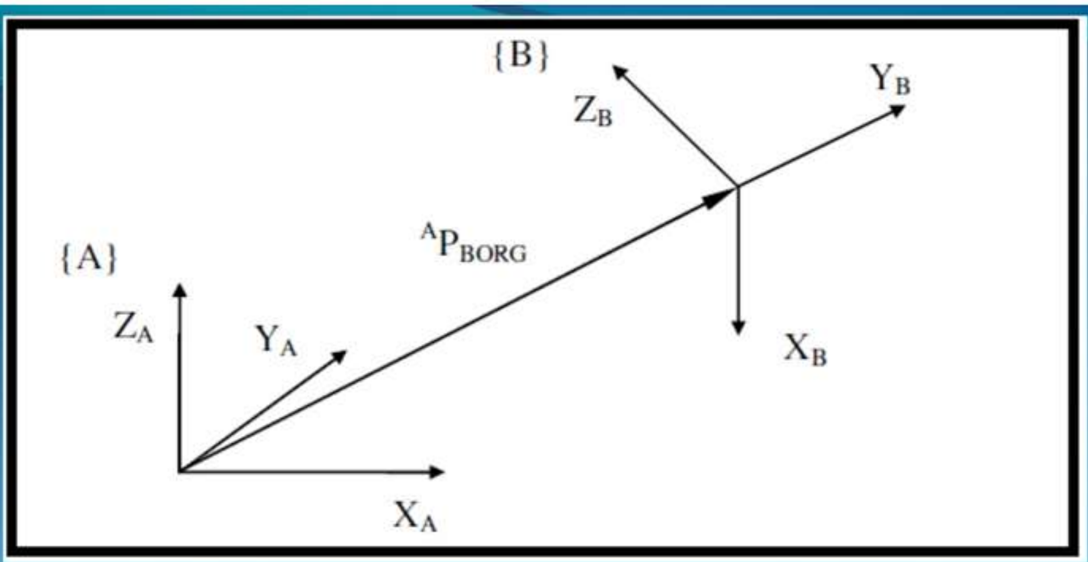
- The above equation describes the general transformation mapping of a vector from its description in one frame to a description in a second frame.

Homogenous Transformation

Description of A Homogeneous Transformation Matrix:

- The homogenous transformation matrix is used to describe both the position and the orientation of co-ordinate frames in space.
- A homogenous transformation matrix is a 4 x 4 matrix that maps an object defined in a homogeneous co-ordinate system.
- A homogenous transformation matrix can be thought of as two sub-matrices, i.e. a translation matrix and a rotation matrix.
- For example, according to below figure frame {B} is described by ${}^{A}_{B}R$ and ${}^{A}P_{BORG}$, Where ${}^{A}P_{BORG}$ is the vector which locates the origin of the frame {B}:

Homogenous Transformation



General transform of a vector

Homogenous Transformation

$$\{B\} = \{ {}^A_BR, {}^AP_{BORG} \} \text{-----------------------}(13)$$

- The homogeneous transformation matrix for the example above can be written in the following form:

$${}^A_BT = \begin{bmatrix} {}^A_BR & {}^AP_{BORG} \\ 0 \quad 0 \quad 0 & 1 \end{bmatrix} \text{---------------------}(14)$$

and in the general case, the homogeneous transformation matrix can be written as;

Homogenous Transformation

$$T = \left[\begin{array}{ccc|c} & \text{Rotation} & & \text{Translation} \\ \hline 0 & 0 & 0 & 1 \end{array}\right] \quad \text{----------}(15)$$

- The last row in the homogeneous transformation matrix is in the field of computer graphics used for projection and scaling.
- But in robotics, the projection vector is always equal to [0 0 0] and the scaling factor is always [1].

Rigid body Transformation

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & p \\ 0 & 1 & 0 & q \\ 0 & 0 & 1 & r \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \mathbf{R}_z = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

H=RT → Homogeneous Transformation matrix

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Minimal Representations of Orientation:

- The elements of the rotation matrix are not independent but related by six constraints due to the orthogonality conditions.
- Since six of the elements are related to these constraints, only three of the nine elements are independent.
- Therefore, we will show that the orientation of an object can be described with only three parameters (α, β, γ).
- Orientation is frequently specified by a sequence of rotations about the X, Y, and Z axes.
- Two types of angles that can be used to describe the possible orientation of the wrist motion.

- They are
  1. roll-pitch-yaw (RPY) angles.
  2. Z-Y-Z Euler angles.

1. Roll-pitch-yaw angles:

With this method, each of the three rotations takes place about an axis in the fixed reference frame, and therefore, this convention of specifying an orientation is often called X-Y-Z fixed angles.

Start with the frame coincident with a known reference frame {A}.First rotate {B} about X_A by an angle g, then rotate about Y_A by an angle β, and then rotate about Z_A by an angle α.

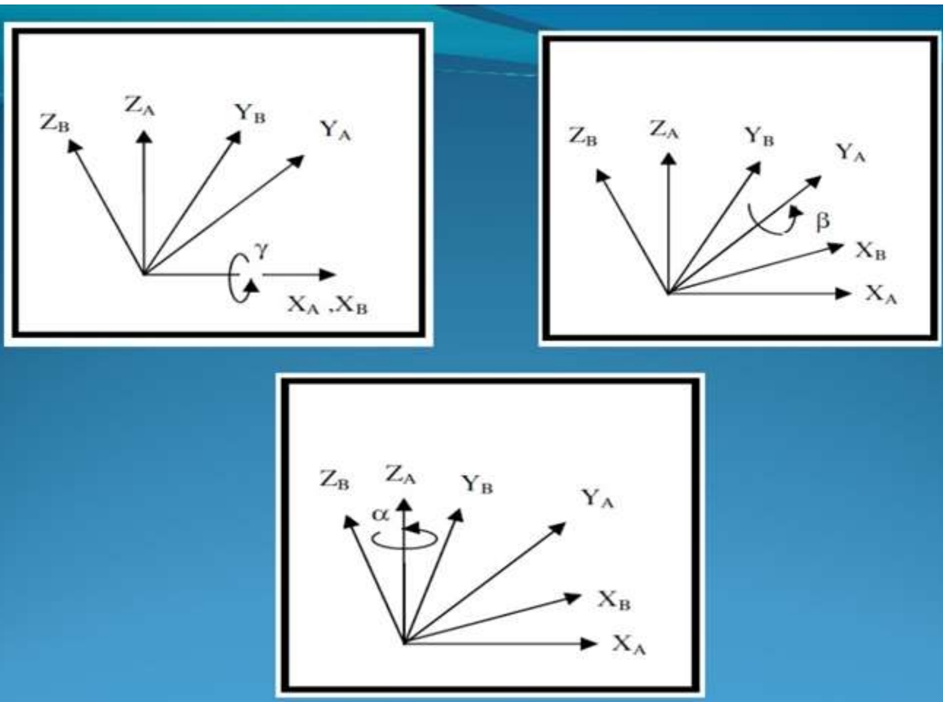

Figure:-Roll-pitch-yaw angles

- Since the rotations take place about a fixed frame, the total transformation must be obtained by pre-multiplication as:

$$ {}^{A}_{B}R_{XYZ}(\gamma,\beta,\alpha) = R(Z,\alpha)\ R(Y,\beta)\ R(X,\gamma) $$

$$ = \begin{bmatrix} c\alpha & -s\alpha & 0 \\ s\alpha & c\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c\beta & 0 & s\beta \\ 0 & 1 & 0 \\ -s\beta & 0 & c\beta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\gamma & -s\gamma \\ 0 & s\gamma & c\gamma \end{bmatrix} $$

$$ = \begin{bmatrix} c\alpha c\beta & c\alpha s\beta s\gamma - s\alpha c\gamma & c\alpha s\beta c\gamma + s\alpha s\gamma \\ s\alpha c\beta & s\alpha s\beta s\gamma + c\alpha c\gamma & s\alpha s\beta c\gamma - c\alpha s\gamma \\ -s\beta & c\beta s\gamma & c\beta c\gamma \end{bmatrix} \text{---------------(8)} $$

Where C(α) = Cos(α), S(α) = Sin(α),
C(β) = Cos(β), S(β) = Sin(β),
C(γ) = Cos(γ), S(γ) = Sin(γ),

2. Euler Angles:

In this representation, each rotation is performed about an axis of the moving system {B}, rather than the fixed reference, {A} as in the case of the RPY-angles. There are 12 different ways to achieve an Euler angle set, where the Z-Y-Z is the most common. In robotics, the set of angles that is used to describe the orientation of the wrist depends on the mechanical configuration of the robot's wrist.

Start with the frame coincident with a known frame {A}. First rotate {B} about ZB by an angle α, then rotate about YB by an angle β, and then rotate about ZB by an angle γ.

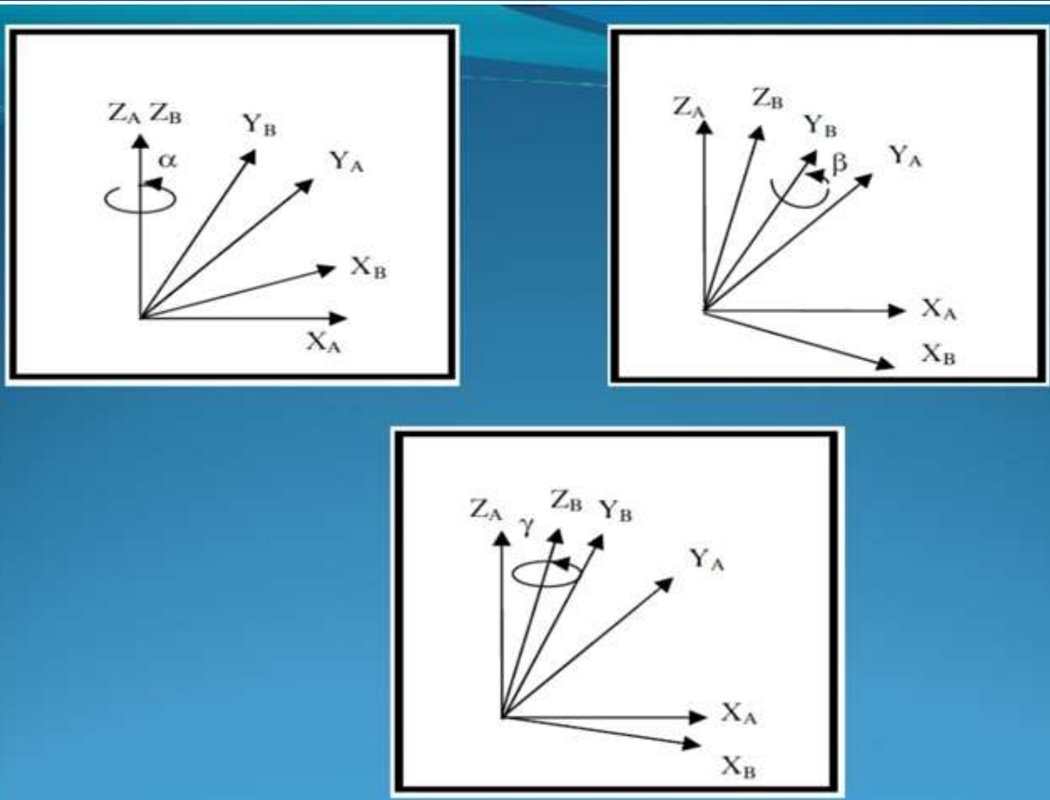

Figure:-Z-Y-Z Euler angles

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- Since these rotations occur with relations to a new frame the total transformation can be obtained by post-multiplication as:

$$ {}^{A}_{B}R_{Z'Y'Z'}(\alpha,\beta,\gamma) = R(Z,\alpha)\ R(Y,\beta)\ R(Z,\gamma) $$

$$ = \begin{bmatrix} c\alpha & -s\alpha & 0 \\ s\alpha & c\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c\beta & 0 & s\beta \\ 0 & 1 & 0 \\ -s\beta & 0 & c\beta \end{bmatrix} \begin{bmatrix} c\gamma & -s\gamma & 0 \\ s\gamma & c\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} $$

$$ = \begin{bmatrix} c\alpha c\beta c\gamma - s\alpha s\gamma & -c\alpha c\beta s\gamma - s\alpha c\gamma & c\alpha s\beta \\ s\alpha c\beta c\gamma + c\alpha s\gamma & -s\alpha c\beta s\gamma + c\alpha c\gamma & s\alpha s\beta \\ -s\beta c\gamma & s\beta s\gamma & c\beta \end{bmatrix} \quad \text{---------(9)} $$

Where $C(\alpha) = \mathrm{Cos}(\alpha)$, $S(\alpha) = \mathrm{Sin}(\alpha)$,
$C(\beta) = \mathrm{Cos}(\beta)$, $S(\beta) = \mathrm{Sin}(\beta)$,
$C(\gamma) = \mathrm{Cos}(\gamma)$, $S(\gamma) = \mathrm{Sin}(\gamma)$,

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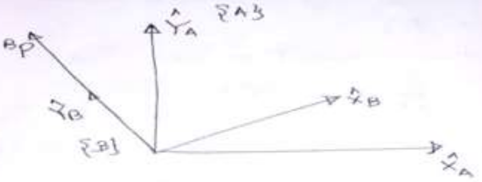
①

unit - 5 Numericals

* Numerical on transformation

Q.1 Find out the position point P in frame {A}. Frame B is rotated relative to frame {A} about $\hat{Z}$ by 30°. The point P is located in frame B



So, here question involves the mapping between frame. There are two frames {A} & {B}. The frame {B} is rotated relative to frame {A} by 30°, & the rotation is about z axis (Note:- z axis is pointing out of the page).

The coordinates of point P in frame B is given. Our objective is to find out the coordinates of point P in {A} frame

Coordinates of $^BP = \begin{bmatrix} 0.0 \\ 2.0 \\ 0.0 \end{bmatrix}$ → X component → Y component → Z component

the point is along the $\hat{Y}_B$ axis 2 units

②

The problem clearly involves the rotation of frame so, we know the rotation matrix from our study of Rigid body transformation

^A_BR → symbol indicates rotation of {B} relative frame {A}

if Rotation is about z dir., then

$$^A_BR = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \rightarrow \text{for 2D}$$

if we convert this into homogeneous coordinates

$$^A_BR = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$\theta = 30°$

$$^A_BR = \begin{bmatrix} \cos 30 & -\sin 30 & 0 \\ \sin 30 & \cos 30 & 0 \\ 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0.866 & -0.5 & 0 \\ 0.5 & 0.866 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$^AP = {^A_BR}\,{^BP} = \begin{bmatrix} 0.866 & -0.5 & 0 \\ 0.5 & 0.866 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} 0 \\ 2 \\ 0 \end{bmatrix}$$

$$^AP = \begin{bmatrix} -1 \\ 1.732 \\ 0 \end{bmatrix}$$

Position of Point P in frame {A}

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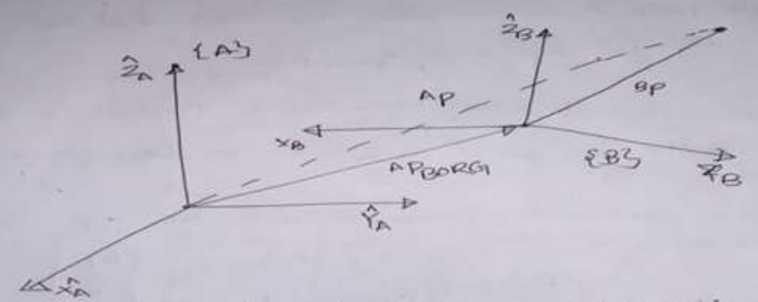
(3)

before we go to next numerical let us discuss Mappings involving general frames



Here, the origin of frames are not coincident with that of frame {A} but has vector offset. Vector that locates {B}'s origin is called $^AP_{Borg}$. rotation of {B} relative to {A} is described by ^A_BR

Given ^BP, we wish to compute ^AP

step → ① First change ^BP to its description relative to intermediate frame that has the same orientation as {A}. this is done by multiplying by ^A_BR.

② Then we account for the translation between origins by simple vector addition.

$$^AP = {}^A_BR\,{}^BP + {}^AP_{Borg}$$

More appealing form of equation

$$^AP = {}^A_BT\,{}^BP \quad \text{—(2)}$$

we go back & see these are arrived at eqn (2)

eqn ① $^AP = {}^A_BR\,{}^BP + {}^AP_{Borg}$

Here eqn involves translation Matrix & rotation ~~$= {}^A_BR\,{}^BP +$~~ both can be written in homogeneous coordinates

More general form would be a 4×4 matrix

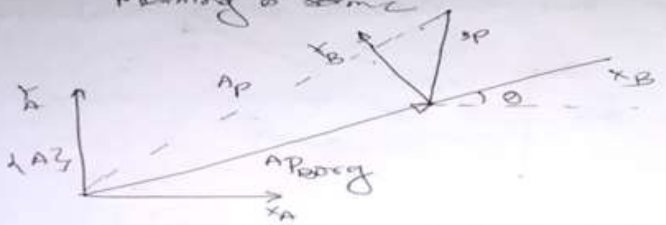
$$\begin{bmatrix} ^AP \\ 1 \end{bmatrix} = \left[\begin{array}{c|c} ^A_BR & ^AP_{BORG} \\ 0\,0\,0 & 1 \end{array}\right] \begin{bmatrix} ^BP \\ 1 \end{bmatrix}$$

↓ Homogeneous transformation Matrix

Ex.

$$^{B}P = \begin{bmatrix} 3 \\ 07 \\ 0 \end{bmatrix} \Rightarrow {}^{B}P = [3 \;\; 07 \;\; 0]^T$$

Meaning is same



$\theta = 30$ about $\hat{Z}$. translation between frames 10 units in $\hat{X}_A$, 5 units in $\hat{Y}_A$

Our transformation matrix would

$$^{A}_{B}T = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 10 \\ \sin\theta & \cos\theta & 0 & 5 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Rotation (upper 3×3); translation: → x component, → Y component, → z component

dummy row (last row)

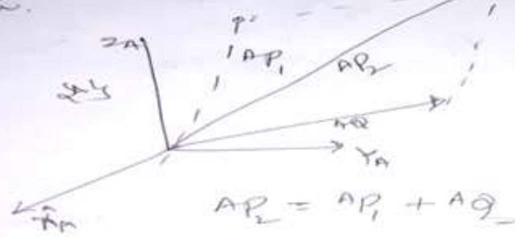
$\theta = 30$

$$^{A}_{B}T = \begin{bmatrix} 0.866 & -0.5 & 0 & 10 \\ 0.5 & 0.866 & 0 & 5 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{A}P = {}^{A}_{B}T \; {}^{B}P = \begin{bmatrix} 9.098 \\ 12.562 \\ 0 \end{bmatrix}$$

Operators

The same mathematical forms used to map points between frames can also be interpreted as operators that translated points, rotate vectors & do both.



$$^{A}P_2 = {}^{A}P_1 + {}^{A}Q$$

Inverting a transform

Consider we know $^{A}_{B}T$ we want to find out $^{B}_{A}T$. So from properties of rotation matrix we know

$$^{B}_{A}R = {}^{A}_{B}R^T$$

$$^{B}_{A}T = \left[\begin{array}{c|c} ^{A}_{B}R^T & -{}^{B}_{A}R^T \, P_{BORG} \\ \hline 0\;0\;0 & 1 \end{array}\right]$$

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Forward Kinematics

- Forward Kinematics:
  to determine where the robot's hand is?
  (If all joint variables are known)

- Inverse Kinematics:
  to calculate what each joint variable is?
  (If we desire that the hand be located at a particular point)

Forward Kinematics

Forward (Direct) Kinematics:

- To deal with the complex geometry of a manipulator we will affix frames to the various parts of the mechanism and then describe the relationship between these frames.
- The study of manipulator kinematics involves, among other things, how the location of these frames change as the mechanism articulates.
- In kinematics, we have two vectors:

$$\underline{\theta} = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \vdots \\ \theta_6 \end{bmatrix}$$

This vector consists of the joint angle of each joint of the manipulator.

Forward Kinematics

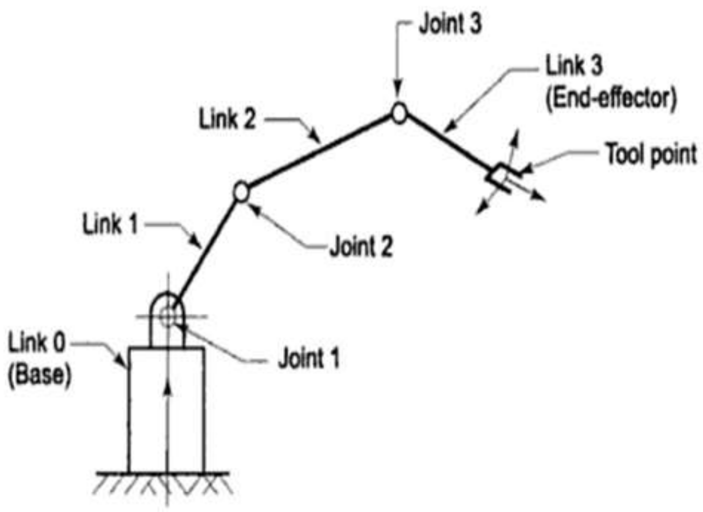
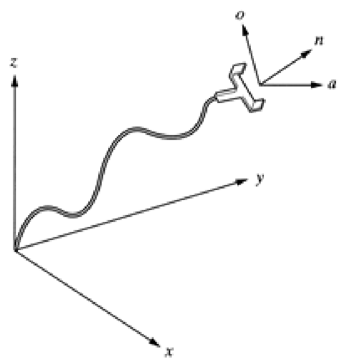


Fig. *A 3-DOF manipulator arm—numbering of links and joints*

Forward Kinematics

FORWARD AND INVERSE KINEMATICS OF ROBOTS

- Forward Kinematics Analysis:
  - Calculating the position and orientation of the hand of the robot.
  - If all robot joint variables are known, one can calculate where the robot is at any instant.



The hand frame of the robot relative to the reference frame.

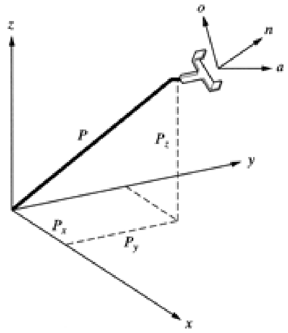
Forward Kinematics

FORWARD AND INVERSE KINEMATICS OF ROBOTS

Forward and Inverse Kinematics Equations for Position

(a) Cartesian (Gantry, Rectangular) Coordinates

- IBM 7565 robot
  - All actuator is linear.
  - A gantry robot is a Cartesian robot.



Cartesian Coordinates.

$$^{R}T_{P} = T_{cart} = \begin{bmatrix} 1 & 0 & 0 & P_x \\ 0 & 1 & 0 & P_y \\ 0 & 0 & 1 & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

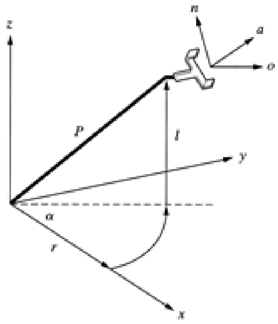
Forward Kinematics

FORWARD AND INVERSE KINEMATICS OF ROBOTS

Forward and Inverse Kinematics Equations for Position

(b) Cylindrical Coordinates

- 2 Linear translations and 1 rotation
  - translation of r along the x-axis
  - rotation of α about the z-axis
  - translation of l along the z-axis



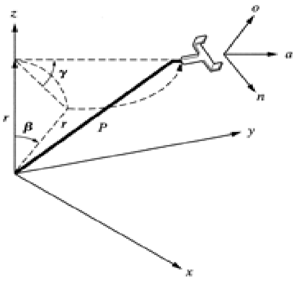
$$^{R}T_{P} = T_{cyl}(r,\alpha,l) = \text{Trans}(0,0,l)\text{Rot}(z,\alpha)\text{Trans}(r,0,0)$$

$$^{R}T_{P} = T_{cyl} = \begin{bmatrix} C\alpha & -S\alpha & 0 & rC\alpha \\ S\alpha & C\alpha & 0 & rS\alpha \\ 0 & 0 & 1 & l \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

FORWARD AND INVERSE KINEMATICS OF ROBOTS

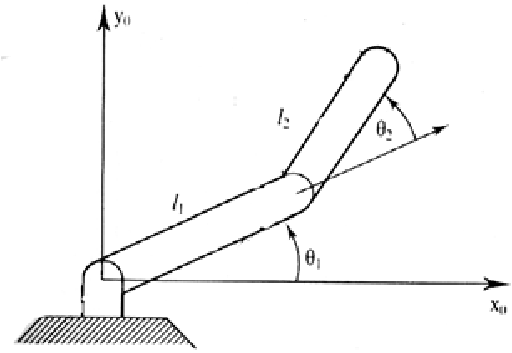
- Spherical Coordinates

  - 2 Linear translations and 1 rotation
    - translation of r along the z-axis
    - rotation of β about the y-axis
    - rotation of γ along the z-axis



$$^{R}T_{P} = T_{sph}(r, \beta, l) = \mathrm{Rot}(z, \gamma)\mathrm{Rot}(y, \beta)\mathrm{Trans}(0,0, \gamma)$$

$$^{R}T_{P} = T_{sph} = \begin{bmatrix} C\beta \cdot C\gamma & -S\gamma & S\beta \cdot C\gamma & rS\beta \cdot C\gamma \\ C\beta \cdot S\gamma & C\gamma & S\beta \cdot S\gamma & rS\beta \cdot S\gamma \\ -S\beta & 0 & C\beta & rC\beta \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



The Situation:

You have a robotic arm that starts out aligned with the x_o-axis.
You tell the first link to move by Θ_1 and the second link to move by Θ_2.

The Quest:

What is the position of the end of the robotic arm?

Solution:

1. Geometric Approach

This might be the easiest solution for the simple situation. However, notice that the angles are measured relative to the direction of the previous link. (The first link is the exception. The angle is measured relative to it's initial position.) For robots with more links and whose arm extends into 3 dimensions the geometry gets much more tedious.

2. Algebraic Approach

Involves coordinate transformations.

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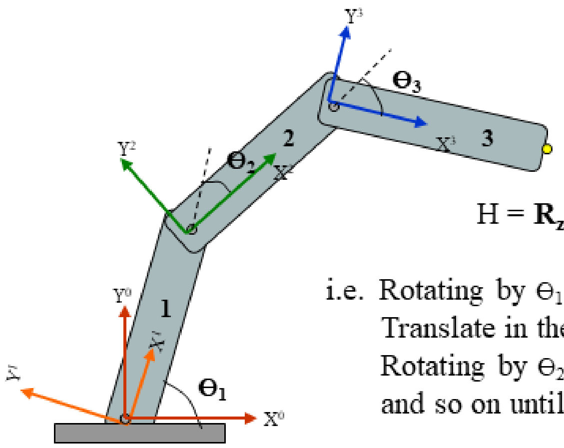
Example Problem:

You are have a three link arm that starts out aligned in the x-axis. Each link has lengths l_1, l_2, l_3, respectively. You tell the first one to move by Θ_1, and so on as the diagram suggests. Find the Homogeneous matrix to get the position of the yellow dot in the X^0Y^0 frame.

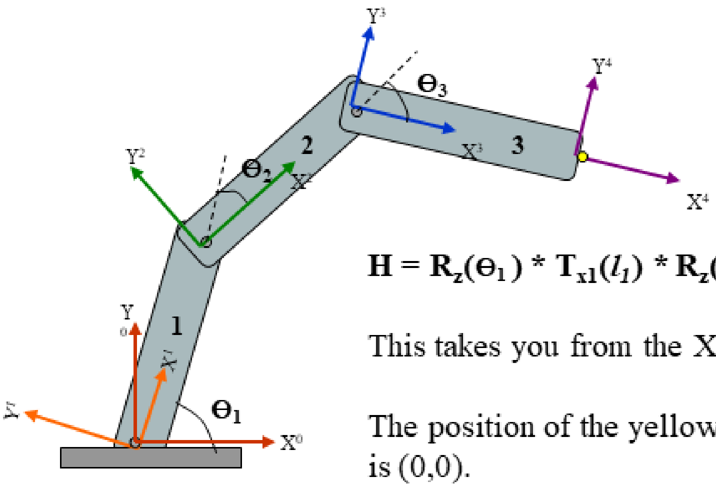


$$H = \mathbf{R_z}(\Theta_1) * \mathbf{T_{x1}}(l_1) * \mathbf{R_z}(\Theta_2) * \mathbf{T_{x2}}(l_2) * \mathbf{R_z}(\Theta_3)$$

i.e. Rotating by Θ_1 will put you in the X^1Y^1 frame.
Translate in the along the X^1 axis by l_1.
Rotating by Θ_2 will put you in the X^2Y^2 frame.
and so on until you are in the X^3Y^3 frame.

The position of the yellow dot relative to the X^3Y^3 frame is $(l_1, 0)$. Multiplying H by that position vector will give you the coordinates of the yellow point relative the X^0Y^0 frame.

Slight variation on the last solution: Make the yellow dot the origin of a new coordinate X^4Y^4 frame



$$\mathbf{H = R_z(\Theta_1) * T_{x1}(l_1) * R_z(\Theta_2) * T_{x2}(l_2) * R_z(\Theta_3) * T_{x3}(l_3)}$$

This takes you from the X^0Y^0 frame to the X^4Y^4 frame.

The position of the yellow dot relative to the X^4Y^4 frame is (0,0).

$$\begin{bmatrix} \mathbf{X} \\ \mathbf{Y} \\ \mathbf{Z} \\ \mathbf{1} \end{bmatrix} = \mathbf{H} \begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{1} \end{bmatrix}$$

← Notice that multiplying by the (0,0,0,1) vector will equal the last column of the H matrix.

More on Forward Kinematics…

Denavit - Hartenberg Parameters

- In this section, we consider position and orientation of the manipulator linkages in static situations.
- In order to deal with the complex geometry of a manipulator, we will affix frames to the various parts of the mechanism and then describe the relationships between these frames.

- The study of manipulator kinematics involves, among other things, how the locations of these frames change as the mechanism articulates.
- The central topic of this section is a method to compute the position and orientation of the manipulator's end-effector relative to the base of the manipulator as a function of the joint variables.

- A manipulator may be thought of as a set of bodies connected in a chain by joints.
- These bodies are called links. Joints form a connection between a neighboring pair of links.
- Mechanical-design considerations favor manipulators' generally being constructed from joints that exhibit just one degree of freedom.
- Most manipulators have revolute joints or have sliding joints called prismatic joints

- The links are numbered starting from the immobile base of the arm, which might be called link 0.
- The first moving body is link 1, and so on, out to the free end of the arm, which is link n.
- In order to position an end-effector generally in 3-space, a minimum of six joints is required.1 Typical manipulators have five or six joints.

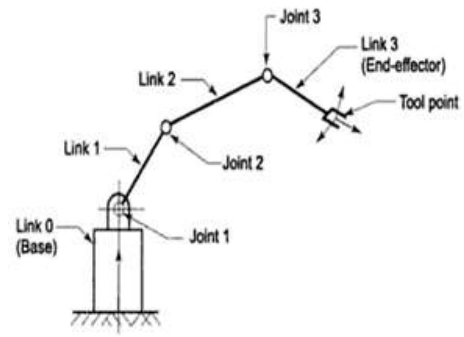


Fig. A 3-DOF manipulator arm—numbering of links and joints

Link Description

- A single link of a typical robot has many attributes that a mechanical designer had to consider during its design: the type of material used, the strength and stiffness of the link, the location and type of the joint bearings, the external shape, the weight and inertia, and more.
- However, for the purposes of obtaining the kinematic equations of the mechanism, a link is considered only as a rigid body that defines the relationship between two neighboring joint axes of a manipulator.

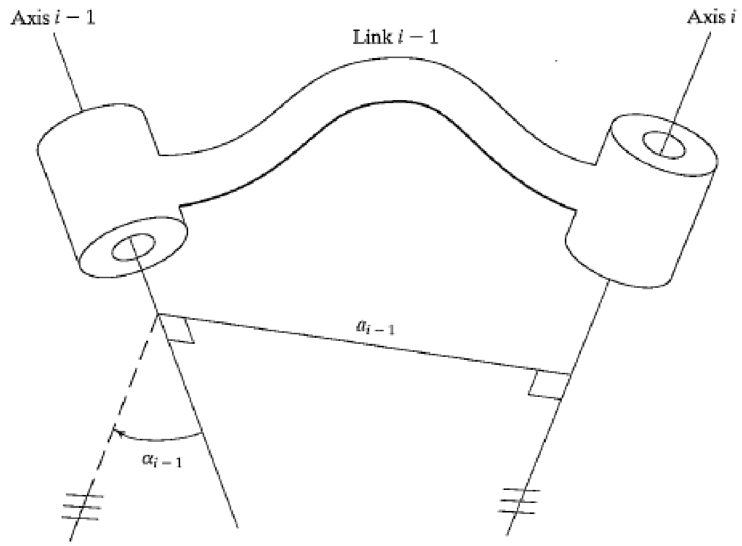


Fig. The kinematic function of a link is to maintain a fixed relationship between the two joint axes it supports. This relationship can be described with two parameters: the link length, a, and the link twist, α.

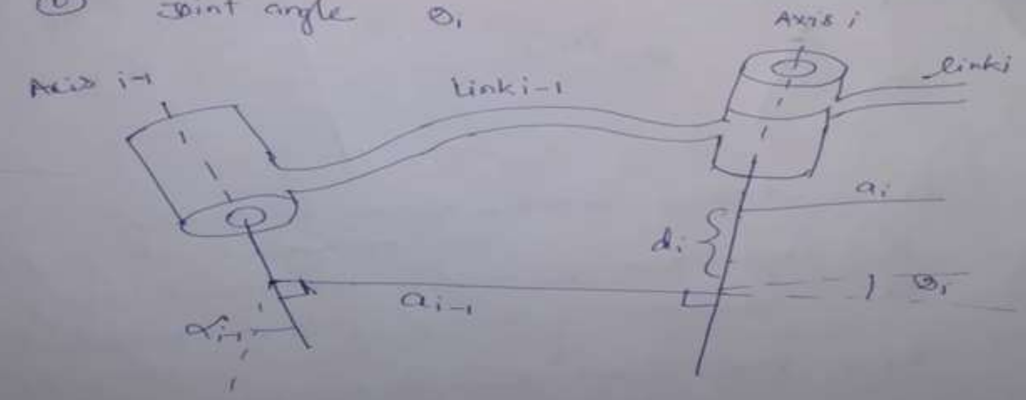
For solving next numerical we will link parameters

a_{i-1} → link length } → link parameters
α_{i-1} → link twist

link connection description

How links are connected

(1) link offset d_i
(2) Joint angle θ_i



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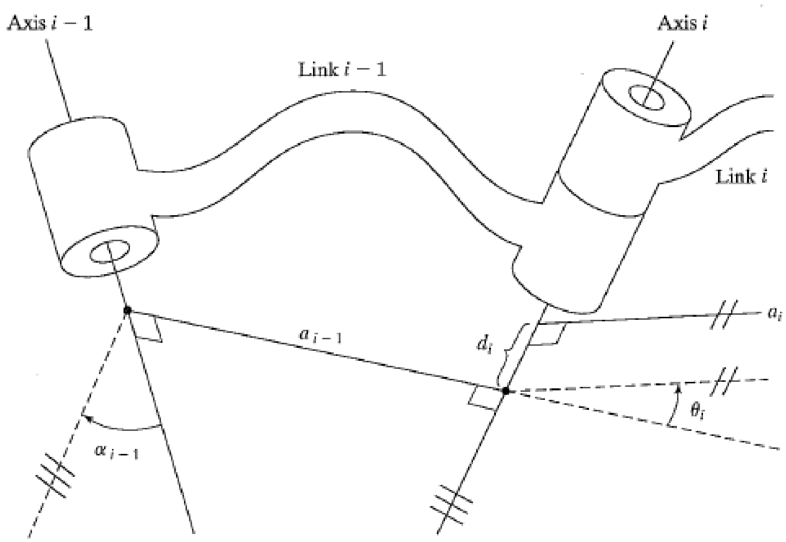
- The second parameter needed to define the relative location of the two axes is called the link twist.
- If we imagine a plane whose normal is the mutually perpendicular line just constructed, we can project the axes i-1 and i onto this plane and measure the angle between them.
- This angle is measured from axis i- 1 to axis i in the right-hand sense about a_i-1. We will use this definition of the twist of link i -1. α_{i-1} is indicated as the angle between axis i-1 and axis i. (The lines with the triple hash marks are parallel.) In the case of intersecting

Link Connection Description

- The problem of connecting the links of a robot together is again one filled with many questions for the mechanical designer to resolve. These include the strength of the joint, its lubrication, and the bearing and gearing mounting.
- However, for the investigation of kinematics, we need only worry about two quantities, which will completely specify the way in which links are connected together.



The link offset, d, and the joint angle, θ, are two parameters that may be used to describe the nature of the connection between neighboring links.

- Neighboring links have a common joint axis between them. One parameter of interconnection has to do with the distance along this common axis from one link to the next. This parameter is called the link offset. The offset at joint axis i is called
- The second parameter describes the amount of rotation about this common axis between one link and its neighbor. This is called the joint angle,

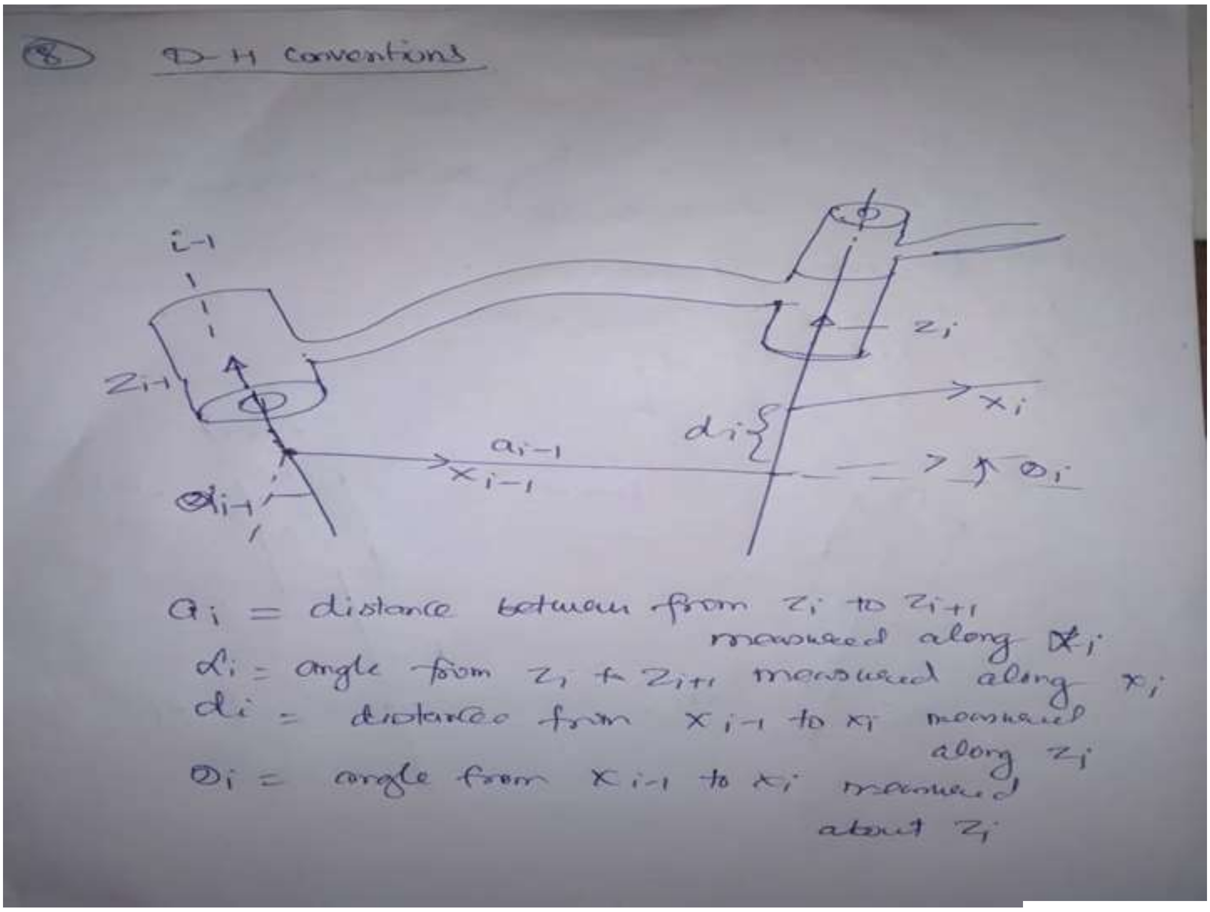
Link Parameters

Hence, any robot can be described kinematically by giving the values of four quantities for each link.

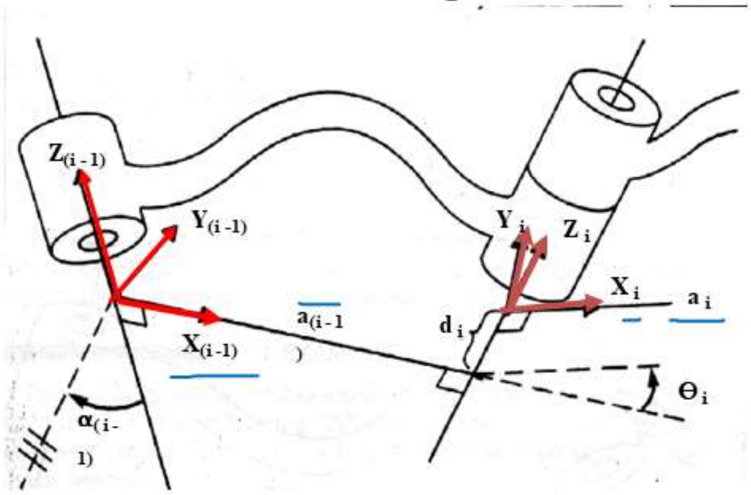
Two describe the link itself, and two describe the link's connection to a neighboring link. In the usual case of a revolute joint, is called the joint variable, and the other three quantities would be fixed link parameters.

For prismatic joints, d1 is the joint variable, and the other three quantities are fixed link parameters.

The definition of mechanisms by means of these quantities is a convention usually called the Denavit—Hartenberg notation.



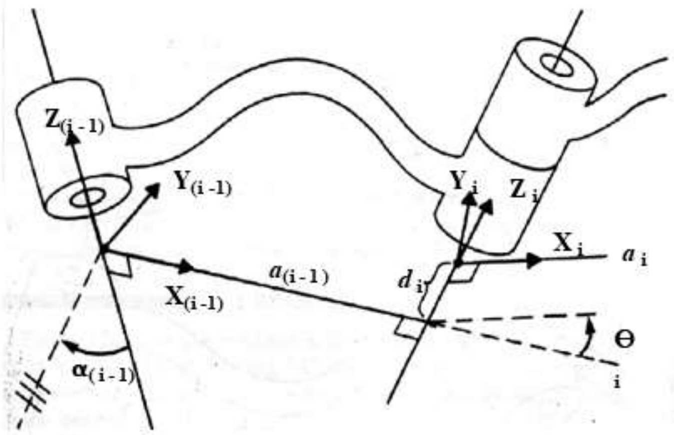
Denavit-Hartenberg Notation



IDEA: Each joint is assigned a coordinate frame. Using the Denavit-Hartenberg notation, you need 4 parameters to describe how a frame (i) relates to a previous frame (i -1).

THE PARAMETERS/VARIABLES: α, a , d, Θ

D-H Parameters



You can align the two axis just using the 4 parameters

1) $a_{(i-1)}$

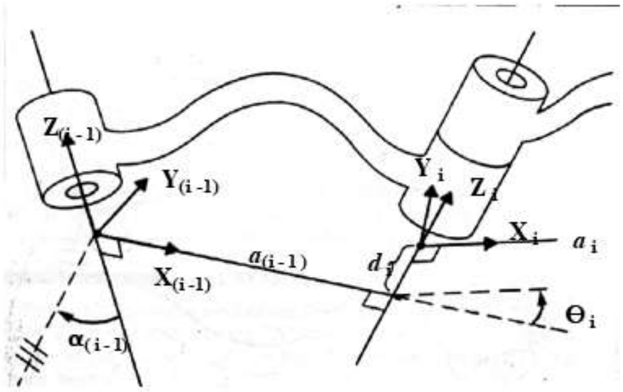
Technical Definition: $a_{(i-1)}$ is the length of the perpendicular between the joint axes. The joint axes is the axes around which revolution takes place which are the $Z_{(i-1)}$ and $Z_{(i)}$ axes. These two axes can be viewed as lines in space. The common perpendicular is the shortest line between the two axis-lines and is perpendicular to both axis-lines.

a*$_{(i-1)}$ *cont...

Visual Approach - "A way to visualize the link parameter $a_{(i-1)}$ is to imagine an expanding cylinder whose axis is the $Z_{(i-1)}$ axis - when the cylinder just touches the joint axis Zi the radius of the cylinder is equal to $a_{(i-1)}$." (Manipulator Kinematics)

It's Usually on the Diagram Approach - If the diagram already specifies the various coordinate frames, then the common perpendicular is usually the $X_{(i-1)}$ axis. So $a_{(i-1)}$ is just the displacement along the $X_{(i-1)}$ to move from the *(i-1)* frame to the *i* frame.

If the link is prismatic, then $a_{(i-1)}$ is a variable, not a parameter.



2) $\alpha_{(i-1)}$

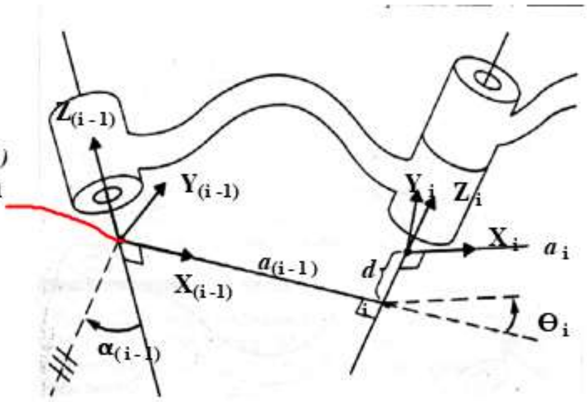
Technical Definition: Amount of rotation around the common perpendicular so that the joint axes are parallel.

i.e. How much you have to rotate around the $X_{(i-1)}$ axis so that the $Z_{(i-1)}$ is pointing in the same direction as the Z_i axis. Positive rotation follows the right hand rule.

3) $d_{(i-1)}$

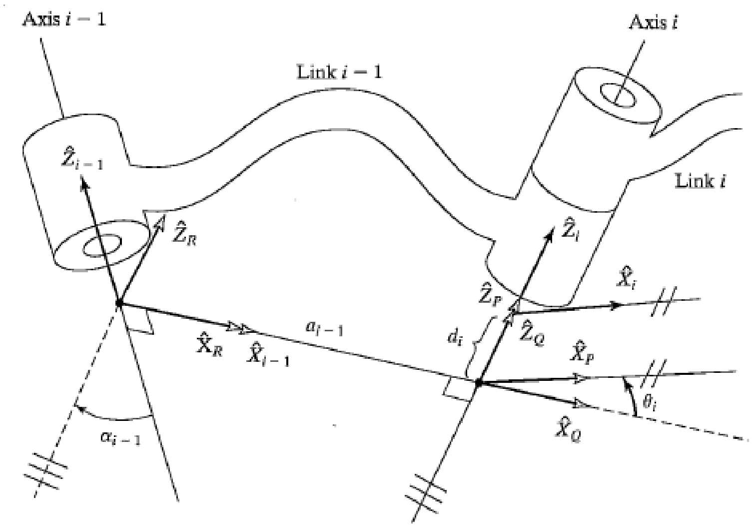
Technical Definition: The displacement along the Z_i axis needed to align the $a_{(i-1)}$ common perpendicular to the a_i common perpendicular.

In other words, displacement along the Z_i to align the $X_{(i-1)}$ and X_i axes.



4) Θ_i

Amount of rotation around the Z_i axis needed to align the $X_{(i-1)}$ axis with the X_i axis.



Location of intermediate frames {P}, {Q}, and {R}.

Frame (Q} differs from {R} by a translation a_{i-1}
Frame {P} differs from {Q} by a rotation θ_i and frame {i} differs from {P} by a translation d_i d. If we wish to write the transformation that transforms vectors defined in {i} to their description in {i-1}

$$^{i-1}P = {}^{i-1}_{R}T\,{}^{R}_{Q}T\,{}^{Q}_{P}T\,{}^{P}_{i}T\,{}^{i}P,$$

$$^{i-1}_{i}T = {}^{i-1}_{R}T\,{}^{R}_{Q}T\,{}^{Q}_{P}T\,{}^{P}_{i}T.$$

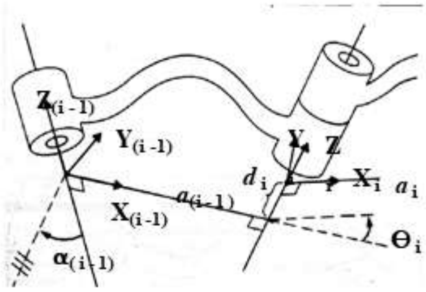
$$^{i-1}_{i}T = R_X(\alpha_{i-1})D_X(a_{i-1})R_Z(\theta_i)D_Z(d_i),$$

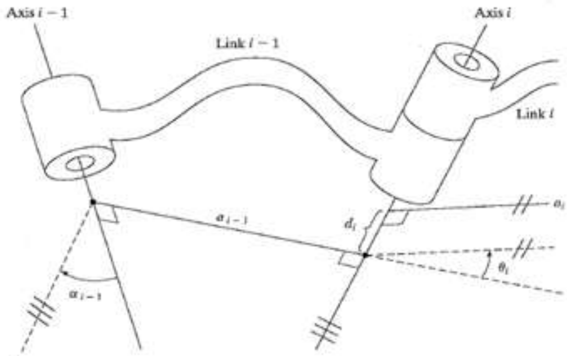
The Denavit-Hartenberg Matrix

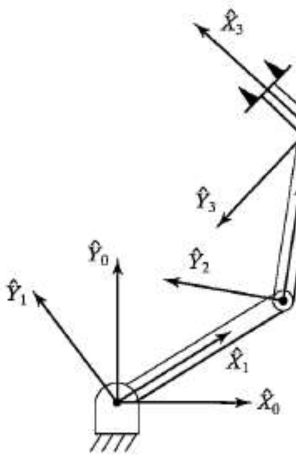
$$\begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_{(i-1)} \\ \sin\theta_i \cos\alpha_{(i-1)} & \cos\theta_i \cos\alpha_{(i-1)} & -\sin\alpha_{(i-1)} & -\sin\alpha_{(i-1)} d_i \\ \sin\theta_i \sin\alpha_{(i-1)} & \cos\theta_i \sin\alpha_{(i-1)} & \cos\alpha_{(i-1)} & \cos\alpha_{(i-1)} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Just like the Homogeneous Matrix, the Denavit-Hartenberg Matrix is a transformation matrix from one coordinate frame to the next. Using a series of D-H Matrix multiplications and the D-H Parameter table, the final result is a transformation matrix from some frame to your initial frame.

Put the transformation here







i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	0	L_1	0	θ_2
3	0	L_2	0	θ_3

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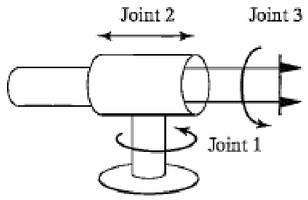
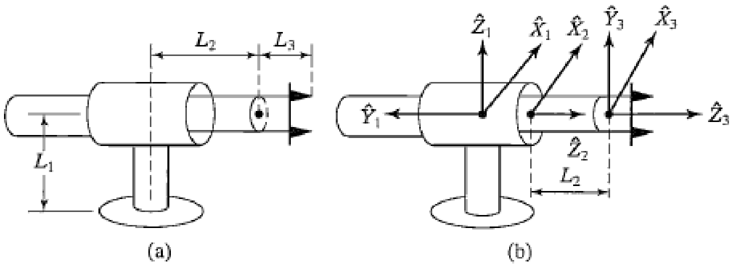
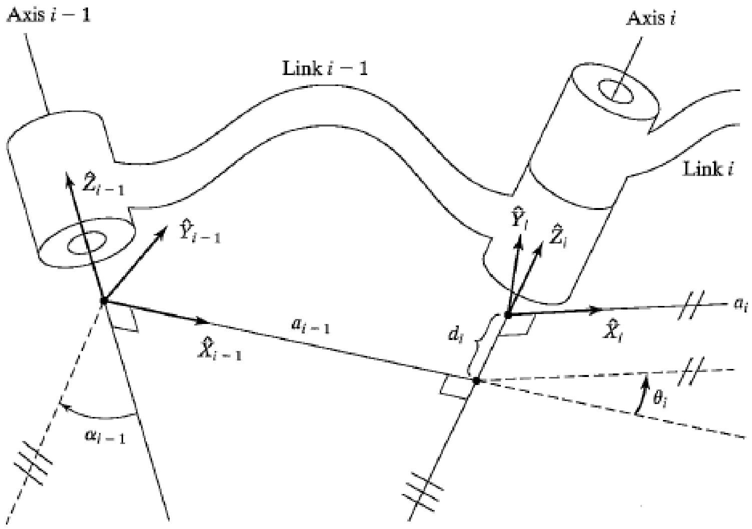
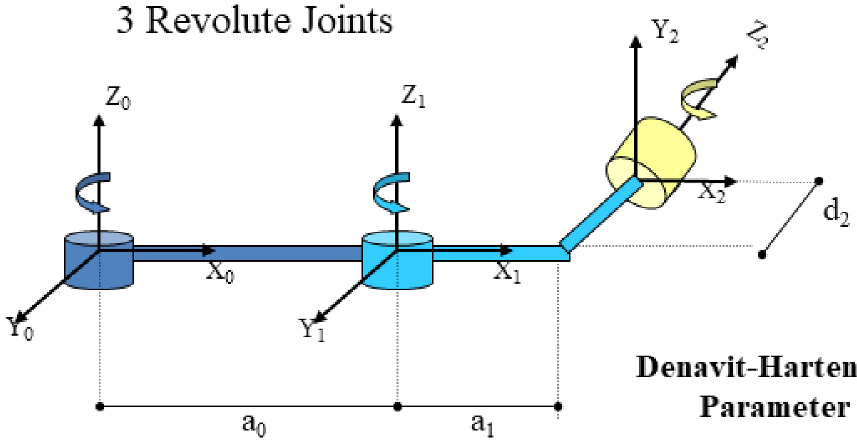




i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	90°	0	d_2	0
3	0	0	L_2	θ_3





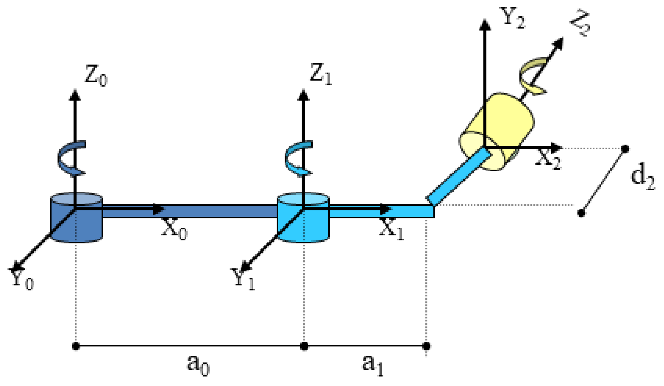
Denavit-Hartenberg Link Parameter Table

i	$\alpha_{(i-1)}$	$a_{(i-1)}$	d_i	θ_i
0	0	0	0	θ_0
1	0	a_0	0	θ_1
2	-90	a_1	d_2	θ_2

Notice that the table has two uses:

1) To describe the robot with its variables and parameters.

2) To describe some state of the robot by having a numerical values for the variables.



i	$\alpha_{(i-1)}$	$a_{(i-1)}$	d_i	θ_i
0	0	0	0	θ_0
1	0	a_0	0	θ_1
2	-90	a_1	d_2	θ_2

$$V^{X_0Y_0Z_0} = T\begin{bmatrix} V^{X_2} \\ V^{Y_2} \\ V^{Z_2} \\ 1 \end{bmatrix}$$

$$T = ({}_0T)({}^0_1T)({}^1_2T)$$

Note: T is the D-H matrix with *(i-1)* = 0 and *i* = 1.

i	$\alpha_{(i-1)}$	$a_{(i-1)}$	d_i	θ_i
0	0	0	0	θ_0
1	0	a_0	0	θ_1
2	-90	a_1	d_2	θ_2

$$ {}_0T = \begin{bmatrix} \cos\theta_0 & -\sin\theta_0 & 0 & 0 \\ \sin\theta_0 & \cos\theta_0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

This is just a rotation around the Z_0 axis

$$ {}^0_1T = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & a_0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

This is a translation by a_0 followed by a rotation around the Z_1 axis

$$ {}^1_2T = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & a_1 \\ 0 & 0 & 1 & d_2 \\ -\sin\theta_2 & -\cos\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

This is a translation by a_1 and then d_2 followed by a rotation around the X_2 and Z_2 axis

$$T = ({}_0T)({}^0_1T)({}^1_2T)$$

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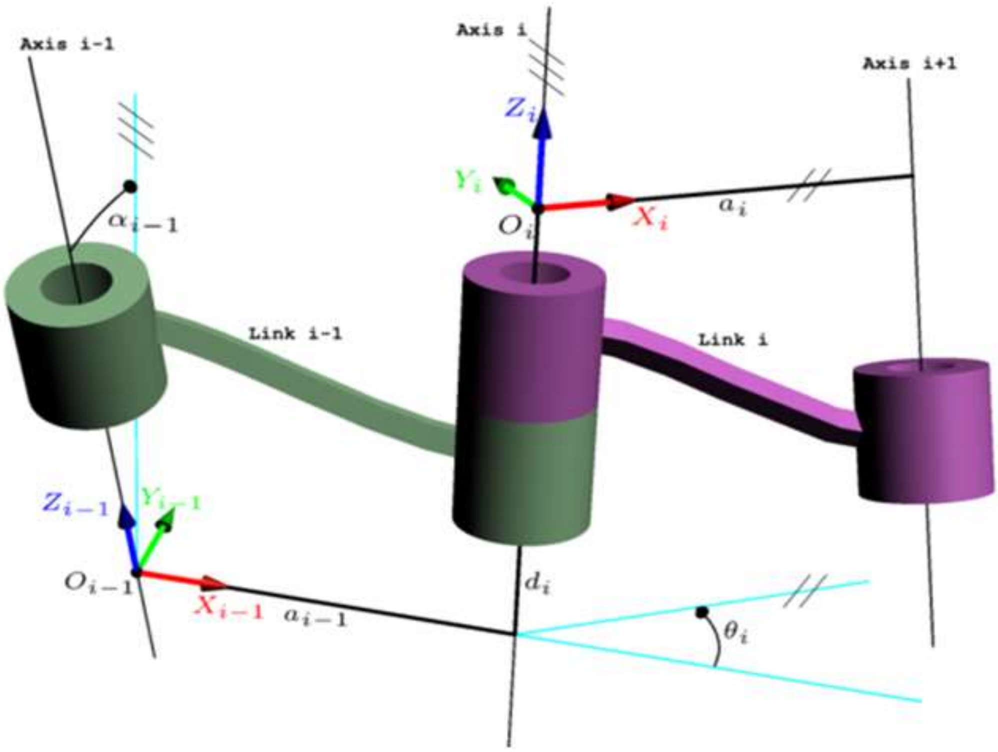
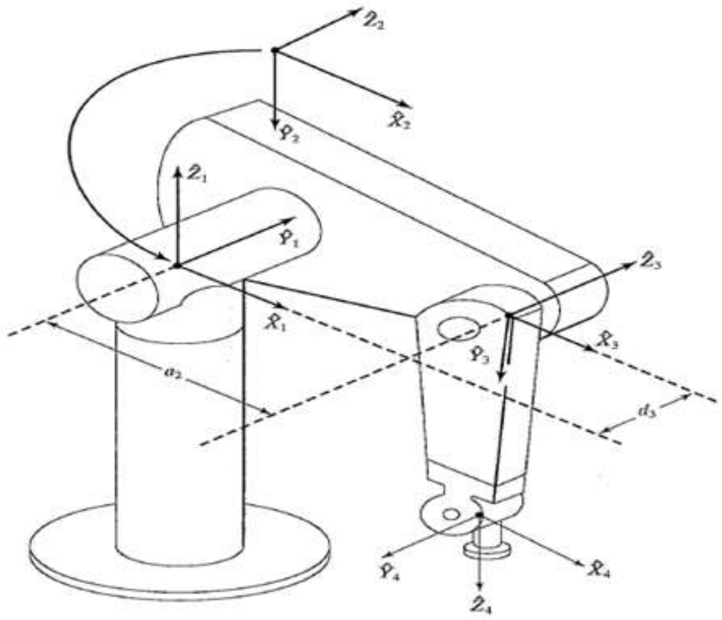


The PUMA 560

The Unimation PUMA 560 is a robot with six degrees of freedom and all rotational joints (i.e., it is a 6R mechanism). It is shown in figure below

link-frame assignments in the position corresponding to all joint angles equal to zero.



- Note that the frame {0} (not shown) is coincident with frame [1} when is zero.
- Note also that, for this robot, as for many industrial robots, the joint axes of joints 4, 5, and 6 all intersect at a common point, and this point of intersection coincides with the origin of frames {4}, {5}, and {6}.
- Furthermore, the joint axes 4, 5, and 6 are mutually orthogonal. This wrist mechanism is illustrated schematically in Fig. in next slide

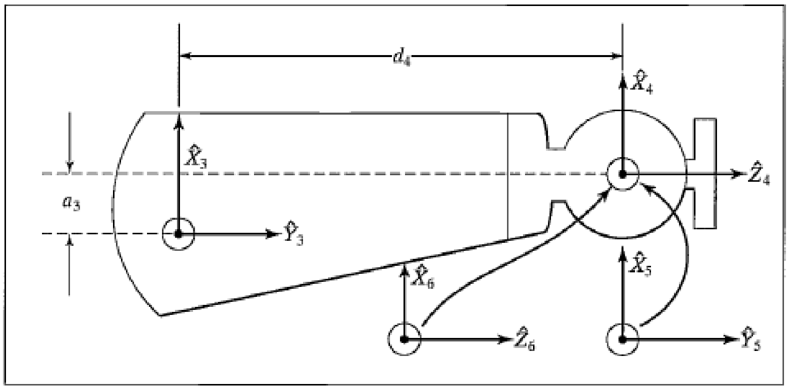
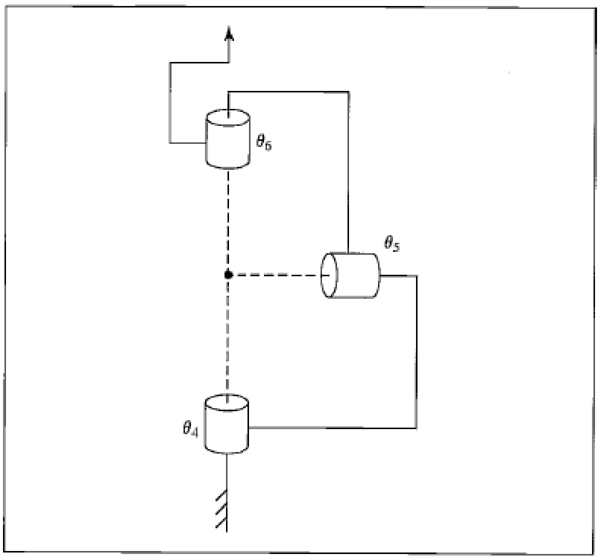
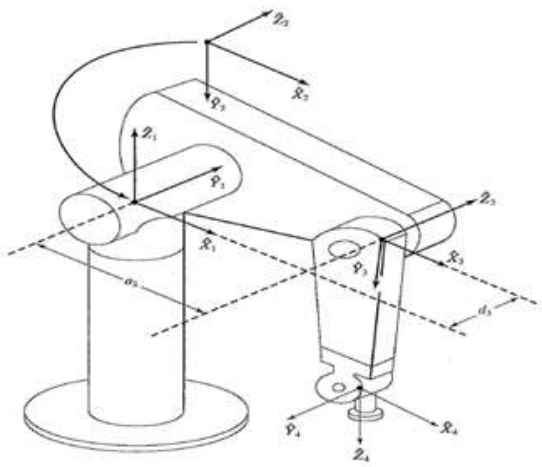


Figure shows a detail of the forearm of the robot.



Schematic of a 3R wrist in which all three axes intersect at a point and are mutually orthogonal. This design is used in the PUMA 560 manipulator and many other industrial robots.

- The link parameters corresponding to this placement of link frames are shown in Fig .
- In the case of the PUMA 560, a gearing arrangement in the wrist of the manipulator couples together the motions of joints 4, 5, and 6.
- What this means is that, for these three joints, we must make a distinction between joint space and actuator space and solve the complete kinematics in two steps.
- However, in this example, we will consider only the kinematics from joint space to Cartesian space.



i	$\alpha_i - 1$	$a_i - 1$	d_i	θi
1	0	0	0	θ_1
2	$-90°$	0	0	θ_2
3	0	a_2	d_3	θ_3
4	$-90°$	a_3	d_4	θ_4
5	90°	0	0	θ_5
6	$-90°$	0	0	θ_6

Link parameters of the PUMA 560.

$$ {}^{0}_{1}T = \begin{bmatrix} c\theta_1 & -s\theta_1 & 0 & 0 \\ s\theta_1 & c\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, $$

$$ {}^{1}_{2}T = \begin{bmatrix} c\theta_2 & -s\theta_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s\theta_2 & -c\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, $$

$$ {}^{2}_{3}T = \begin{bmatrix} c\theta_3 & -s\theta_3 & 0 & a_2 \\ s\theta_3 & c\theta_3 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}, $$

$$ {}^{3}_{4}T = \begin{bmatrix} c\theta_4 & -s\theta_4 & 0 & a_3 \\ 0 & 0 & 1 & d_4 \\ -s\theta_4 & -c\theta_4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, $$

$$ {}^{4}_{5}T = \begin{bmatrix} c\theta_5 & -s\theta_5 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ s\theta_5 & c\theta_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, $$

$$ {}^{5}_{6}T = \begin{bmatrix} c\theta_6 & -s\theta_6 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s\theta_6 & -c\theta_6 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. $$

We now form by matrix multiplication of the individual link matrices. While forming this product, we will derive some sub results that will be useful when solving the inverse kinematic problem. We start by multiplying and that is,

$$ {}^4_6T = {}^4_5T\,{}^5_6T = \begin{bmatrix} c_5c_6 & -c_5s_6 & -s_5 & 0 \\ s_6 & c_6 & 0 & 0 \\ s_5c_6 & -s_5s_6 & c_5 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

where c_5 is shorthand for $\cos\theta_5$, s_5 for $\sin\theta_5$ and so on.

$$ {}^3_6T = {}^3_4T\,{}^4_6T = \begin{bmatrix} c_4c_5c_6 - s_4s_6 & -c_4c_5s_6 - s_4c_6 & -c_4s_5 & a_3 \\ s_5c_6 & -s_5s_6 & c_5 & d_4 \\ -s_4c_5c_6 - c_4s_6 & s_4c_5s_6 - c_4c_6 & s_4s_5 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. $$

Because joints 2 and 3 are always parallel, multiplying and first and then applying sum-of-angle formulas will yield a somewhat simpler final expression. This can be done whenever two rotational joints have parallel axes and we have

$$ {}^1_3T = {}^1_2T\,{}^2_3T = \begin{bmatrix} c_{23} & -s_{23} & 0 & a_2c_2 \\ 0 & 0 & 1 & d_3 \\ -s_{23} & -c_{23} & 0 & -a_2s_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}, $$

Here we have used sum formulae

$$ c_{23} = c_2c_3 - s_2s_3, $$
$$ s_{23} = c_2s_3 + s_2c_3. $$

$$ {}^{1}_{6}T = {}^{1}_{3}T \, {}^{3}_{6}T = \begin{bmatrix} {}^{1}r_{11} & {}^{1}r_{12} & {}^{1}r_{13} & {}^{1}p_x \\ {}^{1}r_{21} & {}^{1}r_{22} & {}^{1}r_{23} & {}^{1}p_y \\ {}^{1}r_{31} & {}^{1}r_{32} & {}^{1}r_{33} & {}^{1}p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}, $$

$$
\begin{aligned}
{}^{1}r_{11} &= c_{23}[c_4c_5c_6 - s_4s_6] - s_{23}s_5s_6, \\
{}^{1}r_{21} &= -s_4c_5c_6 - c_4s_6, \\
{}^{1}r_{31} &= -s_{23}[c_4c_5c_6 - s_4s_6] - c_{23}s_5c_6, \\
{}^{1}r_{12} &= -c_{23}[c_4c_5s_6 + s_4c_6] + s_{23}s_5s_6, \\
{}^{1}r_{22} &= s_4c_5s_6 - c_4c_6, \\
{}^{1}r_{32} &= s_{23}[c_4c_5s_6 + s_4c_6] + c_{23}s_5s_6, \\
{}^{1}r_{13} &= -c_{23}c_4s_5 - s_{23}c_5, \\
{}^{1}r_{23} &= s_4s_5, \\
{}^{1}r_{33} &= s_{23}c_4s_5 - c_{23}c_5, \\
{}^{1}p_x &= a_2c_2 + a_3c_{23} - d_4s_{23}, \\
{}^{1}p_y &= d_3, \\
{}^{1}p_x &= -a_3s_{23} - a_2s_2 - d_4c_{23}.
\end{aligned}
$$

Finally, we obtain the product of all six link transforms:

$$ {}^{0}_{6}T = {}^{0}_{1}T \, {}^{1}_{6}T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}. $$

$$r_{11} = c_1[c_{23}(c_4c_5c_6 - s_4s_5) - s_{23}s_5c_5] + s_1(s_4c_5c_6 + c_4s_6),$$
$$r_{21} = s_1[c_{23}(c_4c_5c_6 - s_4s_6) - s_{23}s_5c_6 - c_1(s_4c_5c_6 + c_4s_6),$$
$$r_{31} = -s_{23}(c_4c_5c_6 - s_4s_6) - c_{23}s_5c_6,$$

$$r_{12} = c_1[c_{23}(-c_4c_5s_6 - s_4c_6) + s_{23}s_5s_6] + s_1(c_4c_6 - s_4c_5s_6),$$
$$r_{22} = s_1[c_{23}(-c_4c_5s_6 - s_4c_6) + s_{23}s_5s_6] - c_1(c_4c_6 - s_4c_5s_6),$$
$$r_{32} = -s_{23}(-c_4c_5s_6 - s_4c_6) + c_{23}s_5s_6,$$

$$r_{13} = -c_1(c_{23}c_4s_5 + s_{23}c_5) - s_1s_4s_5,$$
$$r_{23} = -s_1(c_{23}c_4s_5 + s_{23}c_5) + c_1s_4s_5, \qquad \text{-----(A)}$$
$$r_{33} = s_{23}c_4s_5 - c_{23}c_5,$$

$$p_x = c_1[a_2c_2 + a_3c_{23} - d_4s_{23}] - d_3s_1,$$
$$p_y = s_1[a_2c_2 + a_3c_{23} - d_4s_{23}] + d_3c_1,$$
$$p_z = -a_3s_{23} - a_2s_2 - d_4c_{23}.$$

Equations A constitute the kinematics of the PUMA 560. They specify how to compute the position and orientation of frame {6} relative to frame {O} of the robot. These are the basic equations for all kinematic analysis of this manipulator.

Inverse Kinematics

From Position to Angles

Inverse Kinematics

- In the last section, we considered the problem of computing the position and orientation of the tool relative to the user's workstation when given the joint angles of the manipulator. In this section we investigate the more difficult converse problem:
- Given the desired position and orientation of the tool relative to the station, how do we compute the set of joint angles which will achieve this desired result?
- Solving the problem of finding the required joint angles to place the tool frame, {T}, relative to the station frame, {S}, is split into two parts. First, frame transformations are performed to find the wrist frame, {W}, relative to the base frame, {B}, and then the inverse kinematics are used to solve for the joint angles.

Inverse Kinematics

THE INVERSE KINEMATIC SOLUTION OF ROBOT

- Determine the value of each joint to place the arm at a desired position and orientation.

$${}^{R}T_H = A_1 A_2 A_3 A_4 A_5 A_6$$

$$= \begin{bmatrix} C_1(C_{234}C_5C_6 - S_{234}S_6) - S_1S_5C_6 & C_1(-C_{234}C_5C_6 - S_{234}C_6) + S_1S_5C_6 & C_1(C_{234}S_5) + S_1C_5 & C_1(C_{234}a_4 + C_{23}a_3 + C_2a_2) \\ S_1(C_{234}C_5C_6 - S_{234}S_6) + C_1S_5C_6 & S_1(-C_{234}C_5C_6 - S_{234}C_6) - C_1S_5C_6 & S_1(C_{234}S_5) - C_1C_5 & S_1(C_{234}a_4 + C_{23}a_3 + C_2a_2) \\ S_{234}C_5C_6 + C_{234}S_6 & -S_{234}C_5C_6 + C_{234}C_6 & S_{234}S_5 & S_{234}a_4 + S_{23}a_3 + S_2a_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

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Inverse Kinematics

THE INVERSE KINEMATIC SOLUTION OF ROBOT

$$A_1^{-1} \times \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = A_1^{-1}[RHS] = A_2A_3A_4A_5A_6$$

$$\begin{bmatrix} C_1 & S_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ S_1 & -C_1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = A_2A_3A_4A_5A_6$$

Inverse Kinematics

THE INVERSE KINEMATIC SOLUTION OF ROBOT

$$\theta_1 = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

$$\theta_2 = \tan^{-1}\frac{(C_3a_3 + a_2)(p_z - S_{234}a_4) - S_3a_3(p_xC_1 + p_yS_1 - C_{234}a_4)}{(C_3a_3 + a_2)(p_xC_1 + p_yS_1 - C_{234}a_4) + S_3a_3(P_z - S_{234}a_4)}$$

$$\theta_3 = \tan^{-1}\left(\frac{S_3}{C_3}\right)$$

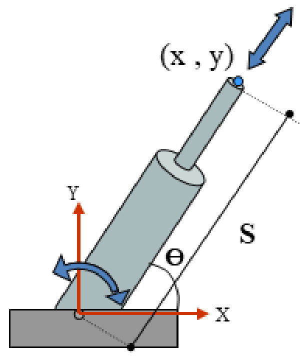
$$\theta_4 = \theta_{234} - \theta_2 - \theta_3$$

$$\theta_5 = \tan^{-1}\frac{C_{234}(C_1a_x + S_1a_y) + S_{234}a_z}{S_1a_x - C_1a_y}$$

$$\theta_6 = \tan^{-1}\frac{-S_{234}(C_1n_x + S_1n_y) + S_{234}n_z}{-S_{234}(C_1o_x + S_1o_y) + C_{234}o_z}$$

A Simple Example

Revolute and Prismatic Joints Combined



Finding Θ:

$$\theta = \arctan\left(\frac{y}{x}\right)$$

More Specifically:

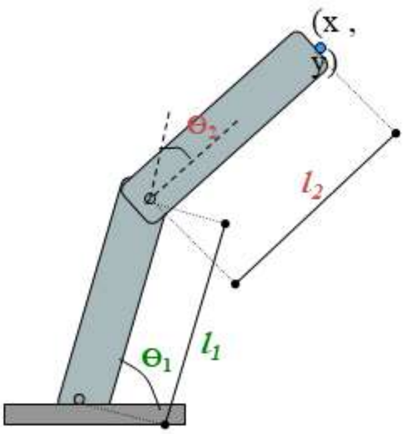
$$\theta = \arctan 2\left(\frac{y}{x}\right)$$

arctan2() specifies that it's in the first quadrant

Finding S:

$$S = \sqrt{(x^2 + y^2)}$$

Inverse Kinematics of a Two Link Manipulator

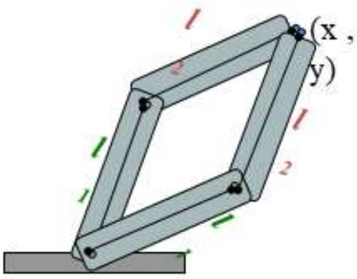


Given: l_1, l_2, x, y

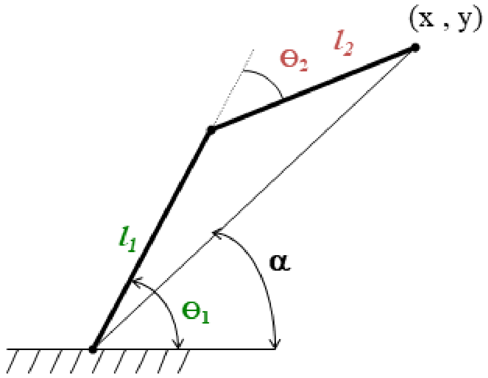
Find: Θ_1, Θ_2

Redundancy:

A unique solution to this problem does not exist. Notice, that using the "givens" two solutions are possible. Sometimes no solution is possible.



The Geometric Solution



Using the Law of Cosines:

$$c^2 = a^2 + b^2 - 2ab\cos C$$

$$(x^2 + y^2) = l_1^2 + l_2^2 - 2l_1l_2\cos(180 - \theta_2)$$

$$\cos(180 - \theta_2) = -\cos(\theta_2)$$

$$\cos(\theta_2) = \frac{x^2 + y^2 - l_1^2 - l_2^2}{2l_1l_2}$$

$$\theta_2 = \arccos\left(\frac{x^2 + y^2 - l_1^2 - l_2^2}{2l_1l_2}\right)$$

Redundant since θ_2 could be in the first or fourth quadrant.

Using the Law of Cosines:

$$\frac{\sin B}{b} = \frac{\sin C}{c}$$

$$\frac{\sin\bar{\theta}_1}{l_2} = \frac{\sin(180 - \theta_2)}{\sqrt{x^2 + y^2}} = \frac{\sin(\theta_2)}{\sqrt{x^2 + y^2}}$$

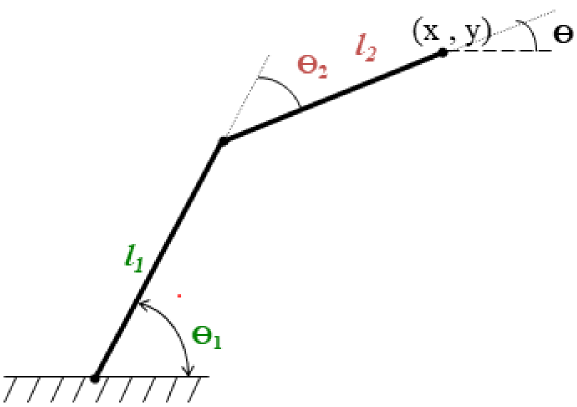
$$\theta_1 = \bar{\theta}_1 + \alpha$$

$$\alpha = \arctan 2\left(\frac{y}{x}\right)$$

Redundancy caused since θ_2 has two possible values

$$\theta_1 = \arcsin\left(\frac{l_2\sin(\theta_2)}{\sqrt{x^2 + y^2}}\right) + \arctan 2\left(\frac{y}{x}\right)$$

The Algebraic Solution



$$c_1 = \cos\theta_1$$

$$c_{1+2} = \cos(\theta_2 + \theta_1)$$

$$(1)\quad x = l_1 c_1 + l_2 c_{1+2}$$

$$(2)\quad y = l_1 s_1 + l_2 \sin_{1+2}$$

$$(3)\quad \theta = \theta_1 + \theta_2$$

$$(1)^2 + (2)^2 = x^2 + y^2 =$$

$$= \left(l_1^2 c_1^2 + l_2^2 (c_{1+2})^2 + 2l_1l_2 c_1(c_{1+2})\right) + \left(l_1^2 s_1^2 + l_2^2(\sin_{1+2})^2 + 2l_1l_2 s_1(\sin_{1+2})\right)$$

$$= l_1^2 + l_2^2 + 2l_1l_2\left(c_1(c_{1+2}) + s_1(\sin_{1+2})\right)$$

$$= l_1^2 + l_2^2 + 2l_1l_2 c_2 \leftarrow \text{Only Unknown}$$

$$\therefore \theta_2 = \arccos\left(\frac{x^2 + y^2 - l_1^2 - l_2^2}{2l_1l_2}\right)$$

Note:

$$\cos(a \pm b) = (\cos a)(\cos b) \mp (\sin a)(\sin b)$$

$$\sin(a \pm b) = (\cos a)(\sin b) \pm (\cos b)(\sin a)$$

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$$x = l_1 c_1 + l_2 c_{1+2}$$
$$= l_1 c_1 + l_2 c_1 c_2 - l_2 s_1 s_2$$
$$= c_1 (l_1 + l_2 c_2) - s_1 (l_2 s_2)$$

Note:

$$\cos(a \pm b) = (\cos a)(\cos b) \mp (\sin a)(\sin b)$$
$$\sin(a \pm b) = (\cos a)(\sin b) \pm (\cos b)(\sin a)$$

$$y = l_1 s_1 + l_2 \sin_{1+2}$$
$$= l_1 s_1 + l_2 s_1 c_2 + l_2 s_2 c_1$$
$$= c_1 (l_2 s_2) + s_1 (l_1 + l_2 c_2)$$

We know what θ_2 is from the previous slide. We need to solve for θ_1 . Now we have two equations and two unknowns (sin θ_1 and cos θ_1)

$$c_1 = \frac{x + s_1 (l_2 s_2)}{(l_1 + l_2 c_2)}$$

$$y = \frac{x + s_1 (l_2 s_2)}{(l_1 + l_2 c_2)} (l_2 s_2) + s_1 (l_1 + l_2 c_2)$$

Substituting for c_1 and simplifying many times

$$= \frac{1}{(l_1 + l_2 c_2)} \left(x\, l_2 s_2 + s_1 (l_1^2 + l_2^2 + 2 l_1 l_2 c_2) \right)$$

Notice this is the law of cosines and can be replaced by $x^2 + y^2$

$$s_1 = \frac{y(l_1 + l_2 c_2) - x\, l_2 s_2}{x^2 + y^2} \qquad \theta_1 = \arcsin\left(\frac{y(l_1 + l_2 c_2) - x\, l_2 s_2}{x^2 + y^2} \right)$$

Question Paper discussion

1. What is difference between forward and inverse kinematics – July 2019- 2 Marks
2. how an transformation matrices are represented for a pure rotation axis –July 2019- 2 marks
3. What is inverse kinematics of a robot- 2 Marks- March 2020
4. What is forward kinematics of a robot- 2 Marks- March 2019
5. Explain with sketches the Denavit- Hartenberg representation to describe the relationship between the adjacent link of a robot- march-2019- 6 marks
6. Prepare a D-H parameter table for a simple 2- axis articulated robot- March-2019-8 marks
7. A point $P(7,3,2)^T$ is attached to a frame (n, o, a) and is subjected to the transformation described next. Find the co-ordinates of the point relative to the reference frame at the conclusion of transformation.- July -2019- 7marks

a. Rotation of 90 degree about Z- axis.
b. Followed by a rotation of 90 degree about y- axis
c. Followed by a translation of [4, -3, 7]

8.Discuss inverse kinematics along with its characteristics. July 2019- 7 Marks

Question Paper discussion

9. Find the effect of a differential rotation of 0.1 rad about the y-axis- followed by a differential translation of [0.1, 0, 0.2] on the given frame B.- 2 Marks [0 1 1 10 ; 1 0 0 5; 0 1 0 3; 0 0 0 1]

10. What is homogenous transformation of coordinates- 2marks
11. Define direct dynamics – 2marks
12. Derive the expression for joint torque for single n link planer robotic manipulator having rotary joint using Newton-Euler dynamics formulation- 10 marks
13. State the Lagrange-Euler equation. Describe all the terms in detail.- 4 marks

Q. What is difference between forward and inverse kinematics – July 2019- 2 Marks

Ans. **Forward Kinematics**: Used to determine where the robot's hand is? (If all joint variables are known) In forward kinematics the problem of computing the position and orientation of the tool relative to the user's workstation when given the joint angles of the manipulator.

- **Inverse Kinematics**: To calculate what each joint variable is? (If we desire that the hand be located at a particular point). Given the desired position an d orientation of the tool relative to the station, how do we compute the set of joint angles which will achieve this desired result?

Q. how an transformation matrices are represented for a pure rotation axis –July 2019- 2 marks

Ans. The rotation matrix for pure rotation are presented by following matrices

the rotation matrices about Z-axis:

$$ {}^{0}_{1}R = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{------------(5)} $$

the rotation matrices about X-axis:

$$ {}^{0}_{1}R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \quad \text{------------(6)} $$

the rotation matrices about Y-axis:

$$ {}^{0}_{1}R = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \quad \text{------------(7)} $$

Q. What is inverse kinematics of a robot- 2 Marks- March 2020

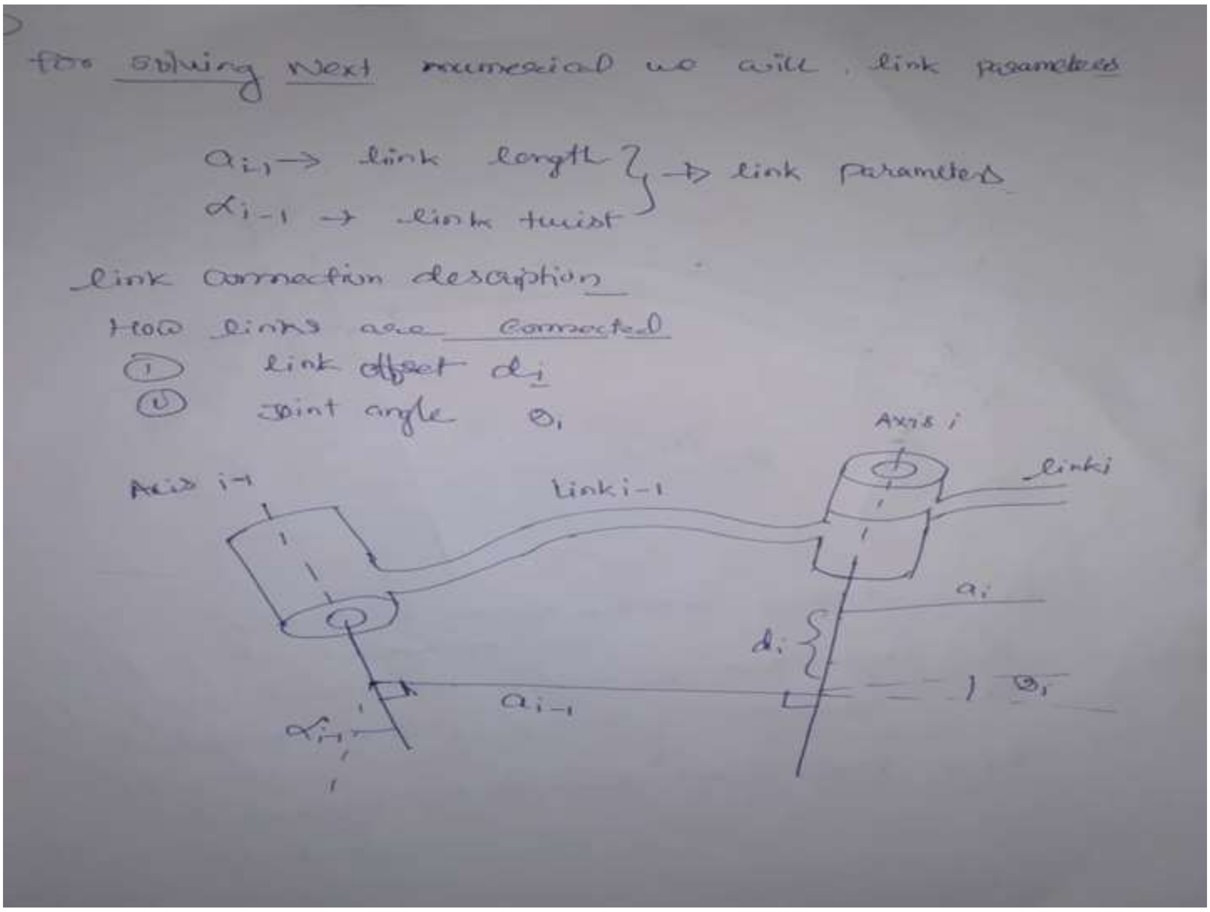
- **Inverse Kinematics**: To calculate what each joint variable is? (If we desire that the hand be located at a particular point). Given t he desired position and orientation of the tool relative to the stati on, how do we compute the set of joint angles which will achieve this desired result?

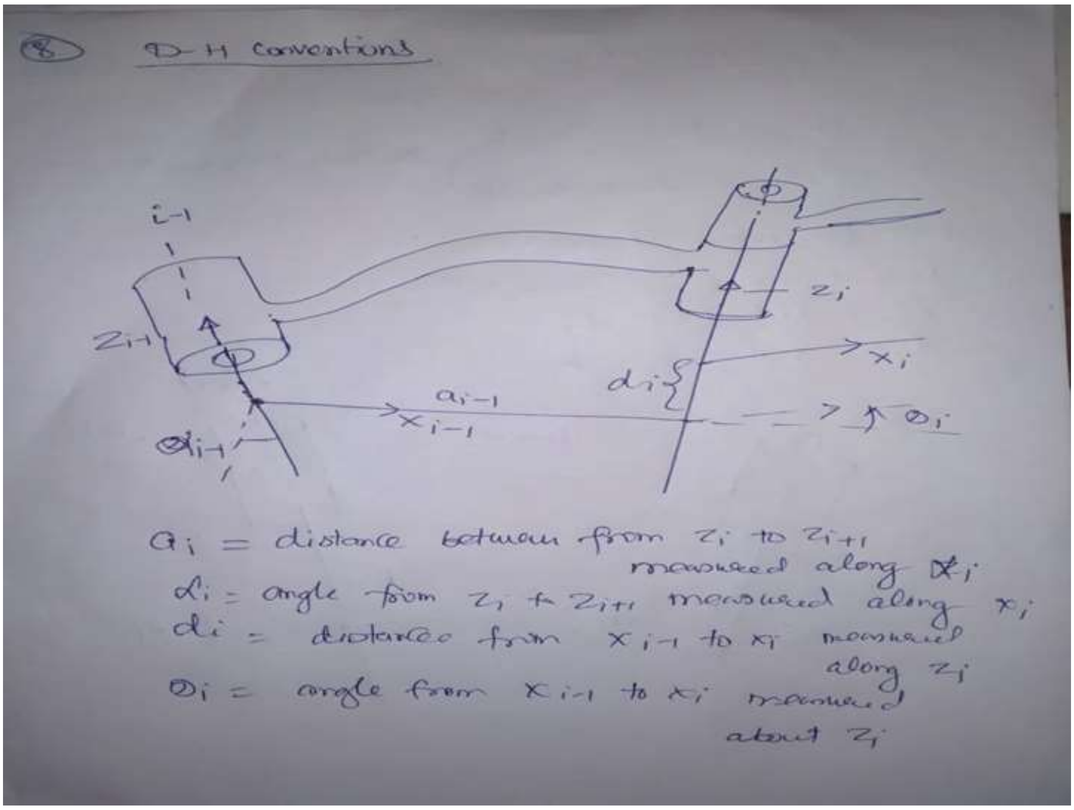
Q. What is forward kinematics of a robot- 2 Marks- March 2019

Forward Kinematics: Used to determine where the robot's hand is? (If all joint variables are known) In forward kinematics the problem of computing the position and orientation of the tool relative to the user's workstation when given the joint angles of the manipulator.

Q. Explain with sketches the Denavit- Hartenberg representation to describe the relationship between the adjacent link of a robot- march-2019- 6 marks

- Ans. any robot can be described kinematically by giving the values of four quantities for each link.
- Two describe the link itself, and two describe the link's connection to a neighboring link.
- The definition of mechanisms by means of these quantities is a convention usually called the Denavit—Hartenberg notation





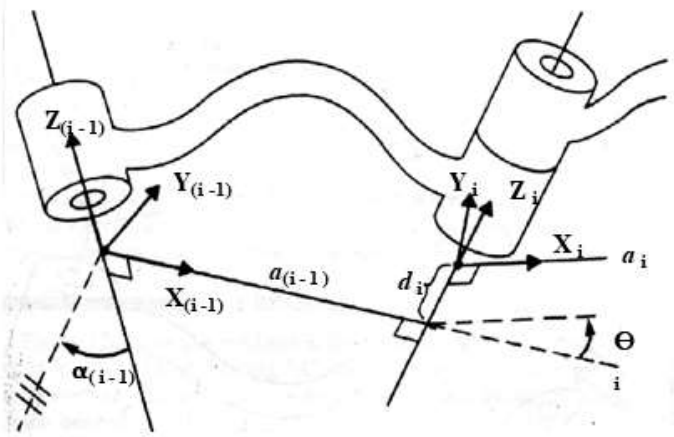
a_i = distance between from z_i to z_{i+1} measured along x_i

α_i = angle from z_i to z_{i+1} measured along x_i

d_i = distance from x_{i-1} to x_i measured along z_i

θ_i = angle from x_{i-1} to x_i measured about z_i

D-H Parameters



You can align the two axis just using the 4 parameters

1) $a_{(i-1)}$

Technical Definition: $a_{(i-1)}$ is the length of the perpendicular between the joint axes. The joint axes is the axes around which revolution takes place which are the $Z_{(i-1)}$ and $Z_{(i)}$ axes. These two axes can be viewed as lines in space. The common perpendicular is the shortest line between the two axis-lines and is perpendicular to both axis-lines.

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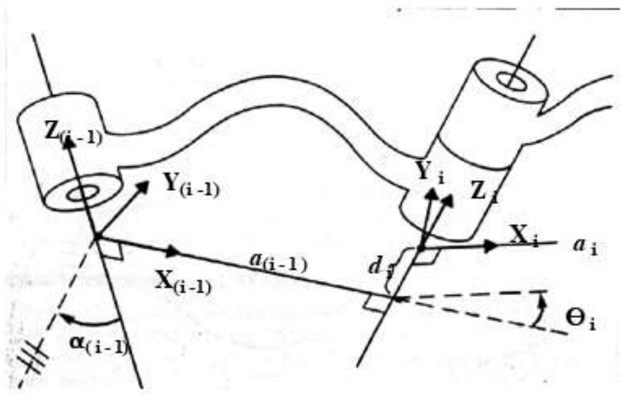
$a_{(i-1)}$ cont...

Visual Approach - "A way to visualize the link parameter $a_{(i-1)}$ is to imagine an expanding cylinder whose axis is the $Z_{(i-1)}$ axis - when the cylinder just touches the joint axis Z_i the radius of the cylinder is equal to $a_{(i-1)}$." (Manipulator Kinematics)

It's Usually on the Diagram Approach - If the diagram already specifies the various coordinate frames, then the common perpendicular is usually the $X_{(i-1)}$ axis. So $a_{(i-1)}$ is just the displacement along the $X_{(i-1)}$ to move from the *(i-1)* frame to the *i* frame.

If the link is prismatic, then $a_{(i-1)}$ is a variable, not a parameter.



2) $\alpha_{(i-1)}$

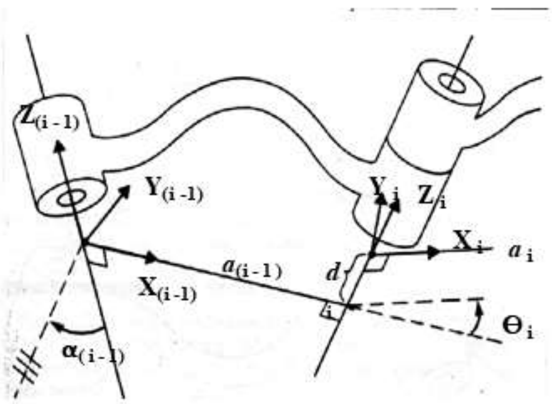
Technical Definition: Amount of rotation around the common perpendicular so that the joint axes are parallel.

i.e. How much you have to rotate around the $X_{(i-1)}$ axis so that the $Z_{(i-1)}$ is pointing in the same direction as the Z_i axis. Positive rotation follows the right hand rule.

3) $d_{(i-1)}$

Technical Definition: The displacement along the Z_i axis needed to align the $a_{(i-1)}$ common perpendicular to the a_i common perpendicular.

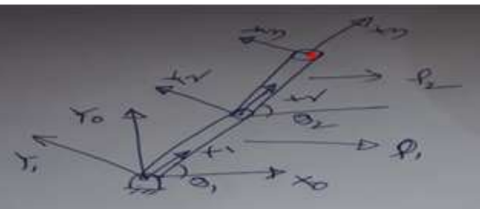
In other words, displacement along the Z_i to align the $X_{(i-1)}$ and X_i axes.



4) Θ_i

Amount of rotation around the Z_i axis needed to align the $X_{(i-1)}$ axis with the X_i axis.

Q. Prepare a D-H parameter table for a simple 2- axis articulated robot- March-2019-8 marks



D – H Table

We start by defining the reference frame, frame {0}. It is fixed to the base and aligns with {1}, when the first joint variable is zero

i → frame no
α_{i-1} → link twist
a_{i-1} → link length
d_i → link offset
θ_i → joint angle

D-H parameter Table →

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	0	l_1	0	θ_2
3	0	l_2	0	0

when i = 1 between frame {0} & frame {1}

α_{i-1} zero, because Z-axis of both frames are parallel.

a_{i-1} → both frames has same origin, so $a_{i-1} = 0$

d_i → link offset is zero because all x axis are in one plane

the mechanism / manipulator has one rotation

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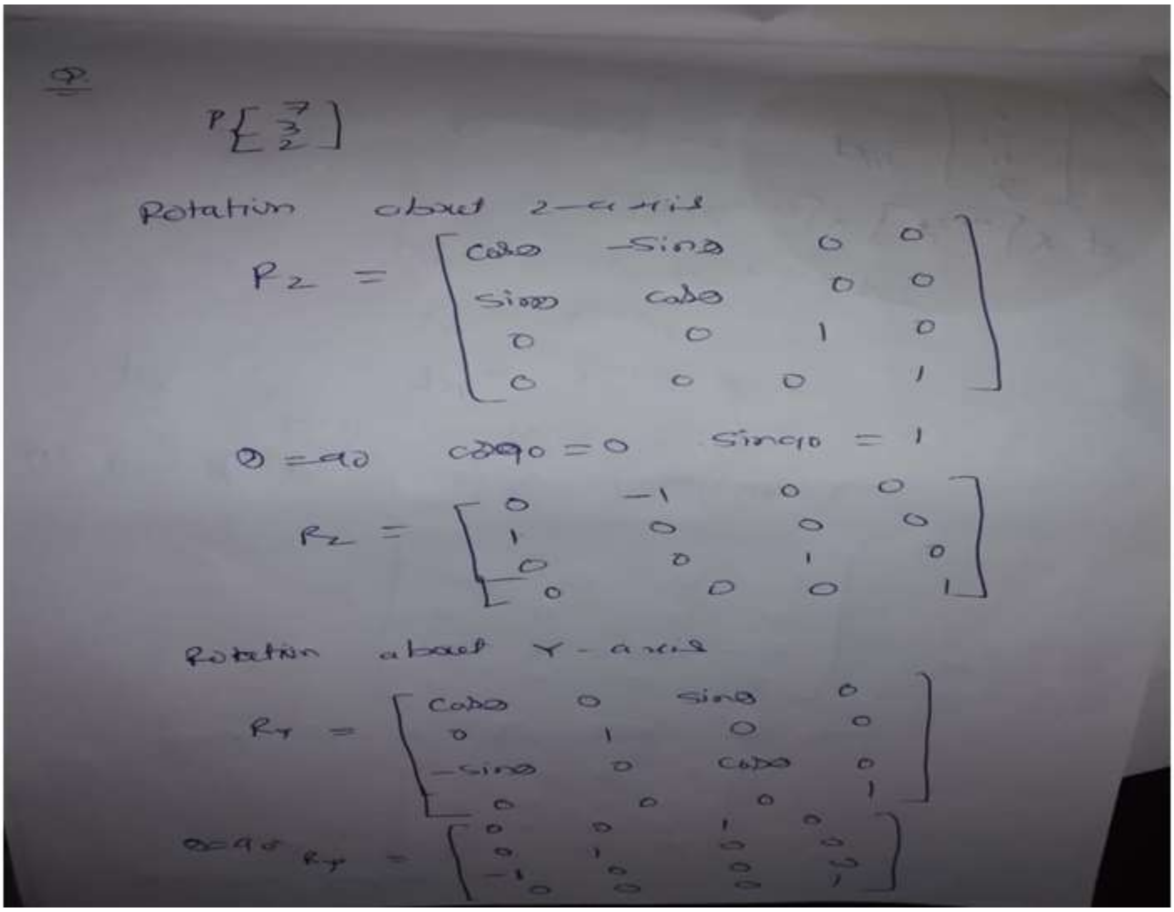
Q. A point $P(7,3,2)^T$ is attached to a frame (n, o, a) and is subjected to the transformation described next. Find the co-ordinates of the point relative to the reference frame at the conclusion of transformation.- July -2019- 7marks

- a. Rotation of 90 degree about Z- axis.
- b. Followed by a rotation of 90 degree about y- axis
- c. Followed by a translation of [4, -3, 7]



$P\begin{bmatrix}7\\3\\2\end{bmatrix}$

Rotation about z-axis

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

$\theta = 90$ $\cos 90 = 0$ $\sin 90 = 1$

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

Rotation about Y-axis

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

$\theta = 90$ $R_y = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

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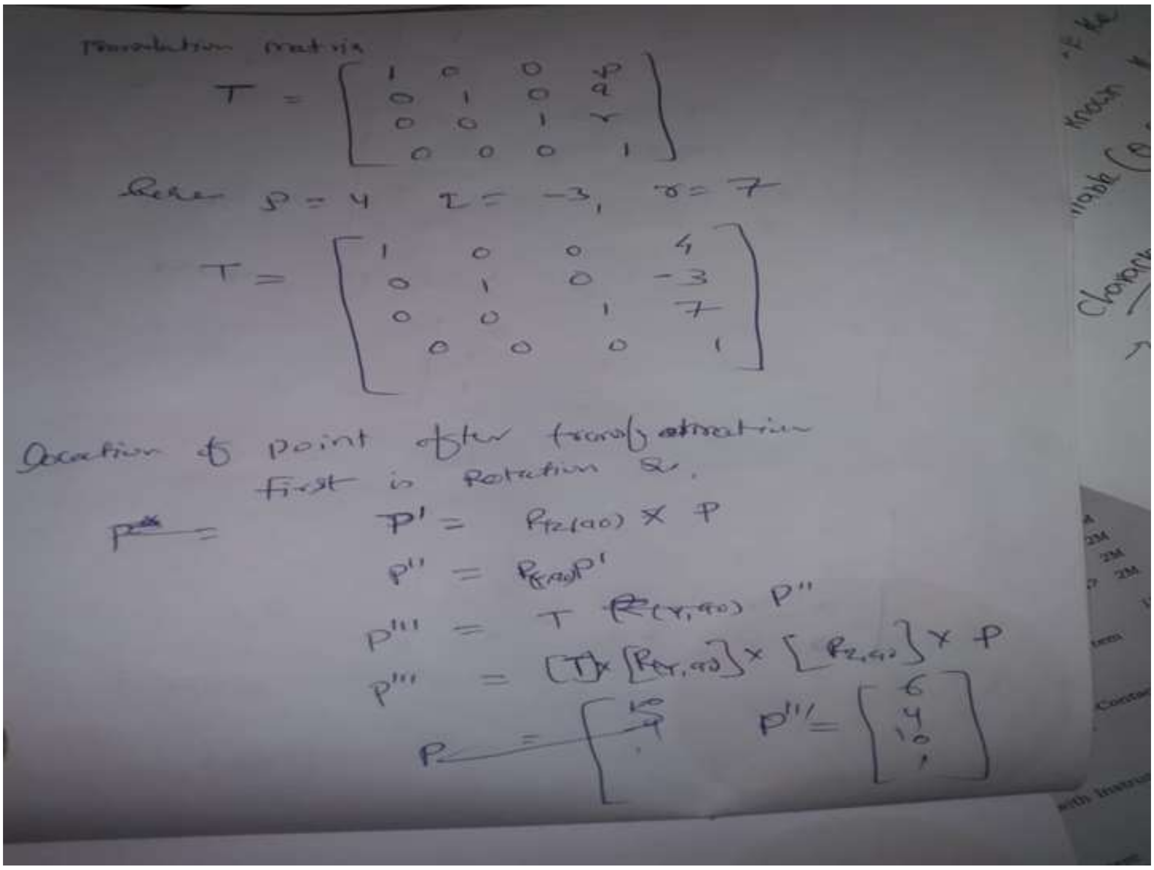


Translation matrix

$$T = \begin{bmatrix} 1 & 0 & 0 & p \\ 0 & 1 & 0 & q \\ 0 & 0 & 1 & r \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Here $p = 4$, $q = -3$, $r = 7$

$$T = \begin{bmatrix} 1 & 0 & 0 & 4 \\ 0 & 1 & 0 & -3 \\ 0 & 0 & 1 & 7 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Location of point after transformation
first is Rotation R,

$P' = R_{z(90)} \times P$

$P'' = R_{(y,90)} P'$

$P''' = T\, R_{(y,90)}\, P''$

$P''' = [T] \times [R_{(y,90)}] \times [R_{(z,90)}] \times P$

$P = [\text{illegible}]$ $\quad P''' = \begin{bmatrix} 6 \\ 4 \\ 10 \\ 1 \end{bmatrix}$

Discuss inverse kinematics along with its characteristics. July 2019- 7 Marks

Ans.

- **Inverse kinematics:** Given the desired position and orientation of the tool relative to the station, how do we compute the set of joint angles which will achieve this desired result?
- **Characteristics of Inverse Kinematics**

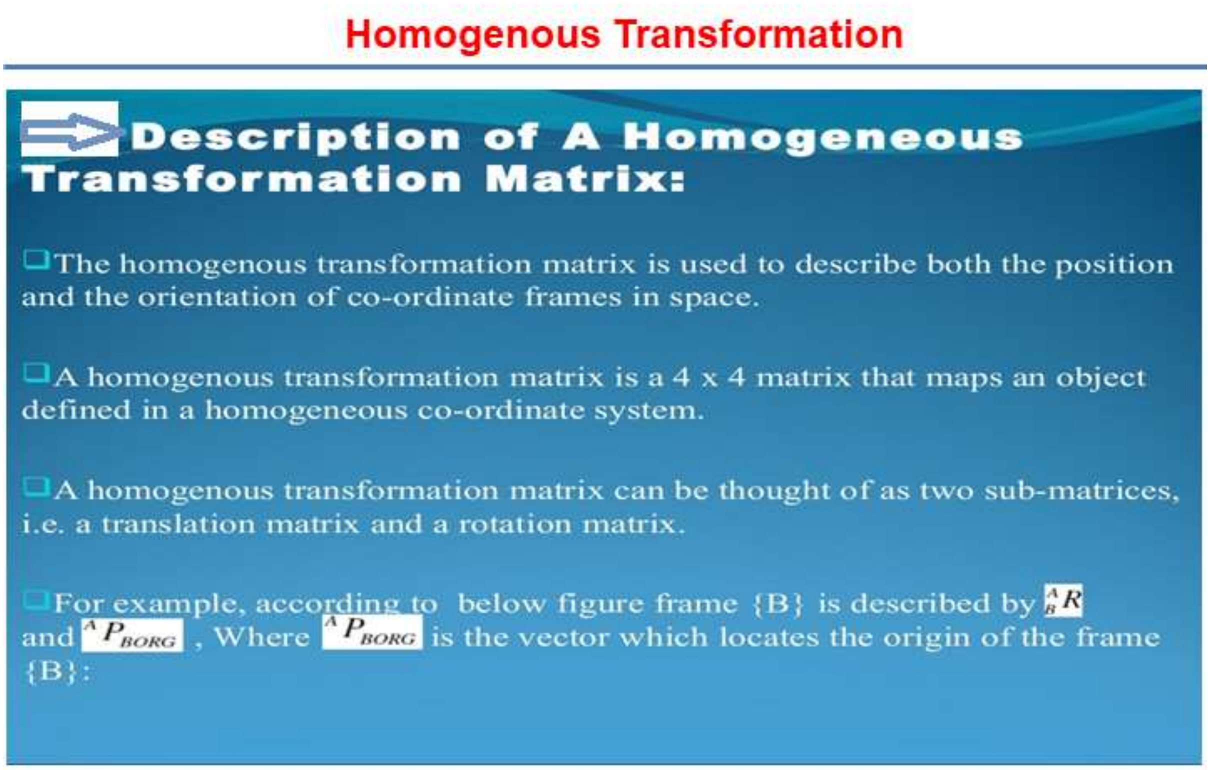
❑ Solving the problem of finding the required joint angles to place the tool frame, {T}, relative to the station frame, {S}, is split into two parts.

❑ First, frame transformations are performed to find the wrist frame, {W}, relative to the base frame, {B}, and then the inverse kinematics are used to solve for the joint angles.

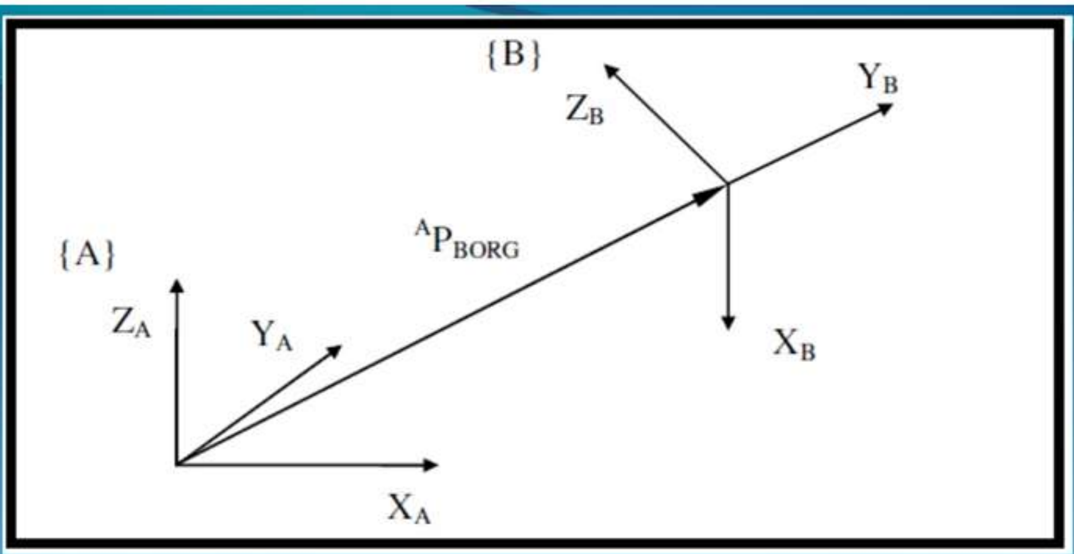
❑ The position and orientation of end effector is collectively called the configuration of robot.

Q. What is homogenous transformation of coordinates- 2marks

Ans. The *homogenous coordinate system*, which has some distinct advantages, is introduced to unify the two transformations namely translation and rotation



Homogenous Transformation



General transform of a vector

Homogenous Transformation

$$\{B\} = \{\, {}^{A}_{B}R,\ {}^{A}P_{BORG} \,\} \quad \text{------------------------(13)}$$

- The homogeneous transformation matrix for the example above can be written in the following form:

$$ {}^{A}_{B}T = \left[\begin{array}{ccc|c} & {}^{A}_{B}R & & {}^{A}P_{BORG} \\ \hline 0 & 0 & 0 & 1 \end{array}\right] \quad \text{---------------------(14)}$$

and in the general case, the homogeneous transformation matrix can be written as;

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Homogenous Transformation

$$T = \left[\begin{array}{ccc|c} & Rotation & & Translation \\ \hline 0 & 0 & 0 & 1 \end{array}\right] \quad \text{----------(15)}$$

- The last row in the homogeneous transformation matrix is in the field of computer graphics used for projection and scaling.
- But in robotics, the projection vector is always equal to [0 0 0] and the scaling factor is always [1].

Rigid body Transformation

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & p \\ 0 & 1 & 0 & q \\ 0 & 0 & 1 & r \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \mathbf{R}_z = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Homogeneous Transformation matrix H is equal to multiplication of translation and rotation matrix

H=RT

Q. Define direct dynamics – 2marks

- **Forward Kinematics**: Used to determine where the robot's hand is? (If all joint variables are known) In forward kinematics the problem of computing the position and orientation of the tool relative to the user's workstation when given the joint angles of the manipulator.

Q. Find the effect of a differential rotation of 0.1 rad about the y-axis- followed by a differential translation of [0.1, 0, 0.2] on the given frame B.- 2 Marks [0 1 1 10 ; 1 0 0 5; 0 1 0 3; 0 0 0 1]

- Ans. Differential transformation matrix is given by

$$\Delta = \begin{bmatrix} 0 & -\delta_z & \delta_y & d_x \\ \delta_z & 0 & -\delta_x & d_y \\ -\delta_y & \delta_x & 0 & d_z \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Sol: $\delta_z = 0 \quad \delta_y = 0.1 \quad \delta_z = 0$

$dx = 0.1 \quad dy = 0 \quad dz = 0.2$

$$\Delta = \begin{bmatrix} 0 & 0 & 0.1 & 0.1 \\ 0 & 0 & 0 & 0 \\ -0.1 & 0 & 0 & 0.2 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

orientation of B-frame

$$[\Delta][B] = \begin{bmatrix} 0 & 0 & 0.1 & 0.1 \\ 0 & 0 & 0 & 0 \\ -0.1 & 0 & 0 & 0.2 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 1 & 1 & 10 \\ 1 & 0 & 0 & 5 \\ 0 & 1 & 0 & 3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 0 & 0.1 & 0 & 0.4 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -0.1 & -0.8 \\ 0 & 0 & 0 & 0 \end{bmatrix} \text{Ans.}$$

Differential Transformation

<u>Differential transformation</u>

Differential forms of Homogeneous transformation can be used to examine pose velocities of frames.

often it is necessary to determine the effect of small displacements on kinematic. ~~transformations~~ transformations.

this can be useful in trajectory planning & path interpolation/extrapolation or in interfacing with sensor systems such as vision or tactile

$$\Delta = \begin{bmatrix} 0 & -\delta_z & \delta_y & d_x \\ \delta_z & 0 & -\delta_x & d_y \\ -\delta_y & \delta_x & 0 & d_z \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

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Introduction

- Robot arm dynamics deals with the mathematical formulations of the equations of robot arm motion.
- They are useful as:
  - An insight into the structure of the robot system.
  - A basis for model based control systems.
  - A basis for computer simulations.

Equations of Motion

The way in which the motion of the manipulator arises from torques applied by the actuators, or from external forces applied to the manipulator.

Forward and Inverse Dynamics

Given a trajectory point, $\Theta, \dot{\Theta}$, and $\ddot{\Theta}$, find the required vectors of joint torques, τ.

: problem of controlling the manipulator

Given a torque vector, τ, calculate the resulting motion of the manipulator, $\Theta, \dot{\Theta}$, and $\ddot{\Theta}$.

: problem of simulating the manipulator

Two Approaches

- Energy based: Lagrange-Euler.

Simple and symmetric.

- Momentum/force approach:Newton-Euler.

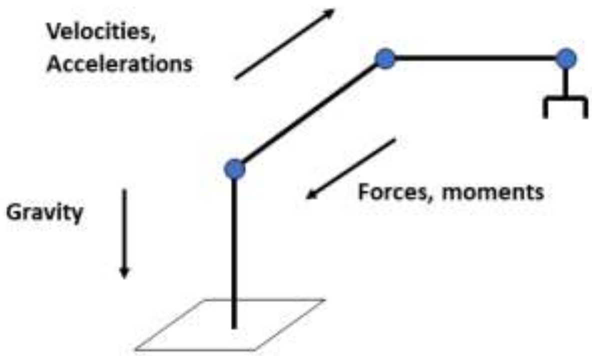
Efficient, derivation is simple but messy, involves vector cross product. Allow real time control.

Newton-Euler Algorithm

- Newton-Euler method is described briefly below. The goal is to provide a big picture understanding of these methods without getting lost in the details.

Newton-Euler Algorithm

- Newton-Euler formulations makes two passes over the links of manipulator



Newton-Euler Algorithm

- **Forward computation**
  - **First compute the angular velocity, angular acceleration, linear velocity, linear acceleration of each link in terms of its preceding link.**
  - **These values can be computed in recursive manner, starting from the first moving link and ending at the end-effector link.**
  - **The initial conditions for the base link will make the initial velocity and acceleration values to zero.**

- **Backward computation**
  - **Once the velocities and accelerations of the links are found, the joint forces can be computed one link at a time starting from the end-effector link and ending at the base link.**

Differentiation of position vectors

Derivative of a vector:

$$^{B}V_{Q} = \frac{d}{dt}\,^{B}Q = \lim_{\Delta t \to 0} \frac{^{B}Q(t+\Delta t) - ^{B}Q(t)}{\Delta t}$$

We are calculating the derivative of Q relative to frame B.

Differentiation of position vectors

A velocity vector may be described in terms of any frame:

$$^{A}\left(^{B}V_{Q}\right)=\frac{^{A}d}{dt}\,^{B}Q$$

We may write it:

$$^{A}\left(^{B}V_{Q}\right)={}^{A}_{B}R\,^{B}V_{Q}.$$

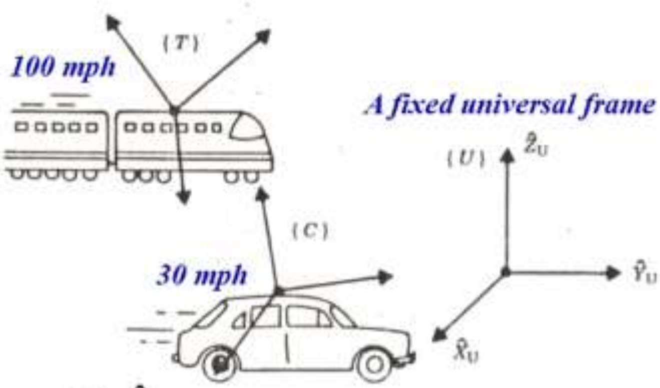
Speed vector is a free vector

Special case: Velocity of the origin of a frame relative to some understood universe reference frame

$$V_{C}={}^{U}V_{CORG}$$

Example

Both vehicles are speeding in X direction of U



$$\frac{^{U}d}{dt}\,^{U}P_{CORG}={}^{U}V_{CORG}=v_{C}=30\hat{X}.$$

$$^{C}(^{U}V_{TORG})={}^{C}v_{T}={}^{C}_{U}Rv_{T}={}^{C}_{U}R(100\hat{X})={}^{U}_{C}R^{-1}100\hat{X}.$$

$$^{C}(^{T}V_{CORG})={}^{C}_{T}R^{T}V_{CORG}={}^{C}_{U}R^{U}_{T}R^{T}V_{CORG}=-{}^{U}_{C}R^{-1U}{}_{T}R70\hat{X}.$$

Angular velocity vector: Ω

Linear velocity → attribute of a point

Angular velocity → attribute of a body

Since we always attach a frame to a body we can consider angular velocity as describing rational motion of a frame.

Angular velocity vector: Ω

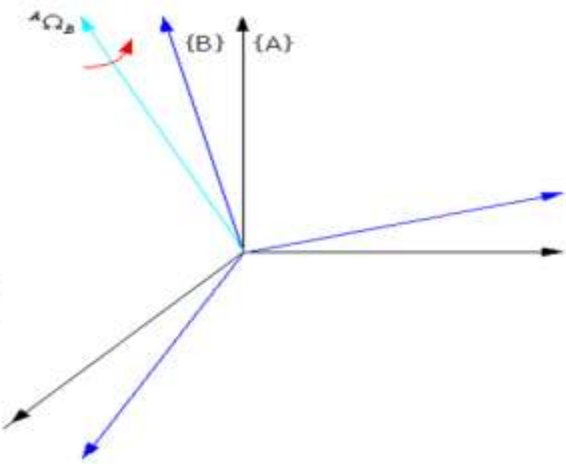
${}^{A}\Omega_{B}$ *describes the rotation of frame {B} relative to {A}*

direction of ${}^{A}\Omega_{B}$ *indicates instantaneous axis of rotation*

Magnitude of ${}^{A}\Omega_{B}$ *indicates speed of rotation*

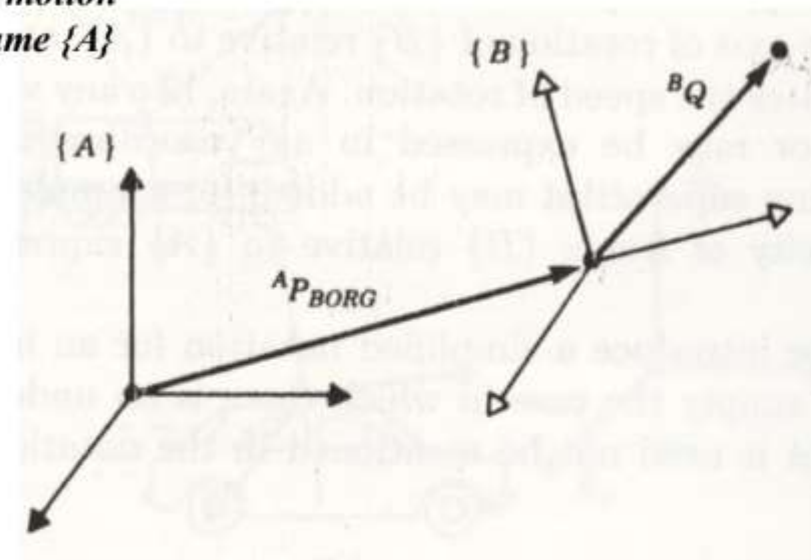
In the case which there is an understood reference frame:

$$\omega_C = {}^{U}\Omega_C$$



Linear velocity of a rigid body

We wish to describe motion of {B} relative to frame {A}



If rotation $^{A}_{B}R$ *is not changing with time:*

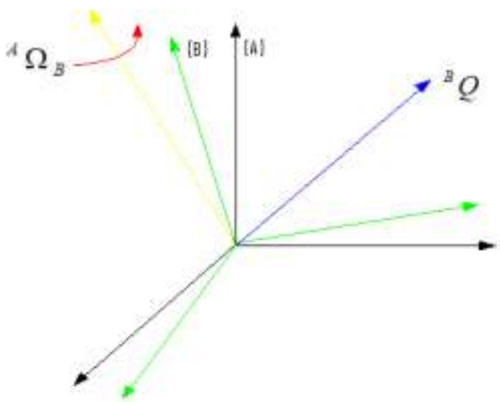
$$^{A}V_{Q} = {}^{A}V_{BORG} + {}^{A}_{B}R\,{}^{B}V_{Q}.$$

Rotational velocity of a rigid body

Two frames with coincident origins

The orientation of B with respect to A is changing in time.

Lets consider that vector Q is constant as viewed from B. $^{B}V_{Q} = 0$



Rotational velocity of a rigid body

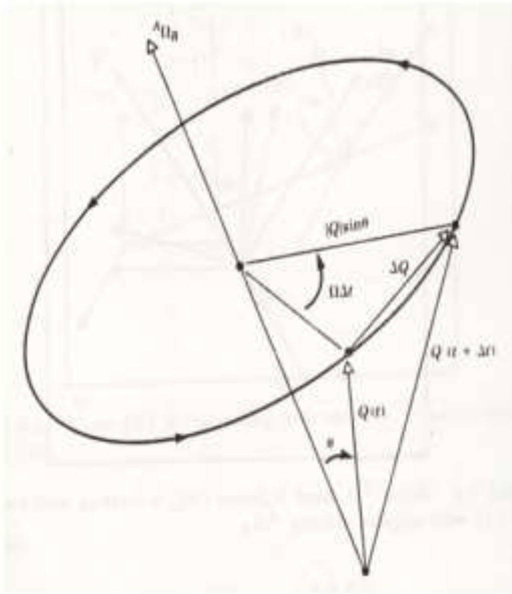
$|\Delta Q|$ Is perpendicular to and ${}^{A}\Omega_{B}$ ${}^{A}Q$

Magnitude of differential change is:

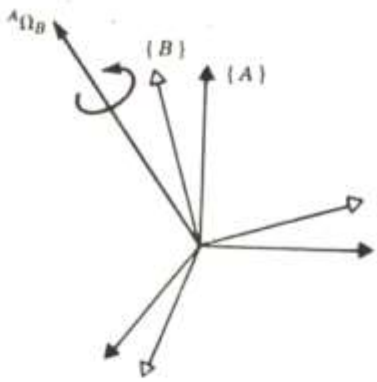
$$|\Delta Q| = (|{}^{A}Q|\sin\theta)(|{}^{A}\Omega_{B}|\Delta t)$$

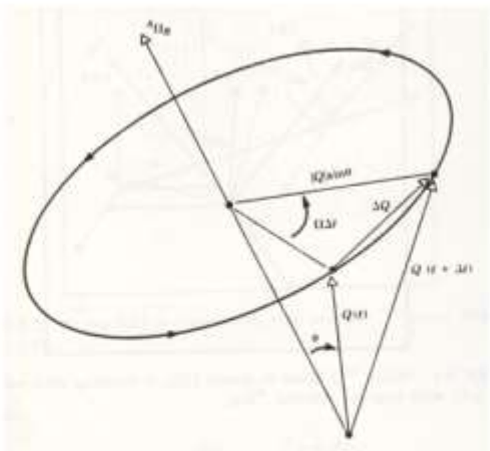
$$\longrightarrow {}^{A}V_{Q} = {}^{A}\Omega_{B} \times {}^{A}Q$$

Vector cross product



Rotational velocity of a rigid body





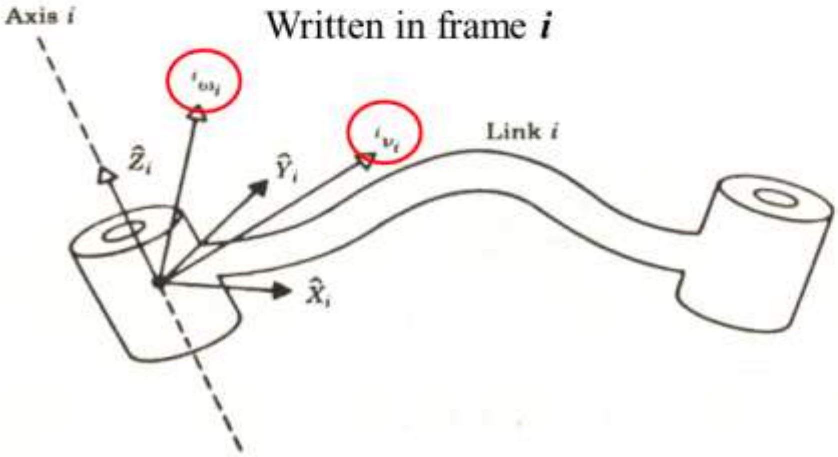
In general case: ${}^{A}V_{Q} = {}^{A}({}^{B}V_{Q}) + {}^{A}\Omega_{B} \times {}^{A}Q$

$$ {}^{A}V_{Q} = {}^{A}_{B}R\,{}^{B}V_{Q} + {}^{A}\Omega_{B} \times {}^{A}_{B}R\,{}^{B}Q. $$

Simultaneous linear and rotational velocity

$$^{A}V_{Q}={}^{A}V_{BORG}+{}^{A}_{B}R\,{}^{B}V_{Q}+{}^{A}\Omega_{B}\times{}^{A}_{B}R\,{}^{B}Q.$$

Motion of the Links of a Robot



At any instant, each link of a robot in motion has some linear and angular velocity.

Velocity of a Link

- **Remember that linear velocity is associated with a point and angular velocity is associated with a body.**
- **Thus, The velocity of a link means the linear velocity of the origin of the link frame and the rotational velocity of the link**

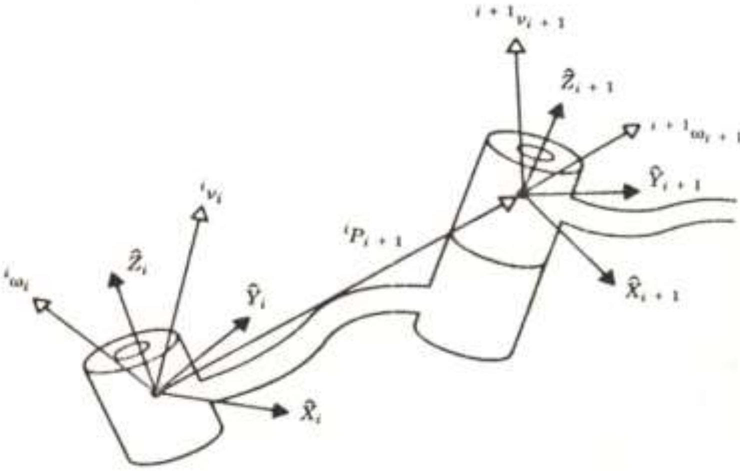
Velocity Propagation From Link to Link

- **We can compute the velocities of each link in order starting from the base.**
- **The velocity of link *i*+1 will be that of link *i*, plus whatever new velocity component added by joint *i*+1.**

Rotational Velocity

- **Rotational velocities may be added when both w vectors are written with respect to the same frame.**
- **Therefore the angular velocity of link *i*+1 is the same as that of link *i* plus a new component caused by rotational velocity at joint *i*+1.**

Velocity Vectors of Neighboring Links



$$ {}^{i}\omega_{i+1} = {}^{i}\omega_i + {}^{i}_{i+1}R\dot{\theta}_{i+1}\,{}^{i+1}\hat{Z}_{i+1}. $$

Velocity Propagation From Link to Link

Note that:

$$ \dot{\theta}_{i+1}\,{}^{i+1}\hat{Z}_{i+1} = {}^{i+1}\begin{bmatrix} 0 \\ 0 \\ \dot{\theta}_{i+1} \end{bmatrix} $$

By premultiplying both sides of previous equation to: ${}^{i+1}_{i}R$

$$ {}^{i+1}_{i}R\,{}^{i}\omega_{i+1} = {}^{i+1}_{i}R\,{}^{i}\omega_i + {}^{i+1}_{i}R\,{}^{i}_{i+1}R\dot{\theta}_{i+1}\,{}^{i+1}\hat{Z}_{i+1}. $$

$$ {}^{i+1}\omega_{i+1} = {}^{i+1}_{i}R\,{}^{i}\omega_i + \dot{\theta}_{i+1}\,{}^{i+1}\hat{Z}_{i+1}. $$

Linear Velocity

The linear velocity of the origin of frame {*i*+1} is the same as that of the origin of frame {*i*} plus a new component caused by rotational velocity of link *i*.

Simultaneous linear and rotational velocity:

$$^{A}V_{Q} = {}^{A}V_{BORG} + {}^{A}_{B}R\,{}^{B}V_{Q} + {}^{A}\Omega_{B} \times {}^{A}_{B}R\,{}^{B}Q.$$

$$^{i}v_{i+1} = {}^{i}v_{i} + {}^{i}\omega_{i} \times {}^{i}P_{i+1}.$$

By premultiplying both sides of previous equation to: ${}^{i+1}_{i}R$

$${}^{i+1}_{i}R\,{}^{i}v_{i+1} = {}^{i+1}_{i}R({}^{i}v_{i} + {}^{i}\omega_{i} \times {}^{i}P_{i+1}).$$

$${}^{i+1}v_{i+1} = {}^{i+1}_{i}R({}^{i}v_{i} + {}^{i}\omega_{i} \times {}^{i}P_{i+1}).$$

Prismatic Joints Link

For the case that joint *i*+1 is prismatic:

$${}^{i+1}\omega_{i+1} = {}^{i+1}_{i}R\,{}^{i}\omega_{i},$$

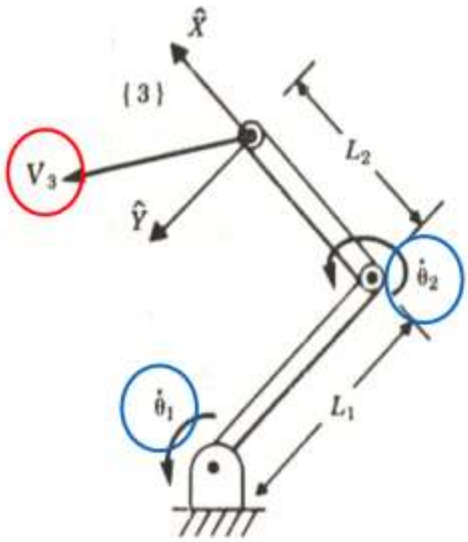
$${}^{i+1}v_{i+1} = {}^{i+1}_{i}R({}^{i}v_{i} + {}^{i}\omega_{i} \times {}^{i}P_{i+1}) + \dot{d}_{i+1}\,{}^{i+1}\hat{Z}_{i+1}.$$

Velocity Propagation From Link to Link

- **Applying those previous equations successfully *from link to link*, we can compute the rotational and linear velocities of the last link.**

Example

Calculate the velocity of the tip of the arm as a function of joint rates?



A 2-link manipulator with rotational joints

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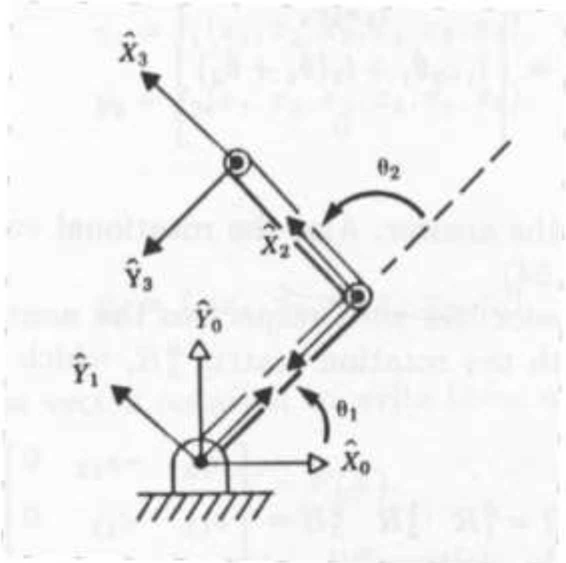
Example

Frame assignments for the two link manipulator



Example

We compute link transformations:

$$ {}^0_1T = \begin{bmatrix} c_1 & -s_1 & 0 & 0 \\ s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad {}^1_2T = \begin{bmatrix} c_2 & -s_2 & 0 & l_1 \\ s_2 & c_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad {}^2_3T = \begin{bmatrix} 1 & 0 & 0 & l_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. $$

Example

Link to link transformation

$$^1\omega_1 = \begin{bmatrix} 0 \\ 0 \\ \dot{\theta}_1 \end{bmatrix}, \qquad {}^1v_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix},$$

$$^2\omega_2 = \begin{bmatrix} 0 \\ 0 \\ \dot{\theta}_1 + \dot{\theta}_2 \end{bmatrix}, \qquad {}^2v_2 = \begin{bmatrix} c_2 & s_2 & 0 \\ -s_2 & c_2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ l_1\dot{\theta}_1 \\ 0 \end{bmatrix} = \begin{bmatrix} l_1 s_2 \dot{\theta}_1 \\ l_1 c_2 \dot{\theta}_1 \\ 0 \end{bmatrix},$$

$$^3\omega_3 = {}^2\omega_2, \qquad {}^3v_3 = \begin{bmatrix} l_1 s_2 \dot{\theta}_1 \\ l_1 c_2 \dot{\theta}_1 + l_2(\dot{\theta}_1 + \dot{\theta}_2) \\ 0 \end{bmatrix} = \begin{bmatrix} l_1 s_2 & 0 \\ l_1 c_2 + l_2 & l_2 \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}.$$

Example

Velocities with respect to non moving base

$$^0_3R = {}^0_1R \quad {}^1_2R \quad {}^2_3R = \begin{bmatrix} c_{12} & -s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

$$^0v_3 = {}^0_3R\,{}^3v_3 = \begin{bmatrix} -l_1 s_1 \dot{\theta}_1 - l_2 s_{12}(\dot{\theta}_1 + \dot{\theta}_2) \\ l_1 c_1 \dot{\theta}_1 + l_2 c_{12}(\dot{\theta}_1 + \dot{\theta}_2) \\ 0 \end{bmatrix} = \begin{bmatrix} -l_1 s_1 - l_2 s_{12} & -l_2 s_{12} \\ l_1 c_1 + l_2 c_{12} & l_2 c_{12} \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}.$$

Jacobian

Jacobian is a multidimensional form of the derivative. Suppose, for example, that we have six functions, each of which is a function of six independent variables:

$$y_1 = f_1(x_1, x_2, x_3, x_4, x_5, x_6),$$
$$y_2 = f_2(x_1, x_2, x_3, x_4, x_5, x_6),$$
$$\vdots$$
$$y_6 = f_6(x_1, x_2, x_3, x_4, x_5, x_6).$$

We could also use vector notation to write these equations

$$Y = F(X).$$

$$\delta y_1 = \frac{\partial f_1}{\partial x_1}\delta x_1 + \frac{\partial f_1}{\partial x_2}\delta x_2 + \cdots + \frac{\partial f_1}{\partial x_6}\delta x_6,$$
$$\delta y_2 = \frac{\partial f_2}{\partial x_1}\delta x_1 + \frac{\partial f_2}{\partial x_2}\delta x_2 + \cdots + \frac{\partial f_2}{\partial x_6}\delta x_6,$$
$$\vdots$$
$$\delta y_6 = \frac{\partial f_6}{\partial x_1}\delta x_1 + \frac{\partial f_6}{\partial x_2}\delta x_2 + \cdots + \frac{\partial f_6}{\partial x_6}\delta x_6.$$

which again might be written more simply in vector notation

$$\delta Y = \frac{\partial F}{\partial X}\delta X.$$

The 6 x 6 matrix of partial derivatives in above equation is what we call the Jacobian, J. Note that, if the functions f_1(X) through f_6 (X) are nonlinear, then the partial derivatives are a function of the x_i so, we can use the notation

$$\delta Y = J(X)\delta X.$$

By dividing both sides by the differential time element, we can think of the Jacobian as mapping velocities in X to those in Y:

$$\dot{Y} = J(X)\dot{X}.$$

At any particular instant, X has a certain value, and J(X) is a linear transformation. At each new time instant, x has changed, and therefore, so has the linear transformation. Jacobians are time-varying linear transformations.

$$^{0}\nu = {}^{0}J(\Theta)\dot{\Theta},$$

For the general case of a six-jointed robot, the Jacobian is 6 x 6, $\dot{\Theta}$ is 6 x 1, and ν_0 is 6 x 1. This 6 x 1 Cartesian velocity vector is the 3 x 1 linear velocity vector and the 3 x 1 rotational velocity vector stacked together:

In the case of a two-link arm, we can write a 2 x 2 Jacobian that relates joint rates to end-effector velocity. From the result of Example 5.3, we can easily determine the Jacobian of our two-link arm. The Jacobian written in frame {3} is

$$^{3}J(\Theta) = \begin{bmatrix} l_1 s_2 & 0 \\ l_1 c_2 + l_2 & l_2 \end{bmatrix}$$

$$^{0}J(\Theta) = \begin{bmatrix} -l_1 s_1 - l_2 s_{12} & -l_2 s_{12} \\ l_1 c_1 + l_2 c_{12} & l_2 c_{12} \end{bmatrix}$$

Derivative of a Vector Function

- If we have a vector function **r** which represents a particle's position as a function of time t:

$$\mathbf{r} = \begin{bmatrix} r_x & r_y & r_z \end{bmatrix}$$

$$\frac{d\mathbf{r}}{dt} = \begin{bmatrix} \frac{dr_x}{dt} & \frac{dr_y}{dt} & \frac{dr_z}{dt} \end{bmatrix}$$

Acceleration of a Rigid Body

Linear and angular accelerations:

$${}^{B}\dot{V}_Q = \frac{d}{dt}{}^{B}V_Q = \lim_{\Delta t \to 0} \frac{{}^{B}V_Q(t+\Delta t) - {}^{B}V_Q(t)}{\Delta t},$$

$${}^{A}\dot{\Omega}_B = \frac{d}{dt}{}^{A}\Omega_B = \lim_{\Delta t \to 0} \frac{{}^{A}\Omega_B(t+\Delta t) - {}^{A}\Omega_B(t)}{\Delta t}.$$

Linear Acceleration

$${}^{A}V_{Q} = {}^{A}_{B}R\,{}^{B}V_{Q} + {}^{A}\Omega_{B} \times {}^{A}_{B}R\,{}^{B}Q.$$ *: origins are coincident.*

$$\frac{d}{dt}({}^{A}_{B}R\,{}^{B}Q) = {}^{A}_{B}R\,{}^{B}V_{Q} + {}^{A}\Omega_{B} \times {}^{A}_{B}R\,{}^{B}Q.$$ *: re-write it as.*

$$\begin{aligned} {}^{A}\dot{V}_{Q} &= \frac{d}{dt}({}^{A}_{B}R\,{}^{B}V_{Q}) + {}^{A}\dot{\Omega}_{B} \times {}^{A}_{B}R\,{}^{B}Q + {}^{A}\Omega_{B} \times \frac{d}{dt}({}^{A}_{B}R\,{}^{B}Q) \\ &= {}^{A}_{B}R\,{}^{B}\dot{V}_{Q} + {}^{A}\Omega_{B} \times {}^{A}_{B}R\,{}^{B}V_{Q} + {}^{A}\dot{\Omega}_{B} \times {}^{A}_{B}R\,{}^{B}Q + {}^{A}\Omega_{B} \times ({}^{A}_{B}R\,{}^{B}V_{Q} + {}^{A}\Omega_{B} \times {}^{A}_{B}R\,{}^{B}Q) \\ &= {}^{A}_{B}R\,{}^{B}\dot{V}_{Q} + 2\,{}^{A}\Omega_{B} \times {}^{A}_{B}R\,{}^{B}V_{Q} + {}^{A}\dot{\Omega}_{B} \times {}^{A}_{B}R\,{}^{B}Q + {}^{A}\Omega_{B} \times ({}^{A}\Omega_{B} \times {}^{A}_{B}R\,{}^{B}Q). \end{aligned}$$ *: by differentiating.*

Linear Acceleration

the case in which the origins are not coincident

$$\begin{aligned} {}^{A}\dot{V}_{Q} &= {}^{A}\dot{V}_{BORG} + {}^{A}_{B}R\,{}^{B}\dot{V}_{Q} + 2\,{}^{A}\Omega_{B} \times {}^{A}_{B}R\,{}^{B}V_{Q} + {}^{A}\dot{\Omega}_{B} \times {}^{A}_{B}R\,{}^{B}Q \\ &+ {}^{A}\Omega_{B} \times ({}^{A}\Omega_{B} \times {}^{A}_{B}R\,{}^{B}Q). \end{aligned}$$

$${}^{B}V_{Q} = {}^{B}\dot{V}_{Q} = 0.$$ *: when ${}^{B}Q$ is constant*

$${}^{A}\dot{V}_{Q} = {}^{A}\dot{V}_{BORG} + {}^{A}\Omega_{B} \times ({}^{A}\Omega_{B} \times {}^{A}_{B}R\,{}^{B}Q) + {}^{A}\dot{\Omega}_{B} \times {}^{A}_{B}R\,{}^{B}Q.$$

: the linear acceleration of the links of a manipulator with rotational joints.

Angular Acceleration

B is rotation relative to A and C is rotating relative to B

$$^{A}\Omega_{C} = {}^{A}\Omega_{B} + {}^{A}_{B}R\,{}^{B}\Omega_{C}.$$

$$^{A}\dot{\Omega}_{C} = {}^{A}\dot{\Omega}_{B} + \frac{d}{dt}\left({}^{A}_{B}R\,{}^{B}\Omega_{C}\right)$$

$$= {}^{A}\dot{\Omega}_{B} + {}^{A}_{B}R\,{}^{B}\dot{\Omega}_{C} + {}^{A}\Omega_{B} \times {}^{A}_{B}R\,{}^{B}\Omega_{C}.$$

: the angular acceleration of the links of a manipulator.

Inertia

- If a force acts of a body, the body will accelerate. The ratio of the applied force to the resulting acceleration is the *inertia (or mass)* of the body.
- If a torque acts on a body that can rotate freely about some axis, the body will undergo an angular acceleration. The ratio of the applied torque to the resulting angular acceleration is the *rotational inertia* of the body. It depends not only on the mass of the body, but also on how that mass is distributed with respect to the axis.

Moment of Inertia

The moment of inertia of a solid body with density $\rho(r)$ *w.r.t.* a given axis is defined by the volume integral

$$I \equiv \int \rho(r) r^2 dv,$$

where r is the perpendicular distance from the axis of rotation.

Moment of Inertia

This can be broken into components as:

$$I_{jk} = \sum_i m_i \left(r_i^2 \delta_{jk} - x_{i,j} x_{i,k} \right)$$ *for a discrete distribution of mass*

$$I_{jk} = \int_V \rho(r) \left(r^2 \delta_{jk} - x_j x_k \right) dV$$ *for a continuous distribution of mass*

$$I = \int_V \rho(x,y,z) \begin{bmatrix} y^2+z^2 & -xy & -xz \\ -xy & z^2+x^2 & -yz \\ -xz & -yz & x^2+y^2 \end{bmatrix} dxdydz.$$

Moment of Inertia

The inertia tensor relative to frame {A}:

$$^{A}I = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix},$$

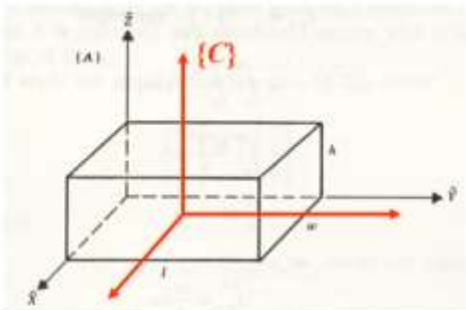
Mass moments of inertia

$$I_{xx} = \iiint_V \left(y^2 + z^2\right)\rho dv,$$
$$I_{yy} = \iiint_V \left(x^2 + z^2\right)\rho dv,$$
$$I_{zz} = \iiint_V \left(x^2 + y^2\right)\rho dv,$$

Mass products of inertia

$$I_{xy} = \iiint_V xy\rho dv, I_{xz} = \iiint_V xz\rho dv, I_{yz} = \iiint_V yz\rho dv.$$

Example



$$^{A}I = \begin{bmatrix} \frac{m}{3}\left(l^2 + h^2\right) & -\frac{m}{4}wl & -\frac{m}{4}hw \\ -\frac{m}{4}wl & \frac{m}{3}\left(w^2 + h^2\right) & -\frac{m}{4}hl \\ -\frac{m}{4}hw & -\frac{m}{4}hl & \frac{m}{3}\left(l^2 + w^2\right) \end{bmatrix}$$

$$^{C}I = \begin{bmatrix} \frac{m}{12}\left(h^2 + l^2\right) & 0 & 0 \\ 0 & \frac{m}{12}\left(w^2 + h^2\right) & 0 \\ 0 & 0 & \frac{m}{12}\left(l^2 + w^2\right) \end{bmatrix}$$

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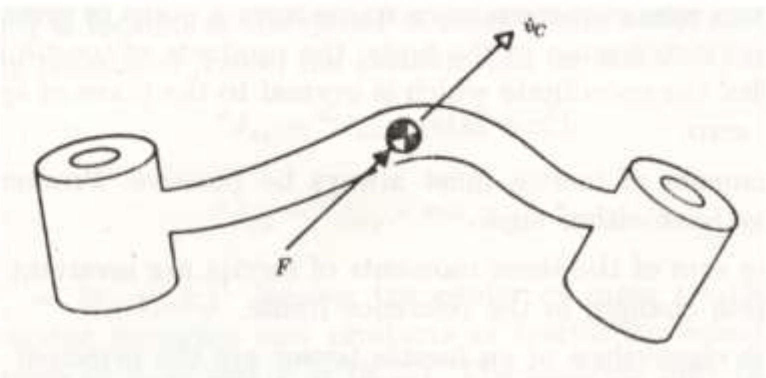
Measuring the Moment of Inertia of a Link

- **Most manipulators have links whose geometry and composition are somewhat complex. A pragmatic option is to *measure the moment of inertia* of each link using an inertia pendulum.**
- **If a body suspended by a rod is given a small twist about the axis of suspension, it will oscillate with angular harmonic motion, the period of which is given by.**

$$T = 2\pi\sqrt{\frac{I}{k}},$$

where k is the torsion constant of the suspending rod , *i.e.*, the constant ratio between the restoring torque and the angular displacement.

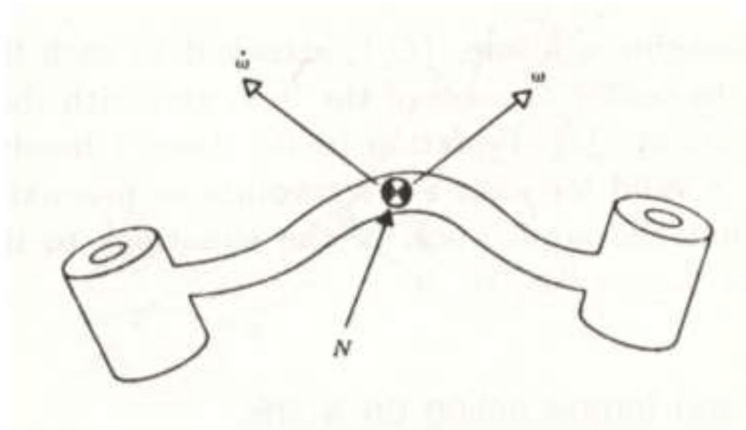
Newton's Equation



$$F = m\dot{v}_C$$

Force causing the acceleration

Euler's Equation



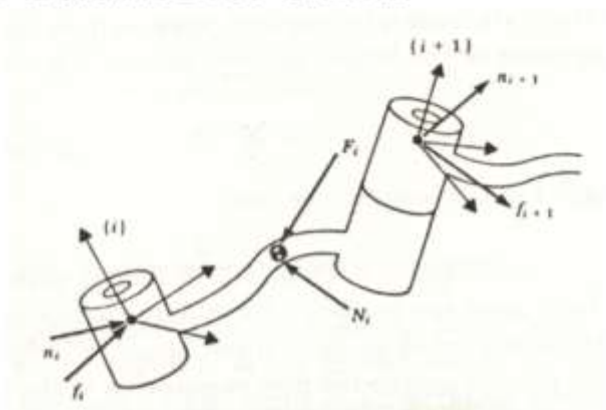
$$N = {}^{C}I\dot{\omega} + \omega \times {}^{C}I\omega$$

Moment causing the rotation

Iterative Newton-Euler Dynamic Formulation

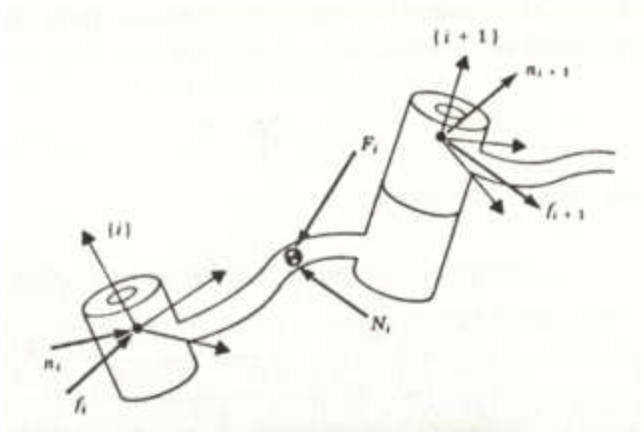
Outward iterations to compute velocities and accelerations The force and torque acting on a link Inward iterations to compute forces and torques

The Force Balance for a Link



$${}^{i}F_{i} = {}^{i}f_{i} - {}_{i+1}^{i}R\ {}^{i+1}f_{i+1}$$

The Torque Balance for a Link



$$^{i}N_i = {}^{i}n_i - {}^{i}n_{i+1} + (-{}^{i}P_{Ci}) \times {}^{i}f_i - ({}^{i}P_{i+1} - {}^{i}P_{Ci}) \times {}^{i}f_{i+1}$$

Force Balance

Using result of force and torque balance:

$$^{i}N_i = {}^{i}n_i - {}_{i+1}^{i}R\,{}^{i+1}n_{i+1} - {}^{i}P_{Ci} \times {}^{i}F_i - {}^{i}P_{i+1} \times {}_{i+1}^{i}R\,{}^{i+1}f_{i+1}$$

In iterative form:

$$^{i}f_i = {}^{i}F_i + {}_{i+1}^{i}R\,{}^{i+1}f_{i+1}$$
$$^{i}n_i = {}^{i}N_i + {}_{i+1}^{i}R\,{}^{i+1}n_{i+1} + {}^{i}P_{Ci} \times {}^{i}F_i + {}^{i}P_{i+1} \times {}_{i+1}^{i}R\,{}^{i+1}f_{i+1}$$

The Iterative Newton-Euler Dynamics Algorithm

1st step:
Link velocities and accelerations are iteratively computed from link 1 out to link n and the Newton-Euler equations are applied to each link.

2nd step:
Forces and torques of iteration and joint actuator torques are computed recursively from link n back to link 1.

- In order to compute inertial forces acting on the links, it is necessary to compute the rotational velocity and linear and rotational acceleration of the center of mass of each link of the manipulator at any given instant.
- These computations will be done in an iterative way, starting with link 1 and moving successively, link by link, outward to link n.

Outward iterations

$$i : 0 \rightarrow 5$$

$$^{i+1}\omega_{i+1} = {}^{i+1}_{i}R\, {}^{i}\omega_{i} + \dot{\theta}_{i+1}\, {}^{i+1}\hat{Z}_{i+1},$$

$$^{i+1}\dot{\omega}_{i+1} = {}^{i+1}_{i}R\, {}^{i}\dot{\omega}_{i} + {}^{i+1}_{i}R\, {}^{i}\omega_{i} \times \dot{\theta}_{i+1}\, {}^{i+1}\hat{Z}_{i+1} + \ddot{\theta}_{i+1}\, {}^{i+1}\hat{Z}_{i+1},$$

$$^{i+1}\dot{v}_{i+1} = {}^{i+1}_{i}R\left({}^{i}\dot{\omega}_{i} \times {}^{i}P_{i+1} + {}^{i}\omega_{i} \times ({}^{i}\omega_{i} \times {}^{i}P_{i+1}) + {}^{i}\dot{v}_{i}\right),$$

$$^{i+1}\dot{v}_{C_{i+1}} = {}^{i+1}\dot{\omega}_{i+1} \times {}^{i+1}P_{C_{i+1}} + {}^{i+1}\omega_{i+1} \times \left({}^{i+1}\omega_{i+1} \times {}^{i+1}P_{C_{i+1}}\right) + {}^{i+1}\dot{v}_{i+1},$$

$$^{i+1}F_{i+1} = m_{i+1}\, {}^{i+1}\dot{v}_{C_{i+1}},$$

$$^{i+1}N_{i+1} = {}^{C_{i+1}}I_{i+1}\, {}^{i+1}\dot{\omega}_{i+1} + {}^{i+1}\omega_{i+1} \times {}^{C_{i+1}}I_{i+1}\, {}^{i+1}\omega_{i+1}.$$

Inward iterations

- Having computed the forces and torques acting on each link, we now need to calculate the joint torques that will result in these net forces and torques being applied to each link.
- We can do this by writing a force-balance and moment-balance equation based on a free-body diagram of a typical link. Each link has forces and torques exerted on it by its neighbors and in addition experiences an inertial force and torque.

$$i : 6 \rightarrow 1$$

$${}^{i}f_i = {}^{i}_{i+1}R\,{}^{i+1}f_{i+1} + {}^{i}F_i,$$

$${}^{i}n_i = {}^{i}N_i + {}^{i}_{i+1}R\,{}^{i+1}n_{i+1} + {}^{i}P_{C_i} \times {}^{i}F_i + {}^{i}P_{i+1} \times {}^{i}_{i+1}R\,{}^{i+1}f_{i+1},$$

$$\tau_i = {}^{i}n_i^T\,{}^{i}\hat{Z}_i.$$

The Structure of the Manipulator Dynamic Equations

$\tau = M(\Theta)\ddot{\Theta} + V(\Theta,\dot{\Theta}) + G(\Theta)$ ***: state space equation***

$M(\Theta) : n \times n$ ***: mass matrix***

$V(\Theta,\dot{\Theta}) : n \times 1$ ***: centrifugal and Coriolis terms***

$G(\Theta) : n \times 1$ ***: gravity terms***

$\tau = M(\Theta)\ddot{\Theta} + B(\Theta)[\dot{\Theta}\dot{\Theta}] + C(\Theta)[\dot{\Theta}^2]G(\Theta)$ ***: configuration space***

$B(\Theta) : n \times n(n-1)/2$ ***: matrix of Coriolis coefficients***

$[\dot{\Theta}\dot{\Theta}] : n(n-1)/2 \times 1, \quad [\dot{\theta}_1\dot{\theta}_2 \quad \dot{\theta}_1\dot{\theta}_3 \quad \cdots \quad \dot{\theta}_{n-1}\dot{\theta}_n]^T$

$C(\Theta) : n \times n$ ***: centrifugal coefficients***

$[\dot{\Theta}^2] : n \times 1, \quad [\dot{\theta}_1^2 \quad \dot{\theta}_2^2 \quad \cdots \quad \dot{\theta}_n^2]^T$

Coriolis Force

- **A fictitious force exerted on a body when it moves in a rotating reference frame.**

$$F_{Coriolis} = 2m(v \times \Omega)$$

Kinetic and Potential Energy of a Manipulator

$$k_i = \frac{1}{2} m_i v_{C_i}^T v_{C_i} + \frac{1}{2} {}^i\omega_i^T \, {}^{C_i}I_i \, {}^i\omega_i,$$

$$k = \sum_{i=1}^{n} k_i.$$ *Total kinetic energy of a manipulator*

$$u_i = -m_i \, {}^0g^T \, {}^0P_{C_i} + \boxed{u_{ref_i},}$$

$$u = \sum_{i=1}^{n} u_i.$$ *Total potential energy of a manipulator*

- **Langrangian**
  - **Is the difference between the *kinetic* and *potential energy* of a mechanical system**

$$L(\Theta,\dot{\Theta}) = k(\Theta,\dot{\Theta}) - u(\Theta).$$

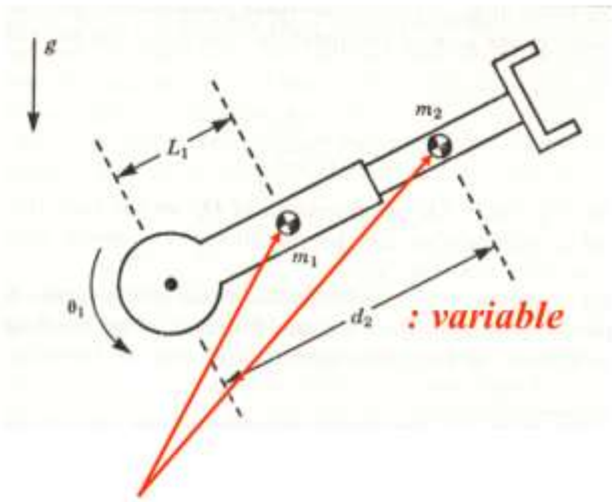
The equations of motion for the manipulator

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{\Theta}} - \frac{\partial L}{\partial \Theta} = \tau$$

$$\frac{d}{dt}\frac{\partial k}{\partial \dot{\Theta}} - \frac{\partial k}{\partial \Theta} + \frac{\partial u}{\partial \Theta} = \boxed{\tau}$$

$n \times 1$ *vector of actuator torque*

Example



The center of mass of link 1 and link 2

$$^{c_1}I_1 = \begin{bmatrix} I_{xx1} & 0 & 0 \\ 0 & I_{yy1} & 0 \\ 0 & 0 & I_{zz1} \end{bmatrix},$$

$$^{c_2}I_2 = \begin{bmatrix} I_{xx2} & 0 & 0 \\ 0 & I_{yy2} & 0 \\ 0 & 0 & I_{zz2} \end{bmatrix},$$

Kinetic energy of link 1

$$k_1 = \frac{1}{2}m_1 l_1^2 \dot{\theta}_1^2 + \frac{1}{2}I_{zz1}\dot{\theta}_1^2$$

Kinetic energy of link 2

$$k_2 = \frac{1}{2}m_2(d_2^2\dot{\theta}_1^2 + \dot{d}_2^2) + \frac{1}{2}I_{zz2}\dot{\theta}_1^2.$$

Total Kinetic Energy is given by

$$k(\Theta, \dot{\Theta}) = \frac{1}{2}(m_1 l_1^2 + I_{zz1} + I_{zz2} + m_2 d_2^2)\dot{\theta}_1^2 + \frac{1}{2}m_2\dot{d}_2^2.$$

Potential Energy of link 1

$$u_1 = m_1 l_1 g \sin(\theta_1) + m_1 l_1 g$$

Potential energy of link 2

$$u_2 = m_2 g d_2 \sin(\theta_1) + m_2 g d_{2max},$$

where d_{2max} is the maximum extension of joint 2. Hence, the total potential energy

$$u(\Theta) = g(m_1 l_1 + m_2 d_2)\sin(\theta_1) + m_1 l_1 g + m_2 g d_{2max}.$$

$$\frac{\partial k}{\partial \dot{\Theta}} = \begin{bmatrix} (m_1 l_1^2 + I_{zz1} + I_{zz2} + m_2 d_2^2)\dot{\theta}_1 \\ m_2 d_2 \end{bmatrix}$$

$$\frac{\partial k}{\partial \Theta} = \begin{bmatrix} 0 \\ m_2 d_2 \dot{\theta}_1^2 \end{bmatrix},$$

$$\frac{\partial u}{\partial \Theta} = \begin{bmatrix} g(m_1 l_1 + m_2 d_2)\cos(\theta_1) \\ g m_2 \sin(\theta_1) \end{bmatrix}.$$

$$\tau_1 = (m_1 l_1^2 + I_{zz1} + I_{zz2} + m_2 d_2^2)\ddot{\theta}_1 + 2 m_2 d_2 \dot{\theta}_1 \dot{d}_2$$
$$+ (m_1 l_1 + m_2 d_2) g \cos(\theta_1),$$
$$\tau_2 = m_2 \ddot{d}_2 - m_2 d_2 \dot{\theta}_1^2 + m_2 g \sin(\theta_1).$$

$$M(\Theta) = \begin{bmatrix} (m_1 l_1^2 + I_{zz1} + I_{zz2} + m_2 d_2^2) & 0 \\ 0 & m_2 \end{bmatrix}$$

$$V(\Theta, \dot{\Theta}) = \begin{bmatrix} 2 m_2 d_2 \dot{\theta}_1 \dot{d}_2 \\ -m_2 d_2 \dot{\theta}_1^2 \end{bmatrix},$$

$$G(\Theta) = \begin{bmatrix} (m_1 l_1 + m_2 d_2) g \cos(\theta_1) \\ m_2 g \sin(\theta_1) \end{bmatrix}.$$

Unit:-6- ROBOT ACTUATORS AND FEED BACK COMPONENTS

Syllabus **Lectures:9**

- **Actuators**
- **Electric & stepper motors**
- **Position sensors – potentiometers**
- **Resolvers**
- **Encoders**
- **Velocity sensors**
- **Tactile sensors**
- **Proximity sensors**
- **Robot applications in Manufacturing**

Introduction

- Position & Velocity sensors are used in robotics as feed back devices, while actuators & power transmission devices are used to accomplish the control actions indicated by the controller.
- Actuators are the muscles of robots. If you imagine that the links and the joints are the skeleton of the robot, the actuators act as muscles, which moves or rotate the links to change the configuration of robots.
- The actuators must have enough power to accelerate and decelerate the links and to carry the loads, yet be light, economical, accurate, responsive, reliable and easy to maintain.

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Introduction

- Position sensors provide the necessary means for determining whether the joints have moved to correct linear or rotational locations in order to achieve the required position & orientation.
- The speed with which the manipulator is moved is another performance feature which must be regulated. Robots utilize a feedback system to ensure proper speed control.
- It is important that a sophisticated control system has to be developed to fine tune the dynamic performance of manipulator during acceleration & deceleration as it moves between the points in work space.

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Actuator

- A hardware device that converts a controller command signal into a change in a physical parameter.
- The change in the physical parameter is usually mechanical, such as a position or velocity change.
- An actuator is a transducer, because it changes one type of physical quantity, such as electric current into another type of physical quantity, such as rotational speed of an electric motor

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Types of Actuators

1. Electrical actuators:Electric actuators are simply electro-mechanical devices which allow movement through the use of an electrically controlled systems of gears.
   - Electric motors
     - ✓ DC servomotors
     - ✓ AC motors
     - ✓ Stepper motors
   - Solenoids

2. Hydraulic actuators
   - Hydraulic actuators allow a robot to move by the use of fluids moving under pressure through a series of valves by the use of pumps. The hydraulic fluids normally consist of oils which are reasonably non-compressible.

3. Pneumatic Actuators
   - Pneumatic actuators use compressed gas to force the movement of pistons through the use of pumps and valves and so allow movement of the robotic part.

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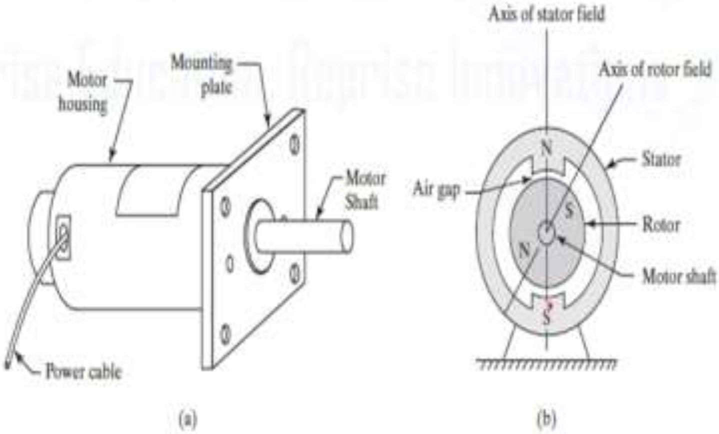
Electrical Actuators-*Electric Motor*

An electric motor converts electrical power into mechanical power. Most electric motors are rotational. They are available in many different styles and sizes, one of which is depicted in Figure



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Electrical Actuators-*Electric Motor-Classification*

The simplest and most common classification is

- Direct current (DC) motors
- Alternating current (AC) motors

Within each category, there are several subcategories.

Four types that are used in automation and industrial control are discussed here: (1) DC motors, (2) AC motors, (3) stepper motors, and (4) linear motors.

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Electrical Actuators- DC Motor

Components of a DC Electric Motor

- The principle components of an electric motor are:
  - North and south **magnetic poles** to provide a strong magnetic field. Being made of bulky ferrous material they traditionally form the outer casing of the motor and collectively form the **stator**
  - An **armature or rotor**, which is a cylindrical ferrous core rotating within the stator and carries a large number of windings made from one or more conductors

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Electrical Actuators- DC Motor

Components Of An Electric Motor (cont...)

- A **commutator**, which rotates with the armature and consists of copper contacts attached to the end of the windings
- **Brushes** in fixed positions and in contact with the rotating commutator contacts. They carry direct current to the coils, resulting in the required motion

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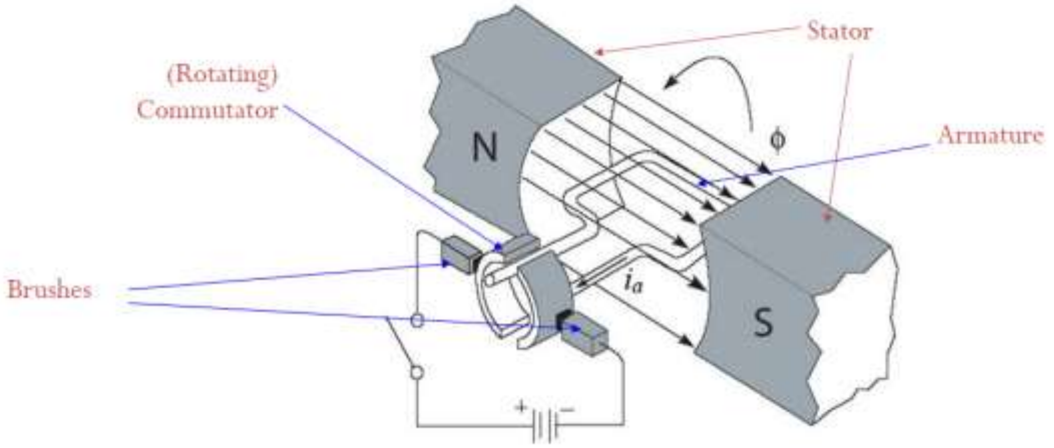
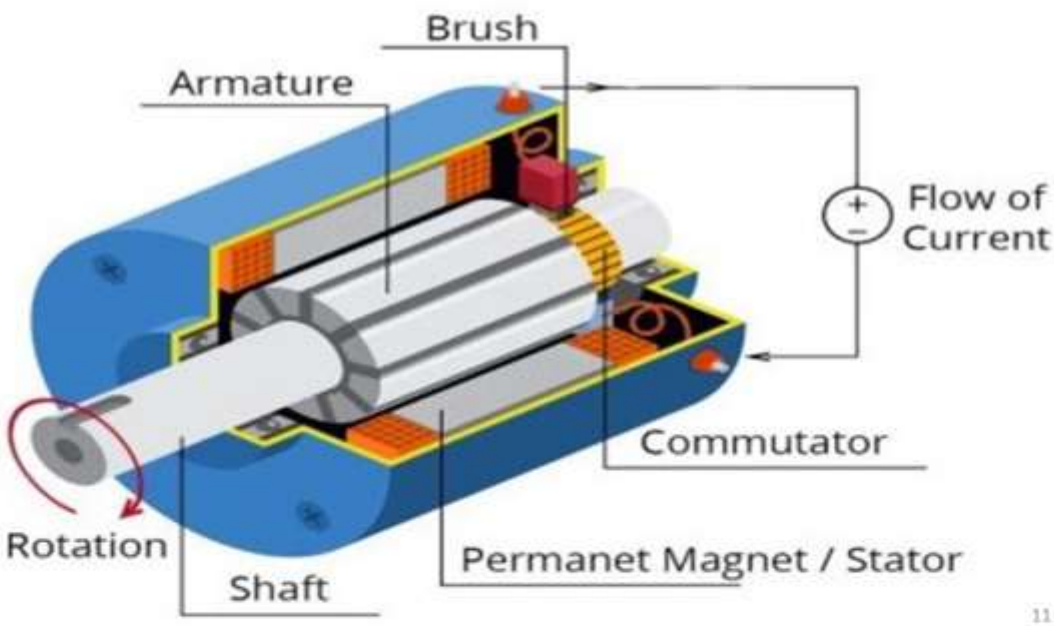
Electrical Actuators- DC Motor

Components Of An Electric Motor (cont...)- Explaining the basic principle



DC motor Construction- Sectional view of actual motor



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Electrical Actuators- DC Motor

How Do Electric Motors Work?

- The classic DC motor has a rotating armature in the form of an electromagnet
- A rotary switch called a commutator reverses the direction of the electric current twice every cycle, to flow through the armature so that the poles of the electromagnet push and pull against the permanent magnets on the outside of the motor
- As the poles of the armature electromagnet pass the poles of the permanent magnets, the commutator reverses the polarity of the armature electromagnet.
- During that instant of switching polarity, inertia keeps the motor going in the proper direction

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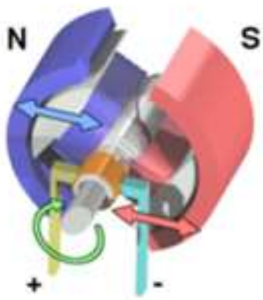
How Do Electric Motors Work? (cont...)



A simple DC electric motor: when the coil is powered, a magnetic field is generated around the armature. The left side of the armature is pushed away from the left magnet and drawn toward the right, causing rotation

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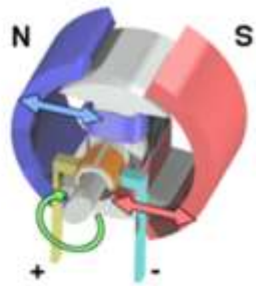
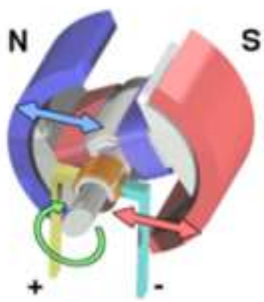
How Do Electric Motors Work? (cont...)



The armature continues to rotate

How Do Electric Motors Work? (cont...)



When the armature becomes horizontally aligned, the commutator reverses the direction of current through the coil, reversing the magnetic field. The process then repeats.

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Electrical Actuators- DC Motor

- Disadvantage of DC motor is arcing, worn brushes, and maintenance problems.
- A special type of DC motor avoids the use of the commutator and brushes. Called a *brushless DC motor*, it uses solid-state circuitry to replace the brushes and commutator components.
- Elimination of these parts has the added benefit of reducing the inertia of the rotor assembly, allowing higher speed operation.

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Electrical Actuators- DC Motor

- **DC motors are widely used for two reasons**

✓ The first is the convenience of using direct current as the power source. For example, the small electric motors in automobiles are DC because the car's battery supplies direct current.

✓ The second reason for the popularity of DC motors is that their torque–speed relationships are attractive in many applications compared to AC motors.

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Electrical Actuators- DC Motor Servomotor

- A **servomotor** is a rotary actuator or linear actuator that allows for precise control of angular or linear position, velocity and acceleration. The term *servomotor* simply means that a feedback loop is used to regulate speed.
- It consists of a suitable **motor** coupled to a sensor for position feedback. Servomotors are used in applications such as robotics, CNC machinery or automated manufacturing.
- DC servomotors are a common type of DC motor used in mechanized and automated systems, and it will be used to represent this class of electric motors.

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DC Servomotor analysis

- In a DC servomotor, the stator typically consists of two permanent magnets on opposite sides of the rotor.
- The rotor, called the *armature* in a DC motor, consists of copper wire windings around a ferrous metal core.
- Input current is provided to the windings through the commutator and interacts with the magnetic field of the stator to produce the torque that drives the rotor.
- The magnitude of the rotor torque is a function of the current passing through the windings, and the relationship can be modeled by the following equation:

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$$T = K_t I_a \qquad \text{Eq. 1}$$

motor torque, N-m; *Ia* = current flowing through the armature, A; and *Kt* = the motor's torque constant, N-m/A.

- When current is first applied to the motor, torque is at its maximum value. This is called the *stall torque*, and the corresponding current is also a maximum value.
- As the armature begins to rotate, both torque and current decrease because rotating the armature in the magnetic field of the stator produces
- a voltage across the armature terminals, called the *back-emf*. In effect, the motor acts like a generator, and the back-emf increases with rotational speed as follows:

$$E_b = K_v \omega \qquad \text{Eq. 2}$$

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where E_b = back-emf, V; ω = angular velocity, rad/sec; and K_v = the voltage constant of the motor, V/(rad/sec). The effect of the back-emf is to reduce the current flowing through the armature windings. The angular velocity in rad/sec can be converted to the more familiar rotational speed as follows:

$$N = \frac{60\omega}{2\pi} \qquad \text{Eq. 3}$$

where N = rotational speed, rev/min.

Given the resistance of the armature R_a and an input voltage V_{in} supplied to the motor terminals, the starting armature current is given by the following:

$$I_a = \frac{V_{in}}{R_a} \qquad \text{Eq. 4}$$

This starting current produces a starting torque as given by Equation Eq 4. But as the armature begins to rotate, it generates the back-emf E_b, which reduces the available voltage. Thus, the actual armature current depends on the rotational speed of the rotor,

$$I_a = \frac{V_{in} - E_b}{R_a} = \frac{V_{in} - K_v\omega}{R_a} \qquad \text{Eq. 5}$$

where all of the terms are defined earlier. Combining Equations Eq 2 and Eq 5, the torque produced by the DC servomotor at a speed ω is

$$T = K_t\left(\frac{V_{in} - K_v\omega}{R_a}\right) \qquad \text{Eq. 6}$$

The mechanical power delivered by the motor is the product of torque and velocity, as defined in the following equation:

$$P = T\omega$$

where P = power in N-m/sec (Watts); T = motor torque, N-m; and ω

= angular velocity, rad/sec. The corresponding horsepower is given by

$$HP = T\omega$$

The servomotor is connected either directly or through a gear reduction to a piece of machinery. The machinery may be a fan, pump, spindle, table drive, or similar mechanical apparatus. The apparatus represents the load that is driven by the motor. The load requires a certain torque to operate, and the torque is usually related to rotational speed in some way. In general, the torque increases with speed. In the simplest case, the relationship is proportional:

$$T_L = K_L\,\omega$$

where T_L = load torque, N-m; and T_L = the constant of proportionality

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A DC servomotor has a torque constant $K_t = 0.095$ N-m/A. Its voltage constant is $K_v = 0.11$ V/(rad/sec). The armature resistance is $R_a = 1.6$ ohms. A terminal voltage of 24 V is used to operate the motor. Determine (a) the starting torque generated by the motor just as the voltage is first applied, (b) the maximum speed at a torque of zero, and (c) the operating point of the motor when it is connected to a load whose torque characteristic is given by $T_L = K_L\omega$ and $K_L = 0.007$ N-m/(rad/sec). Express the rotational speed as rev/min.

Solution: (a) At $\omega = 0$, the armature current is

$$I_a = V_{in}/R_a = 24/1.6 = 15\ A.$$

The corresponding torque is therefore $T = K_t I_a = 0.095(15) =$ **1.425 N-m**

(b) The maximum speed is achieved when the back-emf E_b equals the terminal voltage V_{in}.

$$E_b = K_v\omega = 0.11\omega = 24\text{ V}$$

$$\omega = 24/0.11 = 218.2\text{ rad/sec}$$

$$N = 60(218.2)/2\pi = \mathbf{2{,}084\ rev/min}$$

(c) The load torque is given by the equation $T_L = 0.007\omega$

The motor torque equation is given by Equation (6.9). Using the given data,

$$T = 0.095(24 - 0.11\omega)/1.6 = 1.425 - 0.00653\omega$$

Setting $T = T_L$ and solving for ω results in $\omega = 105.3$ rad/sec

Converting this to rotation speed, $N = 60(105.3)/2\pi =$ **1,006 rev/min**

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In the previous example, what is the power delivered by the motor at the operating point? Express the answer as (a) Watts and (b) horsepower.

Solution: At ω = 105.3 rad/sec, and using the load torque equation,

$$T_L = 0.007(105.3) = 0.737 \text{ N-m}$$

(a) Power $P = T\omega = 0.737(105.3) =$ **776 W**

(b) Horsepower $HP = 77.6/745.7 =$ **0.104 hp**

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Electrical Actuators- AC Motor

Why AC Motors ?

DC motors have several attractive features, they have two important disadvantages:

- The commutator and brushes used to conduct current from the stator assembly to the rotor result in maintenance problems with these motors
- The most common electrical power source in industry is alternating current, not direct current.

Electrical Actuators- AC Motor

Why AC Motors ?

- In order to use AC power to drive a DC motor, a rectifier must be added to convert the alternating current to direct current.
- For these reasons, AC motors are widely used in many industrial applications.
- They do not use brushes, and they are compatible with the predominant type of electrical power.

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Electrical Actuators- AC Motor

- Alternating current motors operate by generating a rotating magnetic field in the stator, and the rotational speed of the rotor depends on the frequency of the input electrical power.
- The rotor is forced to turn at a speed that depends on the rotating magnetic field.
- AC motors can be classified into two broad categories:

✓ synchronous motors

✓ induction motors.

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Electrical Actuators- *Synchronous motors*

- ***Synchronous motors*** operate by energizing the rotor with alternating current, which generates a magnetic field in the gap separating the rotor and the stator.
- This magnetic field creates a torque that turns the rotor at the same rotational speed as the magnetic forces in the stator.
- The term *synchronous* derives from the fact that the rotor rotation is synchronized with the AC frequency in steady-state operation.

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Synchronous AC Motors

- Current is applied to both the Rotor and the Stator.
- This allows for precise control (stepper motors), but requires mechanical brushes or slip rings to supply DC current to the rotor.
- There is no slip since the rotor does not rely on induction to produce torque.

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Synchronous motors

- Synchronous motors cannot start by themselves from zero speed; they require a device, sometimes called an
- *exciter*, to initiate rotation of the rotor when power is first supplied to the motor.
- The exciter, which may be an electric motor itself, accelerates the rotational speed of the rotor so that it can be synchronized with that of the stator's rotating magnetic field.

Synchronous motor working principle

www.LearnEngineering.org

https://www.youtube.com/watch?v=Vk2jDXxZlhs&t=19s&ab_channel=Lesics

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Induction motors

- ***Induction motors*** are probably the most widely used motors in the world, due to their relatively simple construction and low manufacturing cost.
- In the operation of this motor type, a magnetic field is induced (hence the term *induction*) in the rotor from the stator.
- Because of this feature, the rotor in most induction motors does not need electrical current from an external power supply.
- Thus, no brushes or other means of connection are required for the rotating component of an induction motor.

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Induction motors

- Unlike synchronous motors, induction motors operate at speeds that are slower than the synchronous speed.
- The steady-state rotational speed depends on the load that the motor is driving.
- In fact, if the rotor speed were equal to the synchronous speed of the stator magnetic field, then no induced voltage and no torque would be generated in the rotor.
- By the same reasoning, when AC power is first applied to an induction motor, the induced magnetic field and torque are maximum, so no exciter is needed to start the motor turning.

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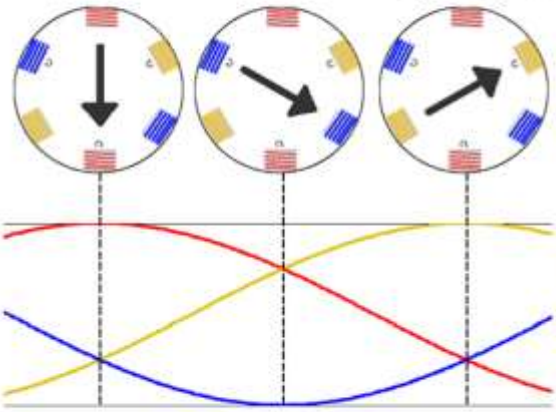
AC Induction Motors (3 Phase)

- Use poly-phase (usually 3) AC current to create a rotating magnetic field on the stator
- This induces a magnetic field on the rotor, which tries to follow stator - slipping required to produce torque
- Workhorses of the industry - high powered applications



Sean DeHart

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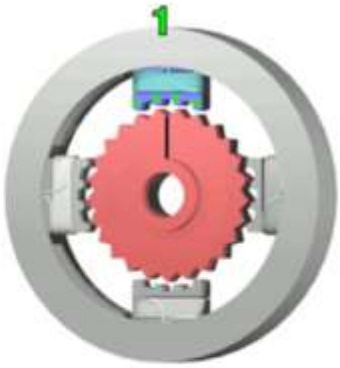
Stepper Motors

- This figure illustrates the design of a stepper motor, arranged with four magnetic poles arranged around a central rotor
- Note that the teeth on the rotor have a slightly tighter spacing to those on the stator, this ensures that the two sets of teeth are close to each other but not quite aligned throughout



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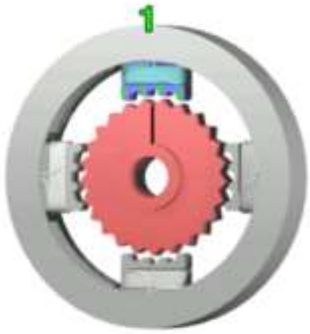
Stepper Motors (cont...)



- Movement is achieved when power is applied for short periods to successive magnets
- Where pairs of teeth are least offset, the electromagnetic pulse causes alignment and a small rotation is achieved, typically 1-2°

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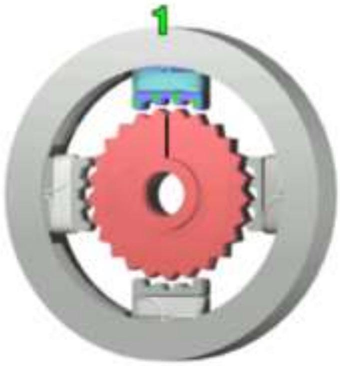
How Does A Stepper Motor Work?



The top electromagnet (1) is charged, attracting the topmost four teeth of a sprocket.

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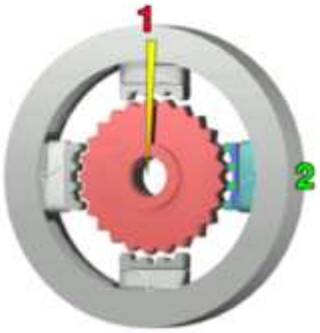
How Does A Stepper Motor Work? (cont...)



The top electromagnet (1) is turned off, and the right electromagnet (2) is charged, pulling the nearest four teeth to the right. This results in a rotation of 3.6°

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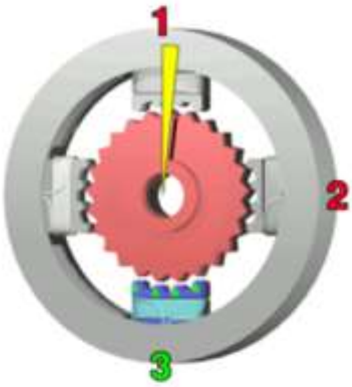
How Does A Stepper Motor Work? (cont...)



The bottom electromagnet (3) is charged; another 3.6° rotation occurs.

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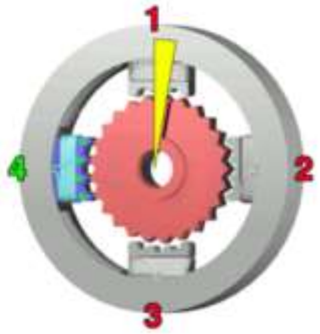
How Does A Stepper Motor Work? (cont...)



The left electromagnet (4) is enabled, rotating again by 3.6°. When the top electromagnet (1) is again charged, the teeth in the sprocket will have rotated by one tooth position; since there are 25 teeth, it will take 100 steps to make a full rotation.

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Stepper Motor-Advantages

- Stepper motors have several advantages:
  - Their control is directly compatible with digital technology
  - They can be operated open loop by counting steps, with an accuracy of ±1 step.
  - They can be used as holding devices, since they exhibit a high holding torque when the rotor is stationary

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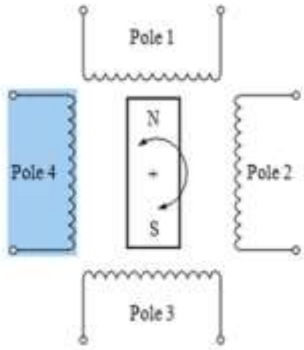

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Stepper Motor- Analysis

- Stepper motor also called *step motors* and *stepping motors*, this motor type provides rotation in the form of discrete angular displacements, called step angles.
- Each angular step is actuated by a discrete electrical pulse.
- The total angular rotation is controlled by the number of pulses received by the motor, and rotational speed is controlled by the frequency of the pulses.
- The step angle is related to the number of steps for the motor according to the relationship

$$\alpha = \frac{360}{n_s}$$

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Where, α= step angle, n_s = the number of steps for the stepper motor, which must be an integer value. Typical values for the step angle in commercially available stepper motors are 7.5°, 3.6°, and 1.8°, corresponding to 48, 100, and 200 steps (pulses) per revolution of the motor.

Total angle through which motor rotates is given by A_m

$$A_m = n_p \alpha$$

where A_m is measured in degrees,°; n_p= the number of pulses received by the motor; and α= the step angle. The angular velocity ω (rad/sec) and speed of rotation N (rev/ min) are given by the expressions

$$\omega = \frac{2\pi f_p}{n_s}$$

$$N = \frac{60 f_p}{n_s}$$

Where f_p = pulse frequency, pulses/sec or Hz; and n_s = the number of steps in the motor, steps/rev or pulses/rev.

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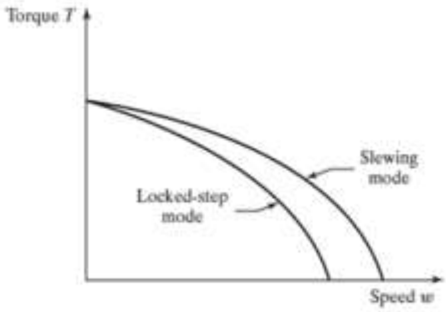
Torque Speed Relationship of Stepper motor



- The typical torque–speed relationships for a stepper motor are shown in Figure.
- As in the DC servomotor, torque decreases with increased rotational speeds. And because
- rotational speed is related to pulse frequency in the stepper motor, torque is lower at higher pulse rates.
- As indicated in the figure, there are two operating modes, locked-step and slewing. In the locked-step mode, each pulse received by the motor causes a discrete angular step to be taken; the motor starts and stops (at least approximately) with each pulse.
- In this mode the motor can be started and stopped, and its direction of rotation can be reversed. In the slewing mode, usually associated with higher speeds, the motor's rotation is more or less continuous and does not allow for stopping or reversing with each subsequent step.
- Nevertheless, the rotor does respond to each individual pulse; that is, the relationship between rotating speed and pulse frequency is retained in the slewing mode.

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Rotary-to-Linear Motion Conversion

The motor types discussed above all produce rotary motion and apply torque. Many actuator applications require linear motion and the application of force. A rotating motor can be used in these applications by converting its rotary motion into linear or translational motion. The following are some of the common conversion mechanisms used for this purpose:

- ***Leadscrews and ball screws***. The motor shaft is connected to a leadscrew or ball screw, which have helical threads throughout their lengths. A lead nut or ball nut is threaded onto the screw and prevented from rotating when the screw rotates; thus, the nut is moved linearly along the screw. Direction of linear motion depends on the direction of rotation of the screw.

Rotary-to-Linear Motion Conversion

- ***Pulley systems***. The motor shaft is connected to the driver wheel in a pulley system, around which a belt, chain, or other flexible material forms a loop with an idler wheel. As the motor shaft rotates, the flexible material is pulled linearly between the pulley wheels.
- • ***Rack and pinion.*** The motor shaft is connected to a pinion gear that is mated with a rack, which is a straight gear with tooth spacings that match those of the gear. As the gear is rotated, the rack is moved linearly.

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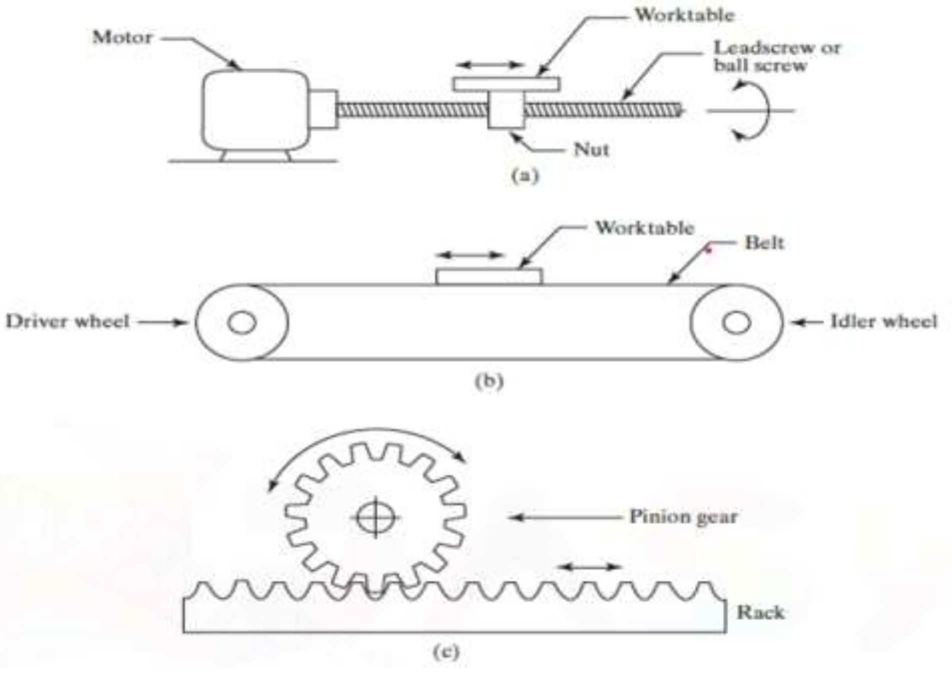
Rotary-to-Linear Motion Conversion



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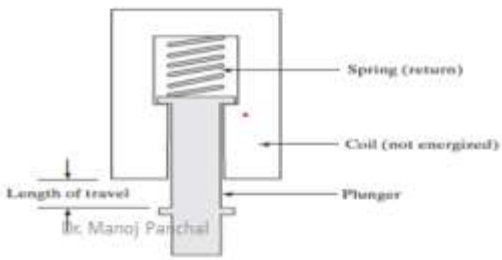
Electrical Actuators -- Other Than Motors

- A ***solenoid*** consists of a movable plunger inside a stationary wire coil, as pictured in Figure .
- When a current is applied to the coil, it acts as a magnet, drawing the plunger into the coil. When current is switched off, a spring returns the plunger to its previous position.
- Linear solenoids of the type described here are often used to open and close valves in fluid flow systems, such as chemical processing equipment. In these applications, the solenoid provides a linear push or pull action. Rotary solenoids are also available to provide rotary motion, usually over a limited angular range (e.g., neutral position to between 25° and 90°).



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Electrical Actuators -- Other Than Motors

- An ***electromechanical relay*** is an on–off electrical switch consisting of two main components,
- a stationary coil and a movable arm that can be made to open or close an electrical contact by means of a magnetic field that is generated when current is passed through the coil.
- The reason for using a relay is that it can be operated with relatively low current levels

Hydraulic and Pneumatic Actuators

- These two categories of actuators are Powered by pressurized fluids. Oil is used in hydraulic systems, and compressed air is used in pneumatic systems.
- The devices in both categories are similar in operation but different in construction due to the differences in fluid properties between oil and air.
- Some of the differences in properties, and their effects on the characteristics and applications of the two types of actuators, are listed in Table.
- Hydraulic and pneumatic actuators that provide either linear or rotary motion are available. The cylinder, illustrated in Figure is a common linear-motion device.

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- Hydraulic and Pneumatic actuators are classified as
  - Linear Actuators (Cylinders)
  - Rotary Actuators (Motors)

- Issues in choosing actuators
  - Load (e.g. torque to overcome own inertia)
  - Speed (fast enough but not too fast)
  - Accuracy (will it move to where you want?)
  - Resolution (can you specify exactly where?)
  - Repeatability (will it do this every time?)
  - Reliability (mean time between failures)
  - Power consumption (how to feed it)
  - Energy supply & its weight

- The cylinder is basically a tube, and a piston is forced to slide inside the cylinder due to fluid pressure. Two types are shown in the figure:
- (a) single acting with spring return and (b) double acting. Although these cylinders operate in a similar way for both types of fluid power,
- It is more difficult to predict the speed and force characteristics of pneumatic cylinders because of the compressibility of air in these devices.
- For hydraulic cylinders, the fluid is incompressible, and the speed and force of the piston depend on the fluid flow rate and pressure inside the cylinder, respectively, as given by the expressions

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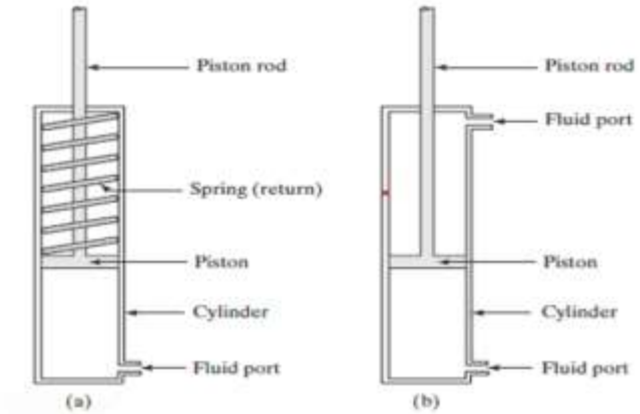


Fig. Cylinder and piston Single Acting with spring return and (b) double acting.

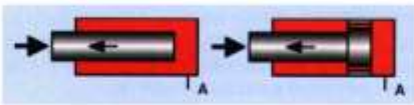
Types of Hydraulic actuators: Cylinders & Motors

Cylinder types:

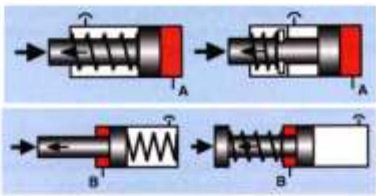
Single acting:

work can be done only in one direction

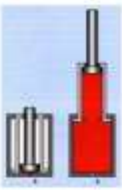
Plunger



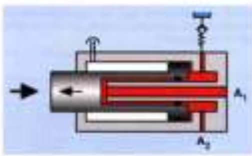
Piston



Telescopic

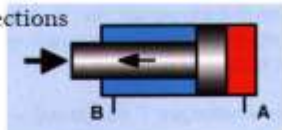


Fast moving

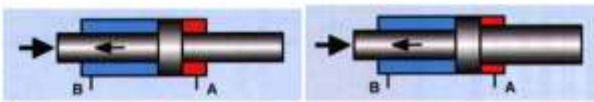


Double acting piston:

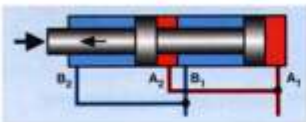
Work is done in both directions



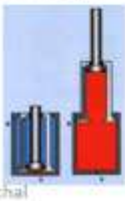
Piston rod on both sides



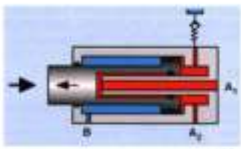
Tandem



Telescopic



Fast moving



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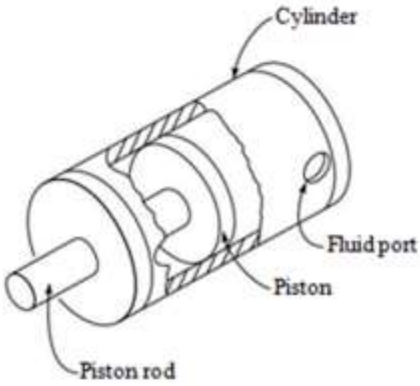

Construction of hydraulic Actuator

Difference Between Electrical, Hydraulic And Pneumatic Actuators:-

Hydraulic	Electric	Pneumatic
+ Good for large robots and heavy payloads + Highest power/weight ratio + Stiff system, high accuracy, better response + No reduction gear needed + Can work in wide range of speeds without difficulty + Can be left in position without any damage – May leak; not fit for clean-room applications – Requires pump, reservoir, motor, hoses, etc. – Can be expensive and noisy; requires more maintenance – Viscosity of oil changes with temperature – Very susceptible to dirt and other foreign material in oil – Low compliance – High torque, high pressure, large inertia on the actuator	+ Good for all sizes of robots + Better control, good for high-precision robots + Higher compliance than hydraulics + Reduction gears reduce inertia on the motor + Does not leak, good for clean room + Reliable, low maintenance + Can be spark-free; good for explosive environments – Low stiffness – Needs reduction gears, increased backlash, cost, weight, etc. – Motor needs braking device when not powered; otherwise, the arm may fall	+ Many components are usually off-the-shelf + Reliable components + No leaks or sparks + Inexpensive and simple + Low pressure compared to hydraulics + Good for on-off applications and pick-and-place + Compliant systems – Noisy – Require pressurized air, filter, and so on – Difficult to control and maintain linear position – Deform under load constantly – Very low stiffness, inaccurate response – Lowest power-to-weight ratio

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Sensors

- A robot moves in space to perform tasks and hence it needs actuators to move the links and sensors to know where each joint is.
- Sensors inform the controller by how much each joint has moved and thus enables the controller to enforce a particular velocity or position during motion.

Types of Sensors

1. Internal sensors: These are responsible for the internal working of the robot and are mainly used for closing the loop in feedback control e.g., position sensors. A robot cannot function properly without these if it is using a closed loop feedback control system. The main internal sensors are position and velocity sensors.
2. External sensors: These are responsible for interaction with the environment. A robot can use external sensors like touch sensor for interaction with the environment. In case any of these sensors fail the robot can still function but its ability to interact with the external world is reduced. The main external sensors are force/torque sensors, vision, touch, pressure sensors, etc.

Internal sensors

Position Sensor :

- A position sensor is a sensor that measures the movement of an object or determine its relative position measured from some reference point. In section we are going to three types of position sensors, that are most commonly use.

✓ Potentiometer
✓ Resolver
✓ Encoder

Position Sensors ➡ Potentiometers

- Potentiometers are analog devices whose output voltage is proportional to the position of wiper.
- Potentiometers offer a low cost method of contact displacement measurement.
- Depending upon their design, they may be used to measure either rotary or linear motion.
- In either case, a movable slide or wiper is in contact with a resistive material or wire winding. The slide is attached to the target object in motion.
- A DC or an AC voltage is applied to the resistive material.
- When the slide moves relative to the material, the output voltage varies linearly with the total resistance included within the span of the slide.
- An advantage of potentiometers is that they can be used in applications with a large travel requirement.
- It is possible to use pots to provide a limited amount of feedback control in robots where high proportional resolution and accuracy are not required.

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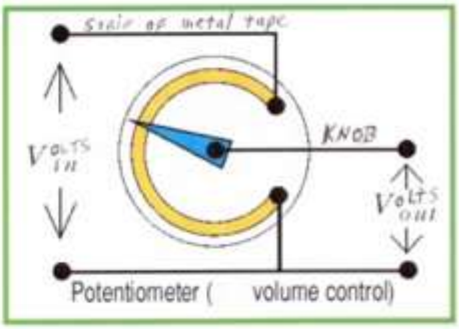
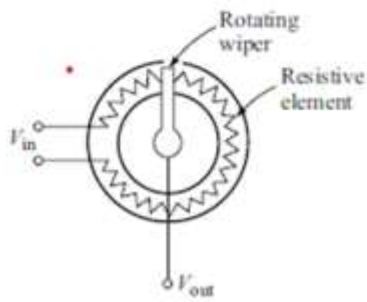
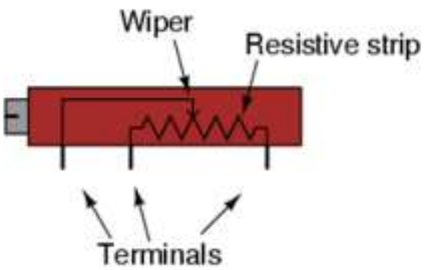




Linear potentiometer construction

$$V_o(t) = K_p\theta(t)$$



where Vo(t) is the output voltage, Kp is the voltage constant of the pot in volts per radian (or volts per inch in the case of a linear pot) and q(t) is the position of the pot in radians (or inches).

Potentiometers- Analysis

Since a potentiometer requires an excitation voltage, in order to calculate Vo, we can use

$$V_o = V_{ex}\frac{\theta_{act}}{\theta_{tot}}$$

where Vex is the excitation voltage, qtot is the total travel available of the wiper, and qact is the actual position of the wiper.

- Potentiometers can be single turn in which the rotating wiper can move only by360° or they can also be multi turn in which the rotating wiper can move by several 360° turns.
- Potentiometers suffer from disadvantages like non-linearity and low life due to the continuous friction between the wiper and the variations in the resistive element.
- In addition, the variation in wiper contact between the coil and the wiper can lead to noise in position measurement.

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Potentiometers

- Benefits:

  Relatively Inexpensive

  Can be used for Distance and Direction

  Low software overhead – Not dependent on interrupts

  Can Sense Speed and Distance

- Drawbacks:

  Sample Rate issues can limit max useable Speed

  Small "Dead" zone, though usually not a big problem

Example on Potentiometer

Find the output voltage of a potentiometer with the following characteristics. Also determine the Kp. The excitation voltage = 12 V; total wiper travel = 320°; wiper position = 64°.

Solution The $K_p = V_{ex}/\theta_{tot}$ which is 12 V/320° = 0.0375 V/deg. The output voltage is

$$(64°)(0.0375 \text{ V/deg}) = 2.4 \text{ V}.$$

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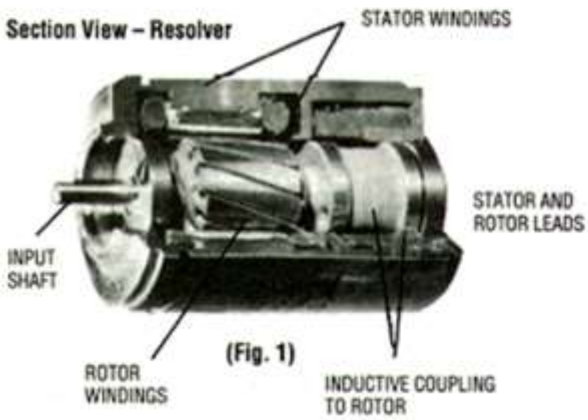
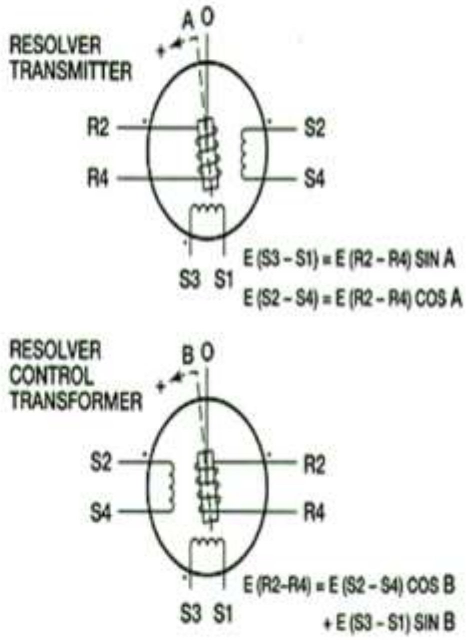
Position Sensors ➡ Resolvers

- A **resolver** is a type of rotary electrical transformer used for measuring degrees of rotation. It is an analog device whose output is proportional to the angle of rotating element with respect to fixed element.
- The primary winding of the transformer, located on rotor shaft, is excited by a sinusoidal electric current, which by electromagnetic induction induces current to flow through the secondary windings located on the stator.
- The two two-phase windings, fixed at right (90°) angles to each other on the stator, produce a sine and cosine feedback current by the same induction process.
- The relative magnitudes of the two-phase voltages are measured and used to determine the angle of the rotor relative to the stator.
- Since a resolver is a rotary transformer we must require an AC signal for excitation. If Dc signal is used there will be no output signal.



(Fig. 1)



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Resolvers- Analysis

- The stator windings are 90° apart If the rotor is excited with a signal of the type $A \sin(\omega t)$ the voltage across the two pairs of stator terminals will be

$$V_{s1}(t) = A \sin(\omega t) \sin\theta$$

$$V_{s2}(t) = A \sin(\omega t) \cos\theta$$

A sin (ωt)= is excitation voltage

Examples on Resolver

Q. At time t the excitation voltage to a resolver is 24 V. The shaft angle is 90°. What is the output signal from the resolver?

Solution

$$V_{s1} = (24\text{ V})(\sin 90°) = 24\text{ V}$$
$$V_{s2} = (24\text{ V})(\cos 90°) = 0\text{ V}.$$

Q. At time t the excitation voltage to a resolver is 24 V and V_{s1} = 17 V and V_{s2} = – 17 V. What is the angle?

$$\arcsin\left(\frac{17}{24}\right) = 45° \text{ or } 135°$$

$$\arccos\left(-\frac{17}{24}\right) = 135° \text{ or } 225°$$

The shaft angle must be 135°.

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Position Sensors ➡ Encoders

- Encoders are sensors which converts linear or angular displacement in to digital code or pulse signals.
- Encoders are mainly classified as Linear encoder and rotary encoder.
- They are also classified as Absolute encoder and incremental encoders.
- Rotary encoders are used to measure the angular position and direction of a motor or mechanical drive shaft.
- Linear encoders measure linear position and direction. They are often used in linear stages or in linear motors.
- Absolute encoders provide actual position relative to a fixed reference position.
- Incremental encoders sense the position from previous position. A robot utilizing an incremental encoder must execute a calibration sequence before position information obtained.

- In a rotary encoder, a glass or metal disk is attached to a motor or mechanical drive shaft. The disk has a pattern of opaque and transparent sectors known as a code track.
- A light source is placed on one side of the disk and a photo detector is placed on the other side.

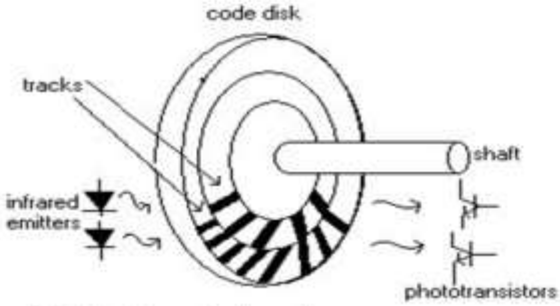

Fig 1. A rotary optical encoder

- As the disk rotates with the motor shaft, the code track interrupts the light emitted onto the photo detector, generating a digital signal output.
- The number of opaque/transparent sector pairs, also known as line pairs, on the code track corresponds to the number of cycles the encoder will output per revolution. The number of cycles per revolution (CPR) defines the base resolution of the encoder.

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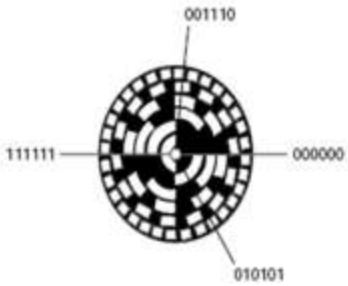
- An absolute encoder consists of the disk which has multiple concentric code tracks and a separate photo detector is used with each code track. The number of code tracks is equivalent to the binary resolution of the encoder., as shown in figure below.
- An 8-bit absolute encoder has eight code tracks. The 8-bit output is read to form an 8-bitword indicating absolute position.
- While absolute encoders are available in a wide variety of resolutions, 8-, 10-, and 12-bit binary are the most common.
- Due to their complexity, absolute encoders are typically more expensive than incremental encoders. Absolute encoders may output position in either parallel or serial format.



Absolute encoder example.

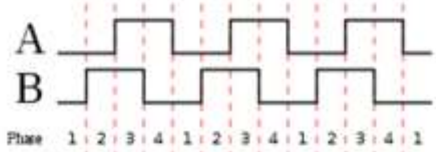
- An incremental rotary encoder, also known as a quadrature encoder or a relative rotary encoder, has two outputs called quadrature outputs.
- Incremental encoders are used to track motion and can be used to determine position and velocity. This can be either linear or rotary motion. Because the direction can be determined, very accurate measurements can be made.
- They employ two outputs called A & B which are called quadrature outputs as they are 90 degrees out of phase.
- The two output wave forms are 90 degrees out of phase, which is all that the quadrature term means. These signals are decoded to produce a count up pulse or a count down pulse and tables are used to decode the direction.
- For example if the last value was 00 and the current value is 01, the device has moved one half step in the clockwise direction.

Gray coding for ccw rotation

Phase	A	B
1	1	0
2	1	1
3	0	1
4	0	0

Gray coding for clockwise rotation

Phase	A	B
1	0	0
2	0	1
3	1	1
4	1	0



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- Benefits:

  Can be used to sense Speed, Distance, and Direction.

- Drawbacks:

  Can be expensive

  Can be cheaply built but at the expense of time!

  Uses more I/O Lines

  Use of Interrupts can be problematic

  Mechanical Noise Issues

Fig. 3.13 *Incremental encoder*

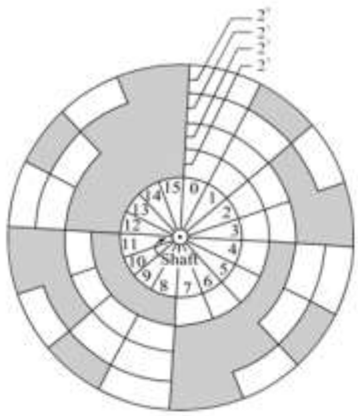

Fig. 3.15 *Absolute optical encoder*

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VELOCITY SENSORS

- Velocity information is required for closed loop feedback control using a PD or PID controller. One of the most commonly used devices for the feedback of velocity in- formation is the dc tachometer.
- A tachometer is essentially a dc generator providing an output voltage proportional to the angular velocity of the armature. Velocity information can also be obtained from an incremental encoder in which the rate at which the dark and transparent slots cross the emitter receiver pair indicate the velocity of the rotating shaft.

$$V_O(t) = K_t(t)\ \omega$$

- where $V_o(t)$ is the output voltage of the tachometer in volts, $K_t\ (t)$ is the tachometer constant, usually in V/rad/s and ω is the angular velocity in radians per second.

Velocity Sensors ➡ Tachometers

- A **tachometer** (also called a **revolution-counter**, **rev-counter**, or **RPM gauge**) is an instrument that measures the rotation speed of a shaft or disk, as in a motor or other machine. The device usually displays the revolutions per minute (RPM) on a calibrated analogue dial, but digital displays are increasingly common.
- Tachometers can be divided in to

1. DC (Digital)tachometer
2. AC (analog) tachometer

In robotics mostly DC tachometer is used.

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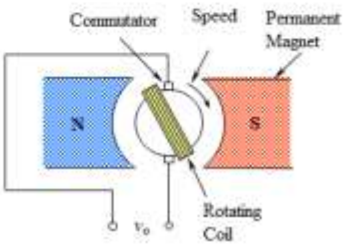
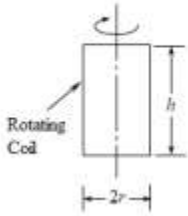
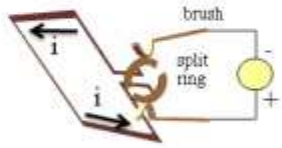
DC Tachometer (Angular Velocity)



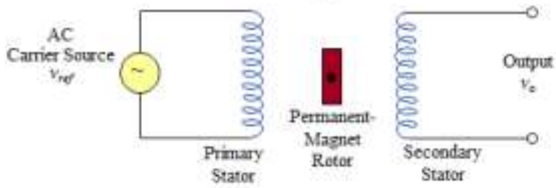




- A tachometer is essentially DC generator providing an output voltage proportional to the angular velocity of the armature
- The rotor is directly connected to the rotating object.
- The output signal that is induced at the rotating coil is picked up using a commutator device (consists of low resistance carbon brushes)
- Commutator is stationary but makes contact with the split slip rings

Permanent Magnet AC Tachometer

- When the rotor is stationary or moving in a quasi-static manner the output voltage will be constant
- As the rotor moves, an additional voltage, proportional to the speed of the rotor will be induced
- The output is an amplitude modulated signal proportional to the rotor speed and demodulation is necessary
- Direction is obtained from the phase angle
- Due to commutator in DC tachometers a slight ripples will appear in output voltage which can not be filtered out, this can overcome by using AC tachometer



- For low frequency applications (~5Hz), supply with 60Hz is adequate
- Sensitivity is in the range 50 – 100mV/rad/s

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- Benefits:

  Can be implemented with limited resources - sensors included in last year's kit

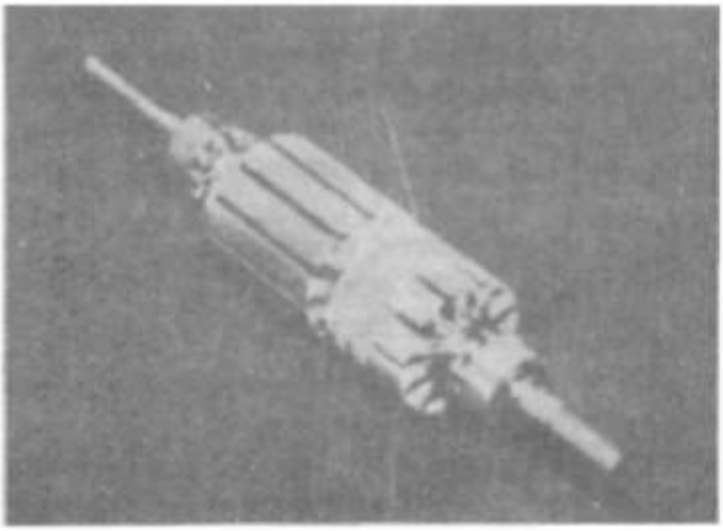
  Can Sense Speed and Distance

- Drawbacks:

  Cannot sense Direction

  Use of Interrupts can be problematic.

  Mechanical Noise can be a problem



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TYPES OF SENSORS USED IN ROBOTICS

1. Tactile sensors.
2. Proximity and range sensors.
3. Miscellaneous sensors and sensor-based systems
4. Machine vision system.
5. Tactile sensors:-There are of 2 types

a) Touch sensor.

b) Force sensor.

Tactile Sensors

- Tactile sensors are device which indicates the touch between themselves and other solid objects.
- Tactile sensors are divided in two categories touch sensors and force sensors

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Touch sensors

- Touch sensors are used to indicate that contact has been made between two objects without regard magnitude of contacting forces.
- Simple examples these kind of sensors are limit switches, micro switches.
- They can be used to indicate the presence or absence of part in fixture or at pick up point along a conveyor. Another use of touching sensing device would be as part of inspection probe which manipulated by robot to measure the dimensions on work parts.

Force sensor

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

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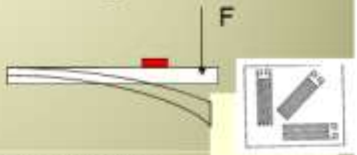
Force Sensors

- Forces can be measured by measuring the deflection of an elastic element.

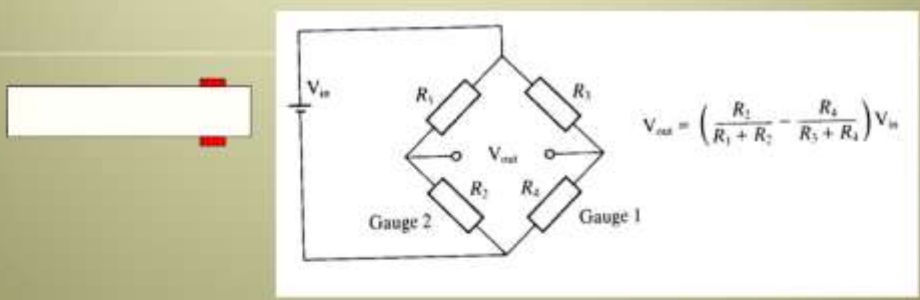
$$\varepsilon = \frac{\Delta l}{l} = strain$$



  - the strain we measure is about 0.005mm/mm
- Strain gauges: Most common sensing elements of force. It converts the deformation to the change of its resistance.
- Gauge resistance varies from 30 to 3K, corresponding to deformation from $30\mu m$ to $100\mu m$

Force Sensors

- Detect the resistance changes of the strain gauge using the Wheatstone bridge circuit.



Using two gauges is to cancel the drift due to temperature change.

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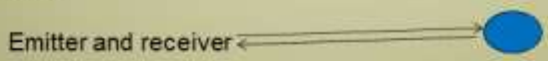
Range Sensors

- To measure the distance from the sensor to a nearby object
- Working principles
  - Triangulation: Use the triangle formed by the traveling path of the signal to calculate the distance

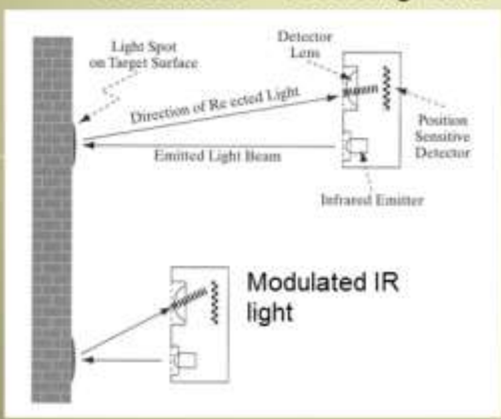
  - Time-of-flight: Use the time of flight of the signals to measure the distance

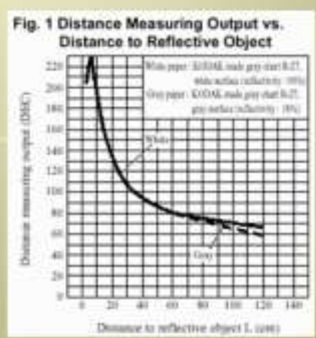


- Typical range sensors
  - Infra-red range sensor (triangulation)
  - Ultrasonic sensors (time-of-flight)
  - Laser range sensor (triangulation)
  - etc

IR Range Sensors

- Principle of operation: triangulation
  - IR emitter + focusing lens + position-sensitive detector





Location of the spot on the detector corresponds to the distance to the target surface.

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Proximity Sensors

- Proximity sensors detect the presence or absence of objects using electromagnetic fields, light, and sound.
- There are many types, each suited to specific applications and environments.

- Types of proximity sensors

1. Non-Contact Sensors :
   - Optical
   - Ultrasonic
   - Inductive
   - Capacitive
2. Contact Sensors (Mechanical)

Proximity Sensors

1. Optical (Photoelectric) proximity Sensors

- **Photoelectric sensors are so versatile that they solve the bulk of problems**
- **All photoelectric sensors consist of a few of basic components:**
  - ✓ An emitter light source (Light Emitting Diode, Infra-red LED, laser diode),
  - ✓ A photodiode or phototransistor receiver to detect emitted light, and
  - ✓ Supporting electronics designed to amplify the receiver signal.

Photoelectric proximity Sensors Configurations:
1. **Through-beam**
2. **Retro-reflective**
3. **Diffuse**

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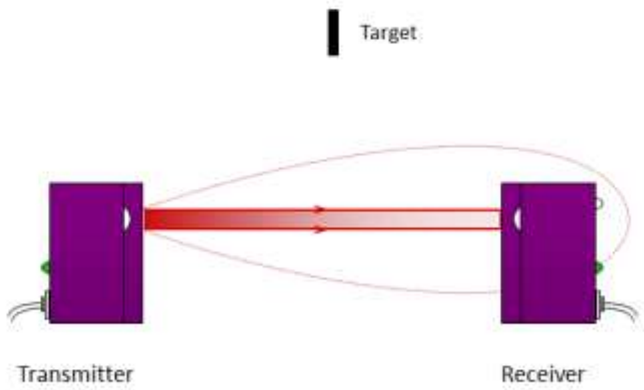
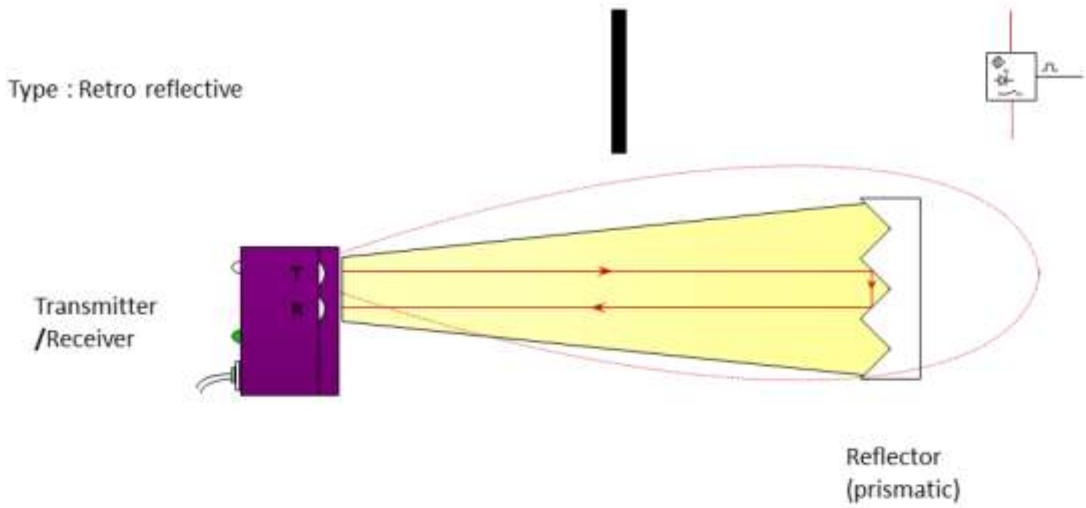
Optical sensors (Through-beam)



- Long sensing distance: up to 30 metres with some devices
- Will detect all but very transparent materials
- Must be accurately aligned

Optical sensors (Retro-reflective)



- Sensing distance : 1/2 to 1/3 of through-beam type
- Not suitable for reflective or transparent targets

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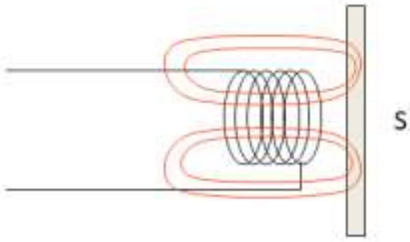
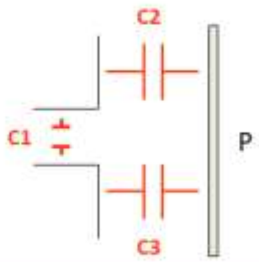
Inductive proximity sensor



- Coil inductance increases as iron / steel object (S) gets closer

Capacitive proximity sensor



- Capacitance increases as metal object (P) gets closer because additional capacitance paths C2 & C3 are added and increase in value as the separation reduces. C1 is always present.

Non-contact Proximity sensors

Ultrasonic (Sonar) sensors

- Ultrasonic sensor utilize the reflection of high frequency (20KHz) sound waves to detect parts or distances to the parts.
- In general, ultrasonic sensors are the best choice for transparent targets. They can detect a sheet of transparent plastic film as easily as a wooden pallet.
- Different Colors has no effect

- The most common configurations are the same as in photoelectric sensing: through beam, retro-reflective, and diffuse versions.

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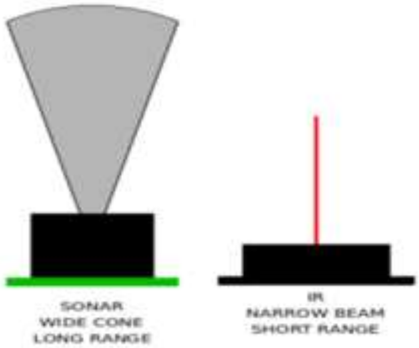
Non-contact Proximity sensors

Ultrasonic (Sonar) versus IR sensors

- The primary difference is that sonar has a wide detection cone and longer range



- Unlike IR sensors, sonars are slightly harder to deal with when it comes to multiple sensors.
- Because of the wide cone, and how sound can reflect, they can interfere with each other quite easily.
- Typically, you must allow a 50ms between each firing of a sonar sensors, to let the ping die off.
- If you have multiple sensors, you can only ping one at a time, and must still obey this 50ms ring down time or have each sonar operating at a different sound frequency

Another optical approach for proximity sensing involves the use of a collimated light beam and a linear array of light sensors. By reflecting the light beam off the surface of the object, the location of the object can be determined from the position of its reflected beam on the sensor array. This scheme is illustrated in Fig. 6.10. The formula for the distance between the object and the sensor is given as follows:

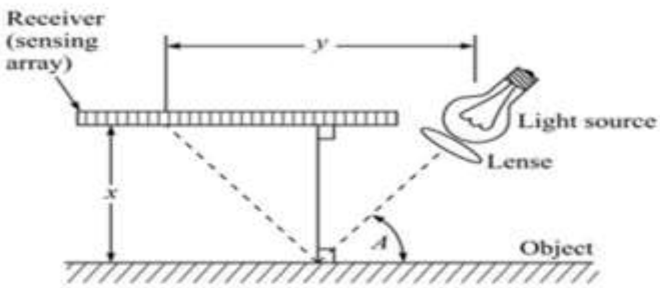


Fig. 6.10 *Scheme for a proximity sensor using reflected light against a sensor array.*

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

where x = the distance of the object from the sensor

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

A = the angle between the object and the sensor array as illustrated in Fig. 6.10.

Use of this device in the configuration shown relies on the fact that the surface of the object must be parallel to the sensing array.

USES OF SENSORS IN ROBOTICS:-

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

SELECTION OF SENSOR

1. Accuracy: The accuracy of the measurement should be as high as possible. Accuracy is interpreted to mean that the true value of the variable can be sensed with no systematic positive or negative errors in the measurement. Over many measurements of the variable, the average error between the actual value and the sensed value will tend to be zero

2. Precision: The precision of the measurement should be as high as possible. Precision means that there is little or no random variability in the measured variable. The dispersion in the values of a series of measurements will be minimized.

3. Operating range: The sensor should possess a wide operating range and should be accurate and precise over the entire range.

4. Speed of response: The transducer should be capable of responding to changes in the sensed variable in minimum time. Ideally, the response would be instantaneous.

5. Calibration: The sensor should be easy to calibrate. The time and trouble required to accomplish the calibration procedure should be minimum. Further, the sensor should not require frequent recalibration. The term 'drift' is commonly applied to denote the gradual loss in accuracy of the sensor with time and use, and which would necessitate recalibration.

6. Reliability: The sensor should possess a high reliability. It should not be subject to frequent failures during operation.

7. Cost and ease of operation: The cost to purchase, install, and operate the sensor should be as low as possible. Further, the ideal circumstance would be that the installation and operation of the device would not require a specially trained, highly skilled operator

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ROBOT APPLICATIONS

1.Material Handling: Pick-and-Place Operations, Palletizing and Related Operations, Machine loading and unloading

2.Machining Operations: Drilling, routing, and other machining operations, Grinding, polishing, deburring, wire brushing, and similar operations

3.Processing operations: Die casting, Plastic molding, Forging and related operations, Stamping press operations , spot welding, continuous arc welding, spray coating

4.Other processing operations using robots: Riveting , Water jet cutting, Laser drilling and cutting

5. Assembly and inspection

6. Advanced robotic Application: Rehabilitation, Defense, Outer space, Intelligence, Tele presence, Mobility and navigation

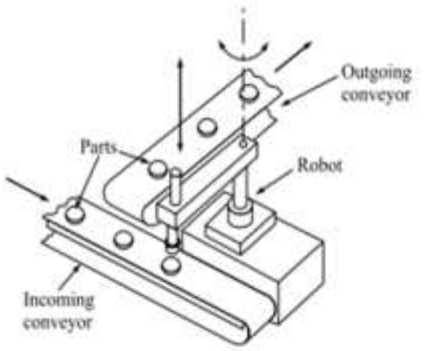

Fig. 13.1 *Simple pick-and-place operation.*

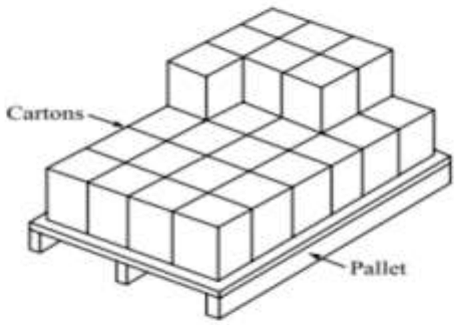

Fig. 13.3 *A typical pallet configuration.*

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Questions

- **What is actuator**
- **Types of actuator**
- **Electric actuator**
- **Hydraulic actuator**
- **AC motor**
- **DC motor**
- **Servo motor**
- **Stepper motor**
- **Comparison between different types of actuator**
- **Sensors**
- **Position sensor**
- **Velocity sensor**
- **Tactile sensors**
- **Force sensors**
- **Encoders**
- **Resolver**
- **Potentiometer**
- **Application of Robotics in manufacturing**

Old question paper

1. What are the various types of actuator- 2 Marks
2. Differentiate between Hydraulic, Pneumatic and electric Actuator 14- Marks
3. Provide a brief explanation about classification of actuator based on drive power- 4 Marks
4. What are the factors needs to considered while selecting a sensor- 14 Marks
5. What are the functions of sensors in robot- 2 Marks
6. Explain various applications of robot- 7 Marks
7. At time 't' the excitation voltage to a resolver is 24v and Vs1=17v and VS2=-17v what is the angle- 2 marks
8. Differentiate between the hydraulic, Pneumatic and electric actuator-14 marks
9. Discuss briefly about position and velocity sensor- 10 Marks

Q. What are the various types of actuator- 2 Marks

Ans. 1. Electric actuator

2. Hydraulic Actuator

3. Pneumatic Actuator

Q. Differentiate between Hydraulic, Pneumatic and electric Actuator 14- Marks

Hydraulic	Electric	Pneumatic
+ Good for large robots and heavy payloads + Highest power/weight ratio + Stiff system, high accuracy, better response + No reduction gear needed + Can work in wide range of speeds without difficulty + Can be left in position without any damage – May leak; not fit for clean-room applications – Requires pump, reservoir, motor, hoses, etc. – Can be expensive and noisy; requires more maintenance – Viscosity of oil changes with temperature – Very susceptible to dirt and other foreign material in oil – Low compliance – High torque, high pressure, large inertia on the actuator	+ Good for all sizes of robots + Better control, good for high-precision robots + Higher compliance than hydraulics + Reduction gears reduce inertia on the motor + Does not leak, good for clean room + Reliable, low maintenance + Can be spark-free; good for explosive environments – Low stiffness – Needs reduction gears, increased backlash, cost, weight, etc. – Motor needs braking device when not powered; otherwise, the arm may fall	+ Many components are usually off-the-shelf + Reliable components + No leaks or sparks + Inexpensive and simple + Low pressure compared to hydraulics + Good for on-off applications and pick-and-place + Compliant systems – Noisy – Require pressurized air, filter, and so on – Difficult to control and maintain linear position – Deform under load constantly – Very low stiffness, inaccurate response – Lowest power-to-weight ratio

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Q. Provide a brief explanation about classification of actuator based on drive power- 4 Marks

Ans.

1. Electrical actuators: Electric actuators are simply electro-mechanical devices which allow movement through the use of an electrically controlled systems of gears.
   - Electric motors
     - DC servomotors
     - AC motors
     - Stepper motors
   - Solenoids
2. Hydraulic actuators
   - Hydraulic actuators allow a robot to move by the use of fluids moving under pressure through a series of valves by the use of pumps. The hydraulic fluids normally consist of oils which are reasonably non-compressible.
3. Pneumatic Actuators
   - Pneumatic actuators use compressed gas to force the movement of pistons through the use of pumps and valves and so allow movement of the robotic part.

Q. What are the factors needs to considered while selecting a sensor- 14 Marks

1. Accuracy: The accuracy of the measurement should be as high as possible. Accuracy is interpreted to mean that the true value of the variable can be sensed with no systematic positive or negative errors in the measurement. Over many measurements of the variable, the average error between the actual value and the sensed value will tend to be zero

2. Precision: The precision of the measurement should be as high as possible. Precision means that there is little or no random variability in the measured variable. The dispersion in the values of a series of measurements will be minimized.

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Q. What are the functions of sensors in robot- 2 Marks

Ans.

- A robot moves in space to perform tasks and hence it needs actuators to move the links and sensors to know where each joint is.
- Sensors inform the controller by how much each joint has moved and thus enables the controller to enforce a particular velocity or position during motion.

Q. Explain various applications of robot- 7 Marks

1. Material Handling: Pick-and-Place Operations, Palletizing and Related Operations, Machine loading and unloading
2. Machining Operations: Drilling, routing, and other machining operations, Grinding, polishing, deburring, wire brushing, and similar operations
3. Processing operations: Die casting, Plastic molding, Forging and related operations, Stamping press operations , spot welding, continuous arc welding, spray coating
4. Other processing operations using robots: Riveting , Water jet cutting, Laser drilling and cutting
5. Assembly and inspection
6. Advanced robotic Application: Rehabilitation, Defense, Outer space, Intelligence, Tele presence, Mobility and navigation

Q. At time 't' the excitation voltage to a resolver is 24v and Vs1=17v and VS2=-17v what is the angle- 2 marks

$$V_{s1}(t) = A\sin(\omega t)\sin\theta$$

A sin (ωt)= is excitation voltage

$$V_{s2}(t) = A\sin(\omega t)\,\text{Cos}\theta$$

$$\arcsin\left(\frac{17}{24}\right) = 45° \text{ or } 135°$$

$$\arccos\left(-\frac{17}{24}\right) = 135° \text{ or } 225°$$

The shaft angle must be 135°.

Q. Discuss briefly about position and velocity sensor- 10 Marks

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Department of Mechanical Engg.

Industrial Automation and Robotics- Assignment No.1

Q.1 Define the term 'Automation'. What are needs of automation discuss them in detail?

Q.2 What are different forms of Computer Process Control?

Q.3 Describe different types of Automation

Q.4 Write down the level of automation? Distinguish the level of automation between the process industries and discrete manufacturing industries?

Q.5 What is numerical control? Describe the basic component of NC with help of Sketch?

Q.6 What are the advantages and disadvantages of Numerical control?

Q.7 What are applications of NC?

Q.8 Describe the manual part programming?

Q.9 Define the cutter offset?

Q.10 Explain APT Part programming Language with example?

Q.11 what is automated assembly lines? Define the following terms

(a) Workstation (b) Starving of stations (c) Blocking of Stations

Q.12 Describe the Models to cope with Product variety in manual assembly lines?

Q.13 Describe the different kind of alternative assembly lines?

Q.14 list out the different System Configurations used in automated production lines?

Q.15 Solve the following Question on Geneva mechanism

A rotary worktable is driven by a Geneva mechanism with five slots.

The driver rotates at 24rev/min. Determine (a) the cycle time, (b) available process time, and (c)indexing time each cycle.

Q.16 Define the term storage buffer?

Q.17 What are the Control Functions in an automated Production Line?

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Q.18 What is transfer line? Discuss the analysis of Transfer lines with No internal storage buffer and with internal storage buffer?

Q.19 A machine tool builder submits a proposal for a 20-station transfer line to machine a certain component currently produced by conventional methods. The proposal states that the line will operate at a production rate of 50pc/hr at 100% efficiency. On similar transfer lines, the probability of station break downs per cycle is equal for all stations: p=0.005breakdowns/cycle. It is also estimated that the average downtime per line stop will be 8.0min. The starting casting that is to be machined on the line costs $3.00 per part. The line operates at a cost of $75.00/hr. The 20 cutting tools (one tool per station) last for 50 parts each, and average cost per toolis$2.00 per cutting edge. Determine (a)production rate, (b)line efficiency, and(c)cost per piece produced on the line.

Q.20 Write down the difference between absolute and incremental positioning in NC System with figure?

RGMCET . NANDYAL

SUB: Industrial Automation And Robotics
Name: D Vivek.

1. Define the term Automation What are Needs of Automation discuss them in detail?
2. What are different forms of computer process Control?
3. Describe different types of Automation
4. Write down the level of Automation ? Distinguish the level of Automation between the process Industries and discrete Manufacturing Industries ?
5. What is Numerical Control? Describe the basic Component of NC with help of sketch
6. What are the Advantages and dis Advantages of Numerical Control
7. What are Application of NC ?
8. Describe the Manual part programming
9. Define the cutter offset ?
10. Explain APT part programming Language with Examples
11. What is Automated assembly lines? Define the following Terms (a) Work station (b) Starving of stations (c) Blocking of stations
12. Describe the Model of Cope with product Variation Manual Assembly lines
13. Describe the different kind of Alternative Assembly lines

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14. List out the different System Configuration Used in Automated production lines?

15. Solve the following Questions on Geneva Mechanism

A rotary Worktable is driven by Geneva Mechanism with five slots. The driver rotates at 24 rev/Min. Determine (a) the cycle time (b) Available process time and (c) Indexing time each cycle

16. Define the term storage buffers

17. What are the Control functions in an Automated production line

18. What is transfer line? Discuss the Analysis of Transfer lines with No Internal Storage buffer and with Internal Storage buffers

19. A Machine tool builder submits a proposal for a 20 station transfer line to Machine a certain Component currently produced by Conventional Methods. The proposal state that the line will operate at a production rate of 50 pc/hr at 100% efficiency. On similar transfer lines, the probability of station break downs per cycle is equal for all stations p=0.005 break down/cycle. Average downtime 8.0 min. Machine line cost $3.00 per part. Line operate cost $2.00 per cutting edge. Determine the (a) production rate (b) line efficiency (c) cost per piece

20. Write down the difference between absolute and incremental positioning in NC System with fig?

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1. Automation in some component of the firm production system are likely to be automated where as others will be operated manually. The Automated of the production system can be separated into two categories.

→ Automated Machine tools that process parts
→ Transfer lines that perform a series of Machining operation
→ Automated assembly systems
→ Manufacturing systems that use industrial robots to perform processing or Assembly operations
→ Automatic inspection system for quality control

2 Different forms of Computer process control.

1 program Computer process Monitoring
2 Direct digital control 3 Numerical control and Robotics
4. programmable logic controllers 5 Supervisory Controls

Different types of Automation

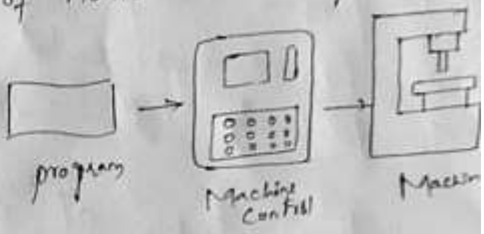
1 Fixed Automation
2. Programmable Automation
3 Flexible Automation

4. Levels of Automation in the process Industries and discrete Manufacturing Industries

Level	Level of Automation in the process Industries	Level of Automation in discrete Manufacturing Industries
5	Corporate level	Corporate level
4	Plant level	Plant or factory level
3	Supervisory Control	Manufacturing cell
2	Regulatory Control level	Machine level
1	Device level	Device level

5. Numerical control (NC) System is device by direct input of data in the form of numbers, letters, Symbols, word

→ program of Instruction
→ Machine Control Unit
→ Machine Tool



6. Numerical Control

Advantage
→ High productivity
→ Reduced Non-productive time
→ Reduced fixturing
→ NC Machine are safer to operate

Dis Advantage
→ High Investment Cost
→ High Maintenance Cost
→ Need for Skilled programmer
→ High Utilisation required

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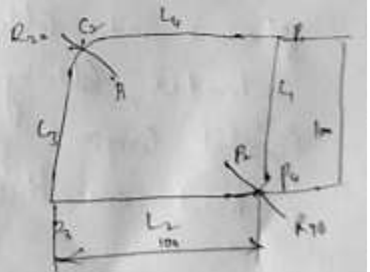
7. Application of NC:
They are widely used in 1. press working
2. Automatic drafting
3. Metal cutting
4. Spot welding
5. Inspection
6.

8. Manual part programming:
In Manual part programming the part programmer specifies the Machining instructions on a form called a Manu Script. Manu Script can in format to have various forms depending on the Machine tool and tape

9. Cutter offset:- It is an offset and shift from centre line of the tools shaft to the cutout edge along a programmed path

10. Apt programming language: Apt is used to program Numerically controlled machine tools to create complex parts using a cutting tool moving in space. It is used to calculated a path that a tool must follow to generate a desired form.



Part No / APT-1
1) Geometry definition
Radius
2) Motion Commands
FINI A1-

11. Automated Assembly line is a production equipment for specification for various assembly, Inspection, Marking, packing in the later stages of product manufacturing

(a) Work Station :- In these increase the productivity and improve the work performance

(b) Auto Automation Blocking :- It is to find out how in stage to help to automate the blocking.

12. Manual Assembly process:-
Manual Assembly is typically used for prototype and Manual Assembly for odd form components work and in post-automated assembly for ... In these Manual Assembly for Both surface mount technology. In these Manual Assembly ... integrated several time to functionally test sections of the ... as it is assembled. Manual Assembly may involve both ... placement and soldering or a mixture of manual placement and soldering. Manual Assembly can be tedious w... automated soldering. Manual Assembly ... in the PCB project a... Consistent component placement and orientation ... and manual assemblies

14. List of different system configuration used in Automated production lines

- In line
- Segmented In line
- Rectangular layout
- Rotary

15. Given

driven roller $N = 24$ rev/min

No. of Stations $(N_s) = 5$

1. Cycle Time (T_c)
2. Available process (T_s)
3. Indexing time each cycle (T_r)

1. Angle of rotation

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

$$= \frac{360}{5} = 72^\circ$$

$$\theta = 72^\circ$$

2. The cycle Time $T_c = \frac{1}{N}$

$$= \frac{1}{24}$$

$$T_c = 0.041 \text{ min}$$

3. processing Time $T_s = \frac{180+\theta}{360 \times N}$

$$= \frac{180+72}{360 \times 24} = \frac{252}{8640} = 0.029 \text{ min}$$

$$T_s = 0.029 \text{ min}$$

Indexing Time $(T_r) = \frac{180-\theta}{360 \times N}$

$$= \frac{180-72}{360 \times 24}$$

$$= \frac{108}{8640}$$

$$= 0.012$$

16 Term Storage buffers.

A cell or connected group of cells that convert chemical energy into element

Storage buffer: a part of Ram used for temporary storage of data that is waiting to be sent to a device. Used to compensate for difference in the rate of flow of data between components of a computer

17 Control functions in An Automated production line:

The Basic control functions that can be distinguished in the operation of an automated transfer machine include sequence control, safety monitoring, quality control

Transfer line is synchronous production line consisting of several wor stations in series integrated into one system by a common trans mechanism and control system.

Buffer storage: Buffer storing system is a temporary storage loc for goods being proces

It is located in between process station when processing time are significantly different

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1. Analysis of Transfer Line with Storage Buffer:

In an automated production line with no internal storage of parts the work station are interdependent. When one station breaks down all other station on the line are affected either immediately after cycle of operation. The other stations stop for one or other two reasons

1. Starving of stations 2. Blocking of stations

Starving of station means that a work station is prevented from performing its cycle because it has no part to work on. When a breakdown occur at any work station

Blocking means that station is prevented from performing its working cycle because it cannot pass the part it just completed to the neighbour downstream station.

Two extreme cases of storage buffer effectiveness can be identified.

1. No buffer storage capacity at all. 2. Infinite capacity storage buffer

1. No buffer

The line efficiency of a zero capacity storage buffer

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

that the cycle time T_c is the same for all the stages

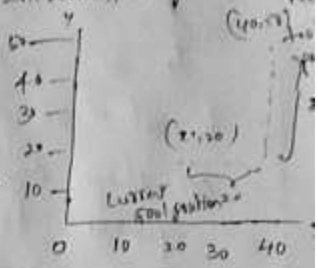
efficiency for an storage is given by

$$E_\infty = \frac{T_c}{T_c + F_i T_{d_i}}$$

E_∞ = Minimum (E_i)

Given:

Difference between Absolute and Incremental position of NC system



Absolute position	Incremental position
An Absolute position in the cutting tool is stationary	→ Incremental position in the cutting tool current based position
→ Zero point (coordinate based)	→ Distance based
→ Motion Control	→ relation on previous location of the [illegible]

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MECHANICAL ENGINEERING

(Affiliated to J.N.T.U.A, Anantapuramu)

Mid Semester Exam-I

R-15

College Code: 09

Rajeev Gandhi Memorial College of Engineering & Technology

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IV B.Tech II-Semester Mid-I *Examinations*

I A & R

MECHANICAL ENGINEERING

Max. Marks: 25 | **Date: 07-07-2021** | **Time: 90 Min**

Note: 1.Answer FIRST question compulsorily. (5 x 2 = 10Marks)
2. Answer Any *THREE* from 2 to 5 questions. (3 x 5 = 15 Marks)

Q.1	a)	Define Automation.	2M	CO1
	b)	Define sensor, List some of sensors used in automation system.	2M	CO1
	c)	What is the difference between M00 AND M30?	2M	CO2
	d)	Write any three disadvantages of NC?	2M	CO2
	e)	What is Storage Buffer?	2M	CO3
Q.2	a)	Discuss in brief about the ten strategies for automation process improvement.	3M	CO1
	b)	What is fixed automation and write its features.	2M	CO1
Q.3	a)	Discuss in detail about forms of computer process control.	3M	CO2
	b)	Provide a brief explanation about classification of actuators based on drive power.	2M	CO2
Q.4	a)	What are the factors favoring the manual assembly line?	3M	CO3
	b)	Explain in detail about work transport system in manual assembly line.	2M	CO3
Q.5	a)	Differentiate between Absolute and Incremental coordinate system?	2M	CO2
	b)	Discuss in detail about the classification of NC machines.	3M	CO2

****

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INTERNAL EXAMINATIONS ANSWER BOOKLET

NAME OF THE STUDENT: K.Venkata Harish Reg. No. 1 5 0 9 1 A 0 3 K 3

	1	2	3	4	5
A	2	2	2		1
B	2	2	2		3
C	2				
D	2				
E	2				
Total	10	4	4		4

Grand Total :(In Figures) 22

(in Words): Twenty two

NAME OF THE SUBJECT: IA & R

INTERNAL EXAM : I / II

Date of Exam: 07-07-2021 (FN/AN)

Course : B.Tech. / M.Tech./ MBA / MCA

Year : IVth Sem.: Ist

Branch: mechanical.

Signature of the Invigilator

(Start Writing From Here)

① Automation :-

ⓐ Automation is defined as the process or proceedure is accomplished without human effort is called as the automation.

(2)

* mechanical process is done automaticaly with the help of machines with out human effort is called automation.

ⓑ sensor :-

sensor is a transduser used to convert Physical Property of a variable into mesurable calibrated values that are easy to calculation Process.

(2)

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* Accelero meter
* Dynamo meter
* Psycho meter.

The above are the some sensors used in automation process.

(c) M00 : Is used stop the program

M30 :- Is used to rewind the program

(2)

(d)

Disadvantages of NC :-

1. Highly cost.
2. Not usefull for the small work.
3. Not convienient to change from one place to other place

(2)

(e)

Storage Buffer :-

Storage Buffer is used to store some areas that are used when there no areas.

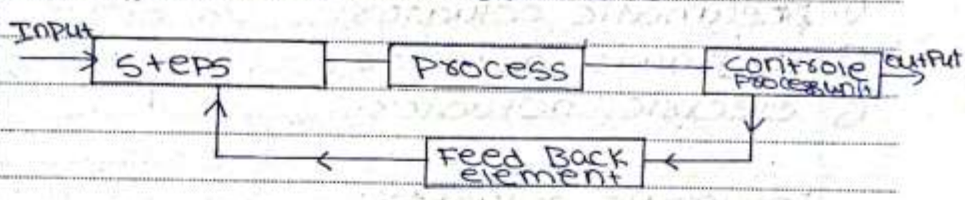
* It is present In between them
* It can provide when the need of this then storage Buffer can provide.

(2)

③

ⓐ Forms of computer process controle :- There are Two Types of computer process controle. They are
① Closed proces controle
② open proces controle

⊛ Closed process controle :- Here mainly Feed back element required

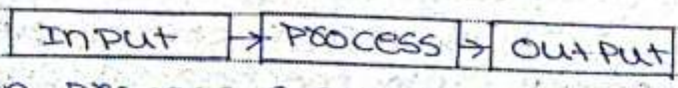


② ⊛ Feed Back element is required to Give information whether work done (or) not to the Input.

⊛ Given Input is Going to be checked and is Going to be Processed in the controle process unit.

⊛ The output come Positive (or) negative It is Going to be send to Input by the Feed Back element.

open process controle :-



In open process controle there is no Feed Back element is there.

* open proces controle work is to give input to the system whether the work is done (or) not is not required

(b) Classification of Actuators:-

Baced on the procedure of their working system actuators are classifing

1. pneumatic actuator.
2. Hydraulic actuator
3. electric actuator.

Pneumatic actuator:- These are linear actuator which uses a Piston inside a hollow cylinder by passing pressurized air as input.

Hydraulic actuator:- Hydraulic is similar to pneumatic but incompressible liquid used instead of pressurised air

electric actuator:-

Electric actuator is used to convert electrical energy into Torque i.e, It is used to convert electrical energy into mechanical energy

(2) Strategies For automation process:-

(a) * Automation process can reduce the human effort.
* Productivity is more in automation process
* Automation process is a flexible process
* It Reduce the cost.
* work Done is more & quick.
* proper Functioning of machines
* Different operations done at a time
* Repet of Items also easily done
* No external agent required.

(b) Fixed automation:-

Fixed automation is onetype of automation proces. used in large number.
* The process is Going to be Fixed with Given operation
* It is not Going to be changed. so it is called as Fixed automation process
* whereas in programable automation many parts are there.

Features:-
1. easy to do work.
2. Having more production
3. Less cost.
4. easy to operate.

(5) Classification of NC machines:-

(b) Based on their performance NC machines are classified as follows

(1) Numerical controle machine (NC)
(2) Computer numerical controle (CNC)
(3) Direct Numerical controle (DNC)

NC is a process of doing work with coded language that is understand to computer

Direct Numerical controle can take Directly with out any input

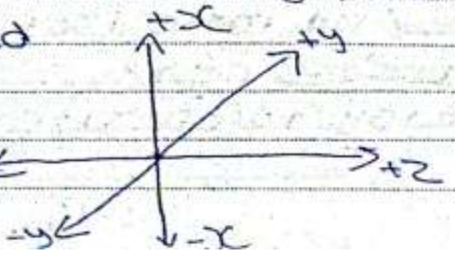
(3)

(a) Absolute co-ordinate system

There is no movement of z-axis and the system is absolute no increment (or) No Dicrement

Incremental:- The co-ordinate system which is having more than required

(1)



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Department of Mechanical Engg.

Parametric Modelling-II- Assignment No.2

1. List out different types of grippers for robot?
2. Discuss in detail about robot configuration along with necessary sketches?
3. Draw the sketch of work volume for cylindrical and cartesian robot?
4. Explain following terms: (i) Spatial Resolution (ii) Accuracy(iii) Repeatability?
5. What is difference between forward and inverse kinematics?
6. how transformation matrices are represented for a pure rotation axis?
7. Explain with sketches the Denavit- Hartenberg representation to describe the relationship between the adjacent link of a robot?
8. Prepare a D-H parameter table for a simple 2- axis articulated robot?
9. A point $P(7,3,2)^T$ is attached to a frame (n, o, a) and is subjected to the transformation described next. Find the co-ordinates of the point relative to the reference frame at the conclusion of transformation?

a. Rotation of 90 degree about Z- axis.
b. Followed by a rotation of 90 degree about y- axis
c. Followed by a translation of [4, -3, 7]

10. Discuss inverse kinematics along with its characteristics?
11. Find the effect of a differential rotation of 0.1 rad about the y-axis- followed by a differential translation of [0.1, 0, 0.2] on the given frame B.?
    [0 1 1 10; 1 0 0 5; 0 1 0 3; 0 0 0 1]
12. What is homogenous transformation of coordinates?
13. State the Lagrange-Euler equation. Describe all the terms in detail?
14. What are the various types of actuators?
15. Differentiate between Hydraulic, Pneumatic and electric Actuator?
16. Provide a brief explanation about classification of actuator based on drive power?
17. What are the factors needs to considered while selecting a sensor?
18. What are the functions of sensors in robot?
19. Explain various applications of robot?
20. At time 't' the excitation voltage to a resolver is 24v and Vs1=17v and VS2=-17v what is the angle?

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1 List out different types of grippers for robot.
2 Discuss in detail about robot Configuration along with Neat diagram
3 Draw the sketch of work Volume for cylindrical and Cartesian
4 Explain following terms (i) Spatial Resolution (ii) Accuracy (iii) Repeatability
5 What is difference between forward and inverse kinematics
6 How transformation matrices are represented for a pure rotation ...
7 Explain with sketches the Denavit Hartenberg representation to describe the relationship between the adjacent link of a robot
8 Prepare D-H parameters table for a simple 2-axis articulated robot
9 A point P(7,3,2) is attached to a frame (n,o,a) and is subjected to the transformations described next. Find out the coordinates of the point relative to the reference frame at the conclusion of transformation
10 Discuss inverse dynamics along with its characteristics
11 Find the effect of a differential rotation of 0.1 rad about the y-axis followed by a differential translation of (0, 1.0, 2) on the given frame
B) [0 1 1 0; 1 0 0 5; 0 1 0 3; 0 0 0 1]
What is homogeneous transformation co-ordinates
12 State the Lagrange-Euler equation. Describe all the terms in details
13 What are the various types of actuators?
14 Difference between Hydraulic, Pneumatic and electric Actuators.
15 Provide a brief explanation that classifications of actuator based on ...
16 What are the factors needs to considered while selecting a ... drive power
17 What are the function of sensors in robot
18 Explain Various application of robot
19 At time 't' the excitation Voltage to a resolver is 24 V and V_{S1} = 17 V, V_{S2} = 17 V. What is the angle.
20

Answers

1. Types of grippers for robots
   1. Vacuum grippers
   2. Pneumatic gripper
   3. hydraulic grippers
   4. Servo electric gripper

Robot configuration :- It has to robots tool moving in a linear motion along each of the Cartesian coordinates (x, y, z) this type of configuration can sweep out a box like work envelop Many 3D printers have these print nozzles mounted on a Cartesian configuration. A robot's work volume is not only defined by the robot's arm but the structure of the robot can also define its motion.

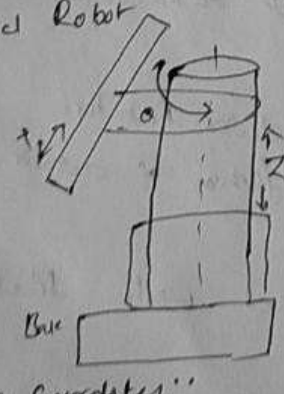
3 cylindrical configuration and Cartesian Robot :

→ It is a vertical column and a slide that can be moved up or down along the column

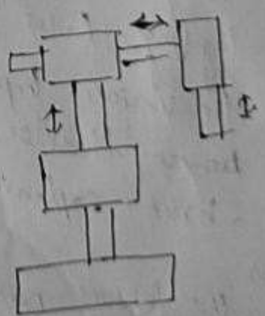
→ The robot arm is attached to the slide so that it can moved radially with respect to the column

→ It contains two linear motions and one rotational motion

Cylindrical Robot



Cartesian robot



Cartesian Coordinates :-

→ Notation LOO:

three sliding joints two of which are orthogonal

4. Spatial Resolution: Spatial resolution is a measure of smallest object that can be resolved by the sensor or the ground area imaged for the instantaneous field of view of the sensor.

Accuracy: The quality or state of being correct or precise.

Repeatability: is defined as the closeness of agreement between independent test results obtained with the same method.

5. difference between forward and inverse kinematics

Forward

The Arm animate the hand's position by rotating at the shoulder

- the transformation of coordinates of the end effector point from the joint space to the world space is known

Inverse

Arm by animating the hand position

- the transformation of coordinates from world space to joint space is known

6. Rotation Matrix:

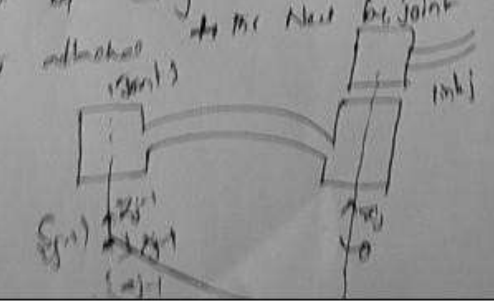
In linear algebra a rotation matrix is a transformation matrix that is used to perform a rotation in Euclidean space.

$$R = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

8. prepare the D-H parameters for a simple 2 axis

→ Model popular by Craig intro to Robotics

→ Link connects adjacent to the next joint



Inverse animation and robotics Inverse kinematics is the mathematic process of calculating the variable joint parameters needed to place the end of kinematic chain

Characteristics:

→ It is given position and orientation relative to the start of the chain

→ the position and orientation of the chains end can be typically be calculated directly using multiple application

12 To combine these three transformation into a single transformation homogeneous coordinates are used. In homogeneous coordinates system two dimension coordinate position (x, y) are represented by triple coordinate. In these homogenous transformation matrix uses the both rotation and translation original coordinate frame to describe

13 The Euler - lagrange Equation will necessary conditions for extremum of a function $I(x) = \int_a^b f(x, t, \dot{x}(t))\,dt$ condition in the form of additional equation. It is necessary that the extremely curve should satisfy and this differential equation is called the Euler largerany equation

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1b Types of Actuators:

→ Electric linear
→ Electric Rotary
→ Fluid power linear
→ Fluid power Rotary
→ Linear Chain Actuators
→ Manual linear

1a Difference between Hydraulic, Pneumatic, electric Actuator

Hydraulic	Pneumatic	Electric
1 Hydraulic linear actuator operate similar to pneumatic but an incompressible liquid is present from a pump	1 Pneumatic linear actuator consist of piston inside a hollow cylinder. pressure from an external pump moves the piston inside	1 An electric linear actuator converts electrical energy into speed and torque. A mechanically connected electric motor turns the lead screw.

1c Classification of actuator: the fundamental classification of the actuator is based on the type of the energy which is converted into the mechanical motion and on the type of the performed motion. the hydraulic and pneumatic actuator converts stored potential energy of the pressurized fluid or gas medium.

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factors of sensor:

→ Linearity
→ frequency response
→ Reliability
→ Repeatability
→ size weight and volume

18 Functions of sensors
→ Temperature
→ Specific gravity
→ Dielectric constant
→ Overpressure
→ Shock and vibration
→ Barometric pressure

19 Robotics are generally used for the fabrication, finishing, transfer and assembly of parts. In material handling industries where finished products are prepared for distribution, robotics are used for picking and palletizing of products.

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MECHANICAL ENGINEERING

(Affiliated to J.N.T.U.A, Anantapuramu)

College Code: 09

Rajeev Gandhi Memorial College of Engineering & Technology

Autonomous

NANDYAL-518501

IV B.Tech II-Semester MID-II *Examinations*

Industrial Automation and Robotics

Mechanical Engineering

Max. Marks: 25 **Date: 07/07/2021** **Time: 1.5 Hours**

Note: 1. Answer FIRST question compulsorily. (5 x 2 = 10 Marks)
2. Answer Any *THREE* from 2 to 5 questions. (3 x 5 = 15 Marks)

Q.1	a)	What are the functions of sensors in robot?	2M	CO1
	b)	How transformation matrices are represented for a pure rotation axis?	2M	CO2
	c)	What is difference between forward and inverse kinematics?	2M	CO2
	d)	Describe the link parameters in context of D-H Conventions?	2M	CO3
	e)	List out different types of grippers for robot?	2M	CO4
Q.2		What is homogenous transformation of coordinates?	5M	CO2
Q.3		Differentiate between Hydraulic, Pneumatic and electric Actuator?	5M	CO1
Q.4		Explain with sketches the Denavit- Hartenberg representation to describe the relationship between the adjacent links of a robot?	5M	CO3
Q.5		Discuss in detail about robot configuration along with necessary sketches?	5M	CO4

****

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RAJEEV GANDHI MEMORIAL COLLEGE OF ENGINEERING & TECHNOLOGY
AUTONOMOUS
Accredited by NAAC of UGC, New Delhi with 'A' Grade:: Accredited by NBA
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Nandyal - 518 501, Kurnool Dist, A.P.

INTERNAL EXAMINATIONS ANSWER BOOKLET

NAME OF THE STUDENT: T. Charshi Vardhan Reg. No. 1 7 0 9 1 A 0 3 8 0

	1	2	3	4	5
A	2	2	4	5	4
B	1				
C	1				
D	2				
E	1				
Total	7	2	4	5	
Grand Total :(In Figures)	18				
(in Words):	eighteen				

NAME OF THE SUBJECT: IA&R
INTERNAL EXAM : I / II
Date of Exam: 7/7/21 (FN/AN)
Course : B.Tech. / M.Tech. / MBA / MCA
Year : IV Sem.: 2nd
Branch: Mechanical

Signature of the Invigilator

(Start Writing From Here)

(3)

Hydraulic Actuator:

1. Robots Can load heavy loads and only one load.
2. High maintenance.
3. High Accuracy
4. Difficult to clean the room
5. fluids can be used.
6. Gears are not reduced
7. More time
8. Eco-friendly

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Electric Actuator :-

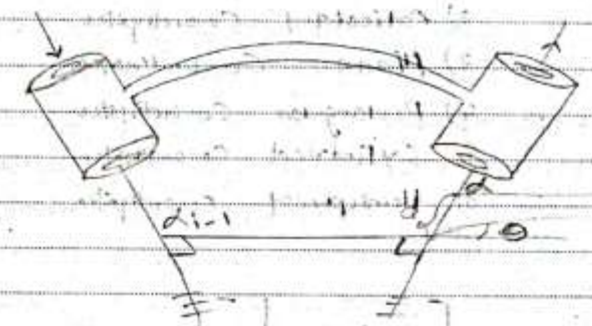
1. Robots can load two (or) more heavy loads
2. It is better than the Hydraulic
3. It Requires motors, Pumps etc
4. It is risk
5. Gears are reduced
6. It Require Power
7. Skilled worker Required.

Pneumatic Actuator :-

1. It is given on (or) off the machine
2. Less High Accuracy
3. Less maintenance
4. Air can be used
5. Pressurized air will not available
6. Its ecofriendly
7. It is better than Hydraulic

4)

Denavit - Hartenberg Representation:



θ = angle between links
d_{i-1} = link segment
d = link line
d = distance between links

(5)

Relationship between the adjacent links of a Robot is same as Human body. It consists of joints and links. Shoulder joint and Ball and socket joint. Robot also consists of links and joints. These are called manipulator. At the end of the link end Reflector (or) manipulator is there to hold the object (or) to perform any function of that Robot. It is defined as the perpendicular distance between the links. At each link it forms 90°. Two cylinders are placed at each side of the links.

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2)

Homogeyous Transformation of Co-ordinates

Homogeyous Transformation of Co-ordinates are
1) Spherical Co-ordinates
2) Articulated Co-ordinates
3) Plane Co-ordinates
4) Rectangular Co-ordinates
5) Cylindrical Co-ordinates
6) Hemispherical Co-ordinates

$$\left[\begin{array}{ccc|c} a_1 & b_1 & c_1 & P_x \\ a_2 & b_2 & c_2 & P_y \\ a_3 & b_3 & c_3 & P_z \\ \hline 0 & 0 & 0 & 1 \end{array}\right]$$

Rotatory | Scalar

Plane Co-ordinates:- In which the base of the Plane is fixed. The plane is moves 90° top & down Position.

Rectangular Co-ordinates:- In which the Rectangular is placed on the base. The Coordinate of the machine moves in Right and Left Position.

Cylindrical Co-ordinates :-

In which the cylindrical is is placed on the base. The Co-ordinates of the Machine Moves in cylindrical (or) Circular Position.

Articulated Co-ordinates :-

In which the Co-ordinates of the Machine Moves in axial Position.

1)

a)

1. To Transfer the loads.
2. To Perform Some work
3. With the help of Sensors Robots work
4. Sense the information from other parts of machine
5. Dry moulding, Grinding, Milling etc

1)

b) Transformation matrices are Represented for a Pure rotation axis because it gives the Correct Transform matrices we can get the Required Values form them.

$$\left[\begin{array}{ccc|c} a_1 & b_1 & c_1 & P_x \\ a_2 & b_2 & c_2 & P_y \\ a_3 & b_3 & c_3 & P_z \\ \hline 0 & 0 & 0 & 1 \end{array}\right]$$

Rotation | Scalar

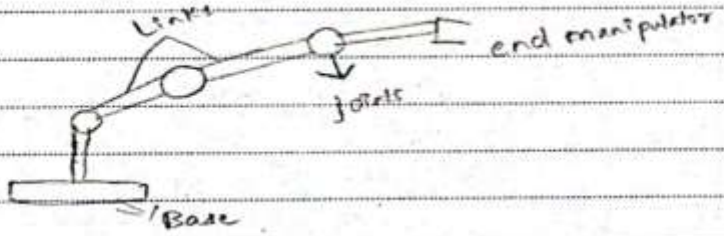
1)
c) Forward Kinematics :-
It is defined as it is a branch of science in which the it deals the acceleration, velocity speed and direction of the object.

Inverse Kinematics :-
It is defined as the mathematical in the function of the Robots can perform. It performs Rotational and vibrational motion

1)
d) link parameter in D-H Convention
θ = angle ~~btw~~ between links
d_{i-1} = link segment
α = link line
d = distance ~~btw~~ between links

1)
e) Grippers are used to hold the object
1) Belts
2) Conveyors
3) Pallated Boxes
4) Robots
5) Machines

1)
5)



Robots Configuration Can form by Joining of the Links and Joints. These are Called manipulator. Actuators are also placed in the Robots. Sensors are also placed in the Robots to Perform the functions as Per w/e Required. It follows the Same as human body mechanism. Human body Consists of Shoulder Joints and Ball & socket joints. It works Similar to the Robots. No need of Humans while using Robots. Its works efficiently and long Period of time.

End Semester Exam

Code: A0336158R0721

RGM COLLEGE OF ENGINEERING & TECHNOLOGY (AUTONOMOUS)
8th July-2021
IV B.Tech II Semester (R15) End Examinations (Regular)
INDUSTRIAL AUTOMATION AND ROBOTICS
MECH

Time: 3 Hrs **Total Marks: 70**

Note 1:Answer Question No.1 (Compulsory) and 4 from the remaining
2:All Questions Carry Equal Marks

1a What is Inverse Kinematic of a robot?

b What are the types of Assembly Line?

c Find the output voltage of a potentiometer with the following characteristics also determine the voltage constant of the part (K_P). The excitation voltage=21v, total wiper travel=320^0, wiper position=64^0.

d What is the Work envelop of a robot?

e List out levels of automation system.

f How is computer numerical control distinguished from conventional numerical control?

g How an Prismatic (sliding) joint is notated for a Manipulator.

2 a) A point p(7,3,2)^T is attached to a frame(n o a) an is subjected to the transformation described next. Find the co-ordinates of the point relative to the reference frame at the conclusion of transformation. (7)
i) Rotation of 90^0 about the Z-axis
ii) Followed by a rotation of 90^0 about Y-axis
iii) Followed by a translation of [4 -3 7]
b) Discuss the Inverse kinematics along with its characteristics. (7)

3 a) Explain in detail about basic components involved in NC system. (10)
b) Write any four advantages of NC system. (4)

4 a) What are the various Joints used in a Manipulator explain and provide their joint notation Scheme. (10)
b) Explain the following terms (4)
i) Polar Configuration
ii) Jointed-arm Configuration

5 a) Discuss in detail about Geneva Mechanism. (7)
b) Provide the reasons why Manual assembly lines are so productive compared to alternative methods. (7)

6 a) Explain the working of stepper Motor. (7)
b) Explain the following sensors. (7)
i) Touch sensor.
ii) Force sensor.

7 a) Define Material handling. (4)
b) Explain in detail about Input& output devices for discrete data. (10)

- xxx -

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RGM College of Engineering & Technology (Autonomous) ①
8th July - 2021
IV B.Tech II sem (R15) End Examinations (Regular)
Industrial Automation & Robotics
Mech. engg. code - A0336158R0721

1 a) Inverse kinematics - Given the final position of End effector, the calculation of all joint variables is called inverse kinematics [2M]

b) Types of Assembly line
1) manual Assembly line
2) Alternative Assembly line
a) A single station manual Assembly cell
b) Assembly cells based on workers teams
c) Automated assembly systems [2M]

c) Given values

$V_{ex} = 21\,V \quad \theta_{tot} = 320°$

$\theta_{ac} = 64°$

$k_p = \frac{V_{ex}}{\theta_{tot}} = \frac{21}{320} = 0.0656\ V/deg$ [1M]

$k_p = 0.0656$

$64° \times 0.0656 = 4.198\,V \simeq 4.2\ Volts$ [1M] [2M]

d) work envelop of a Robot :- It is the three-dimensional space within which the robot can manipulate the end of its waist.

[2M]

②

e) List out levels of automated system

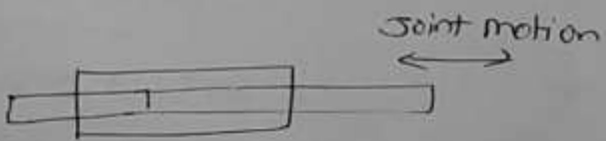
level	
5	Enterprise level
4	plant level
3	System level
2	Machine level
1	Device level

↓↑ Flow of data

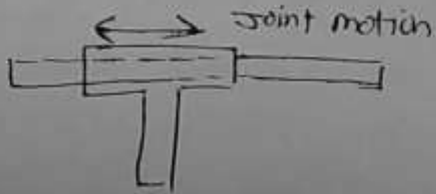
[2M]

f) 1) Storage of more than one part program
2) program editing at the machine tool
3) Fixed cycles & programming sub routines
4) adaptive control
5) Interpolation
6) Positioning features for setup
7) Acceleration & deceleration calculations
8) communications interface
9) Diagnostics [Any two] [2M]

g) sliding joint:-
Linear joint
Notation L



orthogonal joint
notation O



[2M]

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Sol) point $P\begin{bmatrix}7\\3\\2\end{bmatrix}$

(i) Rotation about z-axis

Rotation matrix $R_z = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

$\theta = 90°$

$R_z = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$ [2M]

(ii) Rotation of 90° about y-axis

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

$\theta = 90°$

$R_y = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$ [2M]

(iii) Translation matrix

$T = \begin{bmatrix} 1 & 0 & 0 & p \\ 0 & 1 & 0 & q \\ 0 & 0 & 1 & r \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 4 \\ 0 & 1 & 0 & -3 \\ 0 & 0 & 1 & 7 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

$p = 4 \quad q = -3 \quad r = 7$ [2M]

(4)

location of point after transformations

$P' = [T] \times [R_{y,90}] \times [R_{z,90}] \times P$

$$P' = \begin{bmatrix} 6 \\ 4 \\ 10 \\ 1 \end{bmatrix}$$ [1M]

[7M]

2 b)

Ans:- Inverse kinematics :- Given the position & orientation of End-effector, calculating the joint variables (joint angle) is inverse kinematics [3M]

* Characteristics of Inverse kinematics

a) Solving the problem of finding the required joint angles to place the tool frame {T} relative to station frame, {S}, which is split into two parts

b) First, frame transformations are performed to find the wrist frame, {W}, relative to the base frame, {B}, & then the inverse kinematics are used to solve for joint angles

c) The position & orientation of end effector is collectively called the configuration of robot

[4M]

[7M]

⑤

3)

Basic components involved in NC system

* program of Instruction → 1) The part program of instruction is a set of detailed step by step commands that direct the actions of processing equipment

2) The instructions or individual commands refers positions of a cutting relative to worktable. Additional instructions are, spindle speed, feed rate, cutting tool selection etc.

3) NC program is general written punched tape in alphanumeric code.

[4M]

* Machine control unit → 1) It is hardwired electronics/ microcomputer that stores the program of instructions and executes it by converting each command into mechanical actions of processing equipment, one command at a time

2) The hardware of MCU includes components to interface with processing equipment & feedback control element.

[3M]

* processing Equipment → 1) The processing equipment does the actual productive work. It accomplishes the processing steps to transform the starting workpiece into a completed part.

[3M] [10M]

(6)

7) Into

3(b) Any four Advantages of CNC

1) Non productive time is reduced
2) Greater accuracy & repeatability
3) Lower scrap rates
4) Inspection requirements are reduced
5) More complex part geometries are possible
6) Engineering changes can be accommodated more gracefully
7) Simpler fixtures
8) shorter manufacturing lead times
9) Reduced parts inventory
10) Less floor space
11) Operator skill requirements are reduced

{Any four} [4M]

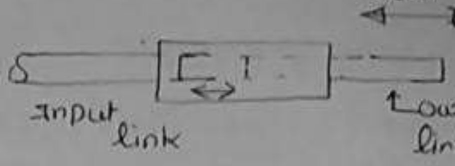
4(a) Various types of manipulator joints

* For translation motion
  a) Linear joint (type L)
  b) Orthogonal joint (type O)
* For Rotary motion
  a) Rotational joint (type R)
  b) twisting joint (type T)
  c) Revolving joint (type V)

Translation motion :- The motion is sliding motion

a) Linear type

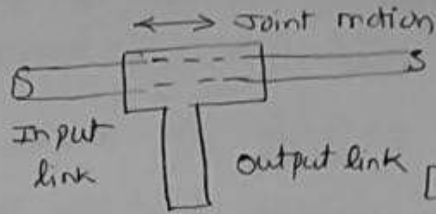
joint Notation L



[2M]

b) orthogonal joint

Joint Notation O

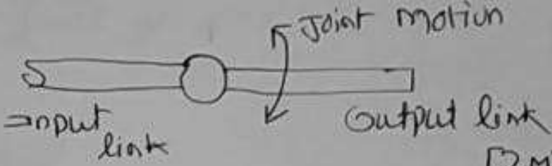


[2M]

Rotary motion :- The motion is Rotary motion between two link

a) Rotational joint

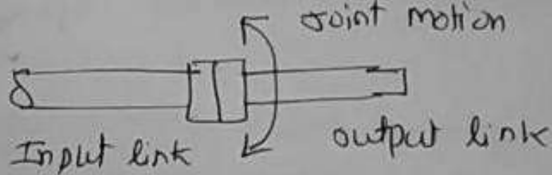
Joint Notation R



[2M]

b) Twisting joint

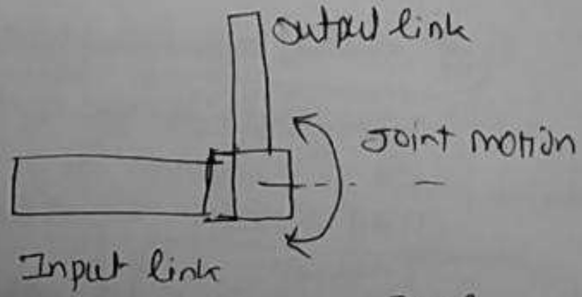
Joint Notation T



[2M]

c) Revolving joint

link notation V



[2M]

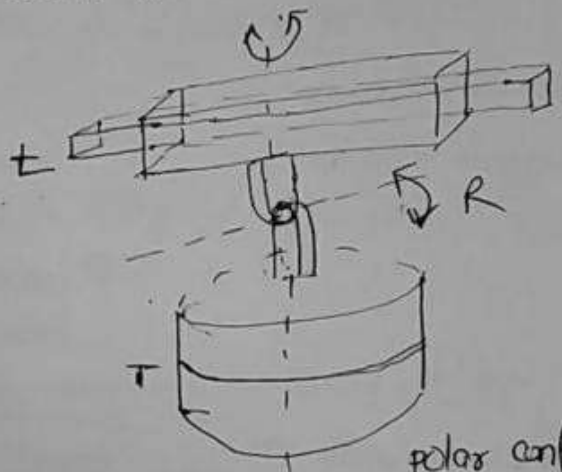
[10M]

(5) (a)

4b)
(i) polar configuration :- it consists of a sliding arm (L type joint), moving relative to body, the arm can further rotate about both vertical axis & horizontal axis

Notation → TRL :- It provides twisting, Rotary & linear motion

DOF :- 3



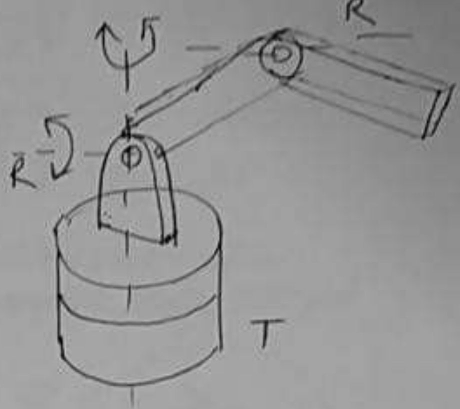
[2M]

(ii) Jointed arm - configuration :- mimics the configuration of a human shoulder & arm

Joint Notation :- TRR :- It provides twisting, Rotation & another Rotation

DOF :- 3

(7)



Jointed arm robot

[2M]

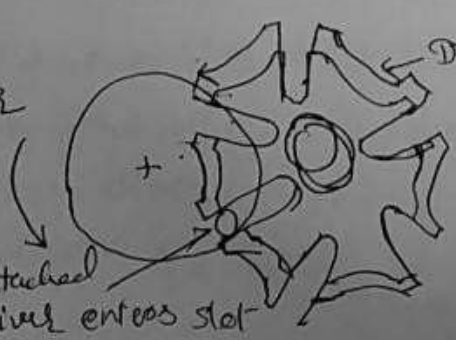
[4M]

5(a)

Geneva mechanism :- 1) It convert the Continuous Rotation in intermittent motion.

2) It uses a continuously rotating driver to index the table through a partial rotation

3) if the driven member has six slots for a station dial indexing table, each turn of the driver results in a 1/6th rotation of the worktable.



[4M]

(10)

Working principle:-

For Geneva mechanism the angle rotation is given by

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

where θ = angle of rotation of worktable

N_s = No. of slots

The available cycle time is given by

$$T_c = \frac{1}{N}$$

where T_c is cycle time N = RPM of driver

The available service time $T_s = \frac{180+\theta}{360N}$

The indexing time $T_r = \frac{180-\theta}{360N}$ [3M]

5(b) [7M]

1) Specialization of labor:- when a large job is divided into small tasks & each task is assigned to one worker, the worker becomes highly skilled in that particular task. [3M]

2) Interchangeable parts:- Each component is manufactured to sufficiently close tolerances that any part of a certain type can be selected at random for assembly with mating component. [3M]

(11)

3) work flow principle - involves moving the work to the worker rather then vice versa.

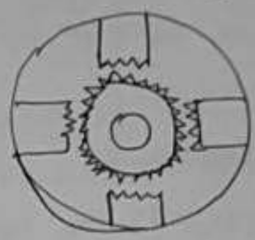
4) line pacing :- workers must complete their task within a certain cycle time. [1] [7M]

6(a)

Working of stepper motor -

1) a stepper motor has four magnetic poles arranged around a central rotor.

2) the teeth are provided on rotor as well as on the magnetic.



stepper motor design

3) Each ~~teeth~~ teeth provide the angular motion

4) the angular rotation is controlled by number of pulses recieved by the motor, and rotational speed is controlled by ~~the number of~~ frequency of pulse.

5) The step angle is related to the number of steps for the motor according to following relation

$$\alpha = \frac{360}{N_s}$$

where α = step angle n_s = number of steps for stepper motor [7M]

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(12) 7

(b)
(i) Touch sensor - Touch sensors are used to indicate that contact has been made between two objects without regard to magnitude of contacting forces.
Some examples of touch sensors are limit switches, microswitches they can be used to indicate the presence or absence of part in fixture or at pickup point along a conveyor.
[4M]

Force sensor:- The capacity to measure forces permits the robot to perform a number of task
a) The forces can be measured by measuring the deflection of an elastic elements
b) The strain gauges are most common type of force sensing element
[3M]
[7M]

7(a)

* Material handling - it is a system by which materials, parts and products are moved, stored & tracked in the world's commercial infrastructure.
* Equipment used for material handling are
1) Transport equipment
2) positioning equipment
3) unit load formation equipment
4) storage equipment
5) Identification & control equipment

[4M]

7(b) Input/output devices for discrete data

Discrete data can be processed by a digital computer without needing any kind of conversion procedures unlike analog ~~sing~~ signals

* Discrete data are divided into three categories
a) Binary data
b) discrete data other than binary
c) pulse data

(14)

i) Contact Input/output interfaces - These interfaces are of two types: input & output these interface read binary data from the process into the computer and send binary sing signals from the computers to the process.

1) Contact input interface - it is a device by which binary data read into the computer from some external source. it consists of a series of simple contacts that can be either close or open (ON or OFF) to indicate the status of binary devices connected to the process such as limited switches.

2) Contact output interface - It is a device that communicates ON/OFF signals from the computer to the process.

The contact positions are set in either of two states ON/OFF

[4M]

(2) Pulse counter :- These are the devices used to convert a series of pulses into a digital value. The value is then entered into the computer through its input channel. it is constructed using sequential logic gates called flip-flops.
examples - Encoder

[3M]

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(5)

3) pulse generator :- It is a device that produces a series of electrical pulses whose total number and frequency are specified by the control computer. the total number of pulses might be used to drive the axis of a positioning system. the frequency of pulse could be used to control the rotational speed of a stepper motor. [3M]

[10M]

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mob. no : 9589089821

2/10/7/21

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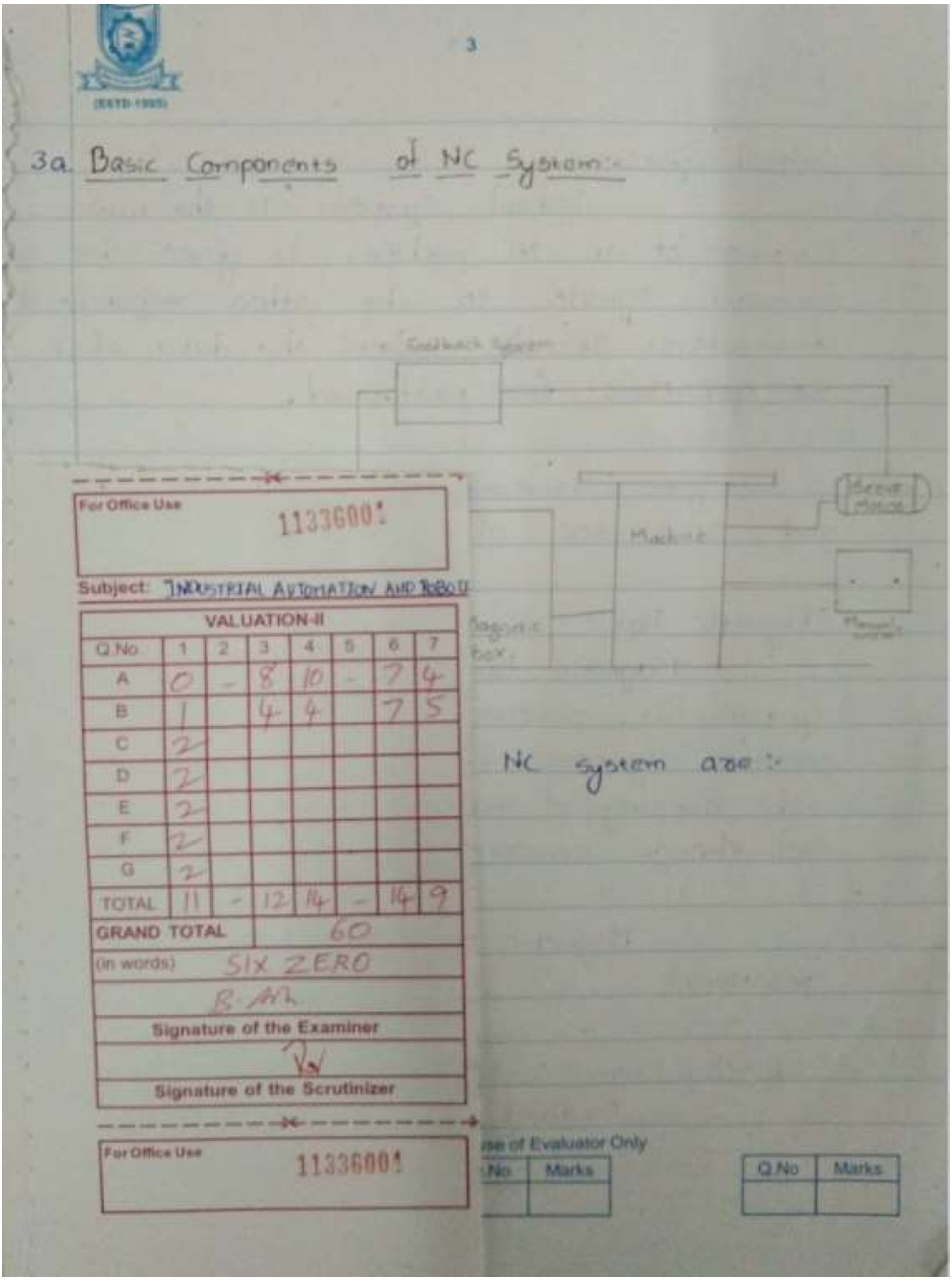
MECHANICAL ENGINEERING

(Affiliated to J.N.T.U.A, Anantapuramu)

End Exam Script Evaluation


3

ESTD 1995

3a. Basic Components of NC System:-

NC system are :-

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Subject: INDUSTRIAL AUTOMATION AND ROBOTI

VALUATION-II

Q.No	1	2	3	4	5	6	7
A	0	-	8	10	-	7	4
B	1		4	4		7	5
C	2						
D	2						
E	2						
F	2						
G	2						
TOTAL	11	-	12	14	-	14	9

GRAND TOTAL 60

(in words) SIX ZERO

Signature of the Examiner

Signature of the Scrutinizer

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Use of Evaluator Only

Q.No	Marks

Q.No	Marks

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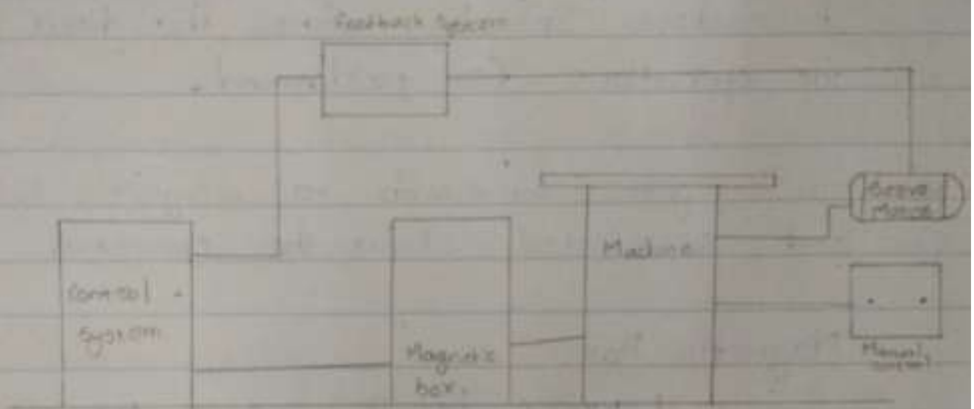
3

3a. Basic Components of NC System:-



Basic components of an NC system are:-

Control system.

Magnetic box.

Feed back system.

Servomotor.

Manual control,

Machine.

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Q.No	Marks

Q.No	Marks

Q.No	Marks

4

Control System:

Control system is the main component of an NC machine. It gives the command signals to the other components of machine. It also collects the data about the operations feo performed.

It gives commands to magnetic box and seovomotoo about the operations.

Magnetic Box:-

Magnetic box is one of the operating system. It receives signals from the control system. It controls the starting and stopping of machine, coolant supply tool change commands.

Magnetic box controls the above operations.

Feedback System:-

Feedback system checks whether

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Q.No	Marks

Q.No	Marks

Q.No	Marks

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the operations are performed according the input or not.

Servomotor :-

It also receives command signals from control system. It receives the information about ve speed, feed, depth of cut operations and it controls those operations.

Manual Control :-

Manual control is operated by a human operator. It consists of equipment like input system, output system, emergency stop. Con

Machine :-

Here all the programed instructions are carried out and performs the instructed operations.

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Q.No	Marks
3(a)	7

Q.No	Marks

Q.No	Marks

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3b. **Advantages of NC System:-**

1) **Reduction in Lead time:-**

As the whole control process is done by a machine controlled by program of instruction then it will helps in decreasing lead time.

2) **Greater Accuracy:-**

The operations performed by NC machines are controlled by a control unit then it will work accurately, but that not completely possible in case of an operator performing the operation.

3) **Increased Production:-**

As the operations are performed by the machine. It completes it's work quickly and accuratedy. This will improve the rate

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Q.No	Marks

Q.No	Marks

Q.No	Marks

of production.

4) Programmable :-

NC systems not only perform a single operation. By giving the set of instructions multiple operations can be performed. Also different designs can be manufactured using different programms.

5) Quick Quality Inspection :-

Due to increase in accuracy and precision. The finished component can get inspected easily as the component is finished very good.

6) No Need of Highly Skilled Labour :-

As the operations are performed by the machine, there will be no need of highly skilled labour.

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Q.No	Marks
3(b)	4

Q.No	Marks

Q.No	Marks

5

4a.

Manipulator is nothing but the device which is used to move of the components of a machine like arms, body, joints.

Joints are the components by which the movement of the assembly is achieved.

From joints the mobility of assembly is possible.

If we compare machine with humans the assembled joints are just like human joints. They help in movement of machine.

Joints are of two types:-

1) ~~Linear Joints~~. Transverse Joints
2) Rotary joints.

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Q.No	Marks
4	

Q.No	Marks

Q.No	Marks

Linear Joints:-

Linear

i) Transverse Joints:-

Transverse joints are joints by which the straight motion is achieved, i.e., the joints slides.

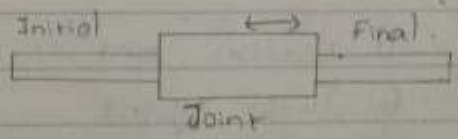
Transverse joints are of two types:-

a) Linear joints.

b) Orthogonal joints.

a) ~~Orthogonal~~

a) Linear Joints:-



Linear joints are joints in which the joints slide in the linear or along the link. Initial and Final movements are lies in a straight line.

Linear joint is denoted by "L".

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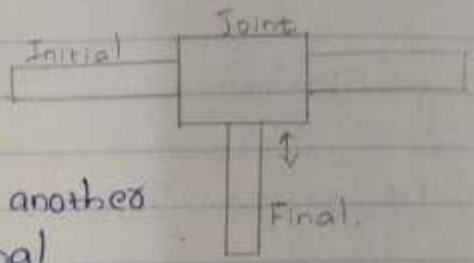
Q.No	Marks

Q.No	Marks

b) Orthogonal Joints:-

In orthogonal joints the joint slides the link orthogonal to another link. Here orthogonal movement is achieved.



It is denoted by "O".

2) Rotary Joints:-

In rotary joints the movement achieved is rotary.
Rotary joints are classified into three types.

a) Rotation joint.
b) Twist joint.
c) Revoluting joint.

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Q.No	Marks

Q.No	Marks

Q.No	Marks

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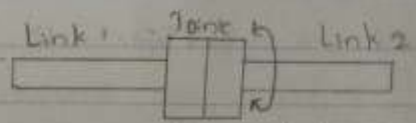
a) Rotation Joint:-

In rotational joint, the joint helps in obtaining a rotational y motion. The joint can rotate in clock wise or counter clock-wise direction based on requirement.

It is denoted by "R".

b) Twist Joint:-



In twist joint the joint helps in twisting the links. Here twist is obtained by between the two links.

It is denoted by "T".

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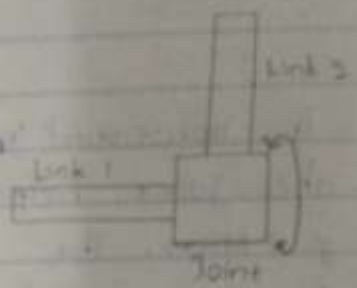
Q.No	Marks	Q.No	Marks	Q.No	Marks

c) Revoluting Joint :-

In revoluting joint the joints get the revolution motion with respect to the other link.



It is denoted by "L".

The joints are divided by : while noting like.

TOR : LO

4b i) Polar Configuration :-

Polar configurat is the classification of body arm assembly, which denotes the types of joints it consists and their movement.

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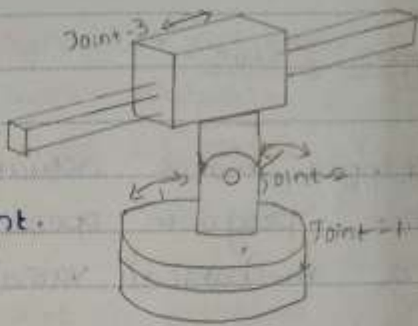
Q.No	Marks
4(a)	10

Q.No	Marks

Q.No	Marks

It consits of two rotary joints and one sliding joint.



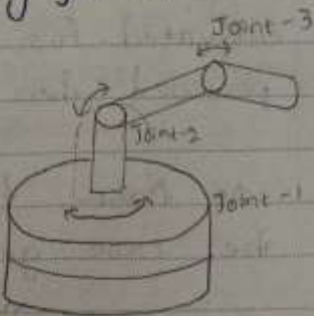
Joint 1 - Rotary
Joint 2 - Rotary
Joint 3 - Prismatic

ii) Jointed - Arm Configuration:-

It is also a classification of a body-and-arm assembly. It is a type of classification which has different assembly.

It consists of three rotary joints.

Joint-1 :- Rotary.
Joint-2 :- Rotary
Joint-3 :- Rotary



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Q.No	Marks
4(b)	4

Q.No	Marks

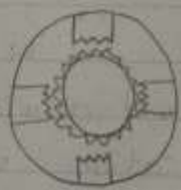
Q.No	Marks

6a. Stepper Motor:-

Stepper motor actuator is used to convert program operation command into the a mechanical variable.

Stepper motor consits of four electromagents at four cos side of motor at orthogonal to each other and ferrous gear core at the center of electromagnets.

The gear teeth of core is placed closed to the electromagnes but not in contact.



In this motor at a time one part is activated. For example if one magnet is powered then remaining are not powered.

At first, first magnet is energized then the core gets attracted to first magnet.

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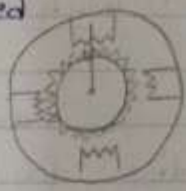
Q.No	Marks

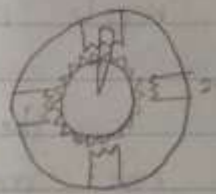
Q.No	Marks

Q.No	Marks

Then second magnet is activated then the core moves towards the 2nd magnet. Angle 3.6° rotation will be obtained.



Then the third magnet is activated in that way the fourth magnet is activated. For each activation of a magnet, the core moves 3.6°. To achieve a complete 360° rotation, cores have to be activate 100 times.



By using this motor angular rotation cant also be achieved in order to satisfy the requirements. It also has high torque ability. It can also be used to hold a compo the shaft at particulation and & angle due to its high torque.

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Q.No	Marks
6(a)	7

Q.No	Marks

Q.No	Marks

6 b. i) Touch Sensor:-

Touch sensors are used to sense the touch whether the contact has been made or not.

Here contact is checked but it does not care about the magnitude of force.

It consists of equipment like diodes which will helps in carrying out the operations.

Basically the sensors works on closing an circuit which was initially an open circuit.

It is like an on/off system. The part ~~are~~ when comes in contact with the sensors the circuit becomes close and activates the output system like a alarm switch.

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Q.No	Marks

Q.No	Marks

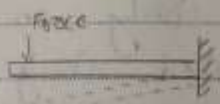
Q.No	Marks

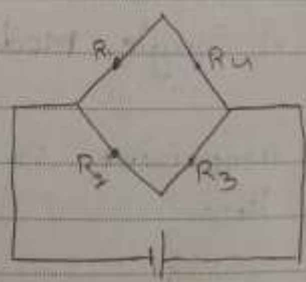
Touch sensors can be used for inspection and measuring purpose.

ii) Force Sensor:-

Force sensors are used for measuring the load acting. It helps in gripping purpose. In end effectors, force sensors help in performing operations like gripping, moving, etc.

Force sensors consists of a resistance circuit like wheatstone bridge which helps in finding the load.





When force is applied on component it consists of a circuit which will be connected to wheatstone bridge.

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Q.No	Marks
6)	7

Q.No	Marks

Q.No	Marks

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When force applied the resistance in the circuit changes, and based on the change load factors can be determine like force, stress, strain, torque, etc.

1a. Inverse kinematic of a robot is defined as the retraction motion of a body after performing operations.

1b. Types of assembly lines are:-

1) Single Model Assembly Line:-
There only on model or component is assembled along the work line.

2) Batch Model Assembly Line:-
In this assembly line a batch of models are assembled.

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Q.No	Marks
1(a)	2

Q.No	Marks
1(b)	1

Q.No	Marks

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3) Mixed Model Assembly line :-

Here a combined models are assembled.

1.c. Given,

Excitation Voltage = 21 V.
Wiper travel = 320°
Wiper position = 64°.

Voltage constant of part $k_p = \frac{\text{Voltage}}{\text{wiper travel}}$

$= \frac{21}{320}$

$= 0.065$ V/Deg

Output voltage $= k_p \times 64°$
$= 0.065 \times 64.$
$= 4.1$ V.

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Q.No	Marks
1(c)	2

Q.No	Marks

Q.No	Marks

1.d. Work envelop of a robot is the three dimensional area/volume in which the robot is able to move with and & restriction or freely

Shape of area/vo volume covered by

* Cartesial co-ordinate body arm assembly - Rectangular
Articulated assembly - Almost spherical.
Polar co-ordinate body arm assembly - Almost Spherical
Cylindrical Body arm assembly - Cylindrical

1.e. Levels of automation system are.

Enterprise level - Corporate system.
↑↓
Industrial - For industries
↑↓
Cell or System level - Group of machines
↑↓
Machine level - Operations like milling, turning, drilling.
↑↓
Device level. - Sensors, actuators.

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Q.No	Marks
1(d)	2

Q.No	Marks
1(e)	2

Q.No	Marks

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21

1 f.

~~Notation of prismatic joint~~

1 f.

Computer Numerical Control is different from Conventional Numerical Control machine.

In CNC there is a micro processor control which ~~wt~~ will store and operations. In CNC different set of programs for multiple designs can be stored at a time but in NC machines we can.

In CNC tool changing is done by the machine by using computer, but in NC tool change has to be done manually.

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Q.No	Marks
1(f)	2

Q.No	Marks

Q.No	Marks

1g. Notation of Prismatic joint for a manipulator
For,
1) Linear joint.
It is noted as "L".

2) Orthogonal joint.
It is noted as "O".

7a. Material Handling:-

Material handling is th defined as the ordering, processing, storage, transporting controlling of the material in an industry.

Material handling place an important role in the industry because based on this the effectiveness of industry will be determined

Material handling is also a cost factor in calculating the overall cost.

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Q.No	Marks
1(g)	2

Q.No	Marks
7(a)	4

Q.No	Marks

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Material handing has to be maintained accurately in order to the industry to work correctly.

7b.

Discrete data gives a set of data where as continuous data gives the data continuously. Discrete data has spatial data.

Input and Output devices of discrete data.

1) Switch type:-

Here input system in an open circuit it has a flow of current through it.

When the input system comes in contact with the system then the control becomes close and completes the circuit.

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Q.No	Marks

Q.No	Marks

Q.No	Marks

(ESTD-1995)

24

The output system is like a switch with ON/OFF options.

When the system circuit becomes close, it indicates by the output system like indicator, alarm, etc.

2) PulseMeter:-

Pulse meter are consisting of devices which are known as flip-flops.

When input system is activated with all the connections required then it will shows pulses which represent the data acquired

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Q.No	Marks
7(b)	4

Q.No	Marks

Q.No	Marks

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CO-PO Attainment (2020-21)

Table 1. Subject details along grading scale

NAME OF THE FACULTY	Dr. Manoj Panchal
COURSE NAME	INDUSTRIAL AUTOMATION AND ROBOTICS
COURSE CODE	A0336158
SESSION OF COURSE	April-2020-July-2021
CLASS	IV B.Tech-II SEMESTER
CREDITS	3
BATCH	2017
TOTAL STRENGTH	160
GRADING SCALE	For CO's
SCORE < 30%	LOW—1
30% < SCORE < 50%	MODERATE --2
SCORE >=50%	STRONGLY--3
GRADING SCALE	For PO's
SCORE < 50%	LOW—1
50% < SCORE < 80%	MODERATE --2
SCORE >=80%	STRONGLY--3

Table 2. CO-PO Mapping of Subject and assigned values for POs

CO/PO Mapping	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PSO1	PSO2	PSO3	PSO4
CO1	3	3	2	2	1	-	-	-	-	-	2	3	2	1	-	1
CO2	2	2		2	1	1	-	-	-	-	-	2	2	-	-	1
CO3	3	2	3	-	2	-	2	-	-	-	2	-	2	-	-	-
CO4	3	2	3	2	3	3	-	-	-	-	-	-	2	-	-	1
Percentage PO (%)	91.67	75.00	88.89	66.67	58.33	66.67	66.67				66.67	83.33	66.67	33.33		33.33
Attainment Value Assigned	3	3	3	2	2	2	2				2	3	2	1		1

Table 3. Percentage of Marks distribution in different Assessment Method

PERCENTAGE OF DISTRIBUTION OF MARKS					
ASSESSMENT METHOD/CO	CO1	CO2	CO3	CO4	Average Cos
EXTERNAL EXAM	23.47%	32.653%	20.41%	23.47%	100.00%
INTERNAL EXAM(I+II)	23.33%	30.0%	23.33%	23.33%	100%
ASSIGNMENTS (I+II)	27.50%	22.50%	22.50%	27.50%	100.00%
AVERAGE	24.77%	28.38%	22.08%	24.77%	

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➢ PERCENTAGE ATTAINMENT OF CO: CALCULATION METHOD

1. **PERCENTAGE OF CO1= (23.47*EXTERNAL MARKS)+(23.33*INTERNAL MARKS (I+II)+27.50*ASSIGNMENT MARKS)/24.77**
2. **PERCENTAGE OF CO2= (32.653*EXTERNAL MARKS)+(30*INTERNAL MARKS (I+II)+22.50*ASSIGMENT MARKS)/28.38**
3. **PERCENTAGE OF CO3= (20.41*EXTERNAL MARKS)+(23.33*INTERNAL MARKS (I+II)+22.50*ASSIGMENT MARKS)/22.08**
4. **PERCENTAGE OF CO4= (23.47*EXTERNAL MARKS)+(23.33*INTERNAL MARKS (I+II)+27.50*ASSIGNMENT MARKS)/24.77**

Table 4. PERCENTAGE ATTAINMENT OF CO: CALCULATION

S.No.	ROLL NO.	INDUSTRIAL AUTOMATION AND ROBOTICS								
		ASSIGNMENT MARKS (5)	INTERNAL MARKS (I+II) (25)	TOTAL INTERNAL MARKS (30)	EXTERNAL MARKS (70)	TOTAL (100)	CO1 (%)	CO2 (%)	CO3 (%)	CO4 (%)
1	14091A03C3	5	15	20	16	36	34.84	30.36	35.73	34.84
2	15091A0385	0	0	0	0	0	0.00	0.00	0.00	0.00
3	15091A03K3	4	20	24	35	59	56.44	64.58	52.48	56.44
4	16091A0349	4	15	19	29	48	46.05	52.39	42.58	46.05
5	16091A0372	4	15	19	34	53	50.78	58.15	46.32	50.78
6	16091A0376	4	13	17	30	47	45.11	51.43	41.16	45.11
7	16091A0399	4	12	16	18	34	32.80	36.57	31.12	32.80
8	16091A03A9	4	14	18	39	57	54.58	62.84	48.96	54.58
9	16091A03B4	4	11	15	12	27	26.17	28.61	25.56	26.17
10	16091A03G4	4	13	17	32	49	47.01	53.73	42.66	47.01
11	17091A0301	5	15	20	40	60	57.58	65.84	51.96	57.58
12	17091A0302	4	10	14	13	27	26.18	28.70	25.22	26.18
13	17091A0303	5	16	21	40	61	58.52	66.90	53.05	58.52
14	17091A0304	5	14	19	21	40	38.64	42.93	36.70	38.64
15	17091A0305	4.5	20	24	37	61	58.42	66.75	54.02	58.42
16	17091A0306	4	13	17	14	31	29.95	33.02	29.22	29.95
17	17091A0308	5	16	21	29	50	48.10	54.24	44.84	48.10
18	17091A0309	5	18	23	50	73	69.88	80.52	62.68	69.88
19	17091A0311	5	23	28	53	81	77.43	89.26	70.34	77.43
20	17091A0312	4.5	21	25	41	66	63.15	72.41	58.09	63.15
21	17091A0313	4	15	19	38	57	54.57	62.75	49.30	54.57
22	17091A0314	4.5	21	25	43	68	65.05	74.71	59.58	65.05
23	17091A0315	4	16	20	30	50	47.94	54.60	44.41	47.94

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24	17091A0316	5	17	22	41	63	60.41	69.11	54.88	60.41
25	17091A0317	5	21	26	46	72	68.92	79.09	62.95	68.92
26	17091A0318	4	16	20	31	51	48.88	55.75	45.16	48.88
27	17091A0319	5	19	24	49	73	69.87	80.43	63.02	69.87
28	17091A0320	5	16	21	36	57	54.73	62.30	50.06	54.73
29	17091A0321	4	17	21	48	69	65.93	76.37	58.93	65.93
30	17091A0322	4	15	19	26	45	43.20	48.94	40.34	43.20
31	17091A0323	5	14	19	34	53	50.95	57.88	46.40	50.95
32	17091A0324	5	23	28	59	87	83.12	96.16	74.82	83.12
33	17091A0325	5	15	20	38	58	55.68	63.54	50.47	55.68
34	17091A0326	5	18	23	33	56	53.77	60.96	49.99	53.77
35	17091A0327	5	21	26	48	74	70.81	81.39	64.44	70.81
36	17091A0328	5	16	21	25	46	44.31	49.64	41.85	44.31
37	17091A0329	4	16	20	30	50	47.94	54.60	44.41	47.94
38	17091A0331	4	21	25	55	80	76.33	88.65	68.49	76.33
39	17091A0332	4.5	22	26	49	75	71.67	82.67	65.14	71.67
40	17091A0333	5	20	25	31	56	53.76	60.77	50.67	53.76
41	17091A0334	5	20	25	45	70	67.03	76.88	61.12	67.03
42	17091A0335	5	21	26	32	58	55.65	62.98	52.50	55.65
43	17091A0336	5	18	23	34	57	54.72	62.11	50.74	54.72
44	17091A0337	4	16	20	29	49	46.99	53.45	43.67	46.99
45	17091A0338	5	22	27	56	83	79.33	91.65	71.49	79.33
46	17091A0340	5	16	21	36	57	54.73	62.30	50.06	54.73
47	17091A0341	5	16	21	37	58	55.68	63.45	50.81	55.68
48	17091A0342	5	18	23	33	56	53.77	60.96	49.99	53.77
49	17091A0345	4.5	17	21	39	60	57.49	65.88	52.26	57.49
50	17091A0346	5	16	21	60	81	77.47	89.91	67.98	77.47
51	17091A0348	5	18	23	45	68	65.14	74.77	58.95	65.14
52	17091A0349	4	15	19	35	54	51.73	59.30	47.06	51.73
53	17091A0350	4	15	19	33	52	49.84	57.00	45.57	49.84
54	17091A0352	5	21	26	50	76	72.71	83.69	65.93	72.71
55	17091A0353	4.5	21	25	53	78	74.52	86.22	67.04	74.52
56	17091A0354	4	15	19	31	50	47.94	54.69	44.08	47.94
57	17091A0355	5	16	21	36	57	54.73	62.30	50.06	54.73
58	17091A0356	4	18	22	38	60	57.40	65.92	52.55	57.40
59	17091A0357	5	21	26	55	81	77.44	89.44	69.66	77.44
60	17091A0358	4.5	16	20	27	47	45.18	51.02	42.22	45.18
61	17091A0359	5	18	23	38	61	58.51	66.71	53.72	58.51
62	17091A0360	4	15	19	28	47	45.10	51.24	41.84	45.10
63	17091A0361	5	19	24	53	77	73.66	85.03	66.00	73.66

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64	17091A0362	5	17	22	51	73	69.89	80.61	62.34	69.89
65	17091A0363	5	21	26	53	79	75.55	87.14	68.17	75.55
66	17091A0364	5	18	23	53	76	72.72	83.97	64.92	72.72
67	17091A0365	5	16	21	29	50	48.10	54.24	44.84	48.10
68	17091A0367	4.5	23	27	48	75	71.67	82.58	65.48	71.67
69	17091A0368	4	13	17	21	38	36.58	41.08	34.44	36.58
70	17091A0369	4.5	21	25	50	75	71.68	82.77	64.80	71.68
71	17091A0370	5	18	23	25	48	46.19	51.76	44.02	46.19
72	17091A0371	5	18	23	35	58	55.67	63.26	51.48	55.67
73	17091A0372	5	18	23	38	61	58.51	66.71	53.72	58.51
74	17091A0374	4.5	19	23	33	56	53.69	61.09	49.95	53.69
75	17091A0375	5	14	19	26	45	43.37	48.68	40.43	43.37
76	17091A0376	5	15	20	41	61	58.53	66.99	52.71	58.53
77	17091A0377	5	17	22	46	68	65.15	74.86	58.61	65.15
78	17091A0380	4.5	20	24	29	53	50.84	57.55	48.05	50.84
79	17091A0381	4	13	17	25	42	40.37	45.68	37.43	40.37
80	17091A0382	5	20	25	25	50	48.08	53.87	46.19	48.08
81	17091A0383	5	15	20	28	48	46.21	52.04	43.01	46.21
82	17091A0384	4	13	17	11	28	27.11	29.57	26.98	27.11
83	17091A0385	4	15	19	13	32	30.89	33.98	30.64	30.89
84	17091A0386	4	14	18	26	44	42.26	47.89	39.26	42.26
85	17091A0387	5	23	28	52	80	76.48	88.11	69.59	76.48
86	17091A0392	5	17	22	35	57	54.73	62.20	50.40	54.73
87	17091A0393	4	18	22	36	58	55.51	63.62	51.06	55.51
88	17091A0394	4	14	18	33	51	48.90	55.94	44.49	48.90
89	17091A0395	4.5	18	22	30	52	49.90	56.58	46.62	49.90
90	17091A0397	5	18	23	41	64	61.35	70.16	55.96	61.35
91	17091A0398	5	18	23	31	54	51.88	58.66	48.50	51.88
92	17091A0399	5	11	16	30	46	44.34	50.11	40.17	44.34
93	17091A03A0	0	0	0	0	0	0.00	0.00	0.00	0.00
94	17091A03A1	4	15	19	17	36	34.68	38.59	33.63	34.68
95	17091A03A2	5	20	25	42	67	64.18	73.43	58.88	64.18
96	17091A03A3	5	18	23	38	61	58.51	66.71	53.72	58.51
97	17091A03A4	5	18	23	44	67	64.20	73.62	58.20	64.20
98	17091A03A5	5	13	18	26	44	42.43	47.62	39.35	42.43
99	17091A03A6	4.5	21	25	44	69	65.99	75.86	60.33	65.99
100	17091A03A7	5	17	22	28	50	48.09	54.15	45.17	48.09
101	17091A03A8	4	15	19	18	37	35.62	39.74	34.37	35.62
102	17091A03A9	4.5	21	25	47	72	68.84	79.31	62.57	68.84
103	17091A03B1	4	16	20	37	57	54.57	62.66	49.64	54.57
104	17091A03B2	5	17	22	43	65	62.31	71.41	56.37	62.31
105	17091A03B3	4	17	21	20	41	39.40	44.15	38.03	39.40

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106	17095A0301	4	17	21	32	53	50.77	57.96	46.99	50.77
107	17095A0327	5	21	26	47	73	69.86	80.24	63.69	69.86
108	18095A0301	5	21	26	50	76	72.71	83.69	65.93	72.71
109	18095A0302	5	20	25	50	75	71.76	82.63	64.85	71.76
110	18095A0303	5	16	21	38	59	56.63	64.60	51.56	56.63
111	18095A0304	5	20	25	47	72	68.92	79.18	62.61	68.92
112	18095A0305	5	22	27	60	87	83.12	96.25	74.48	83.12
113	18095A0306	4.5	22	26	55	81	77.36	89.58	69.62	77.36
114	18095A0307	5	15	20	36	56	53.79	61.24	48.98	53.79
115	18095A0308	5	22	27	40	67	64.17	73.24	59.55	64.17
116	18095A0309	4	17	21	33	54	51.72	59.11	47.74	51.72
117	18095A0310	5	14	19	39	58	55.69	63.64	50.13	55.69
118	18095A0311	5	22	27	49	76	72.70	83.60	66.27	72.70
119	18095A0312	5	21	26	46	72	68.92	79.09	62.95	68.92
120	18095A0313	5	20	25	41	66	63.24	72.28	58.13	63.24
121	18095A0314	5	19	24	40	64	61.35	70.07	56.30	61.35
122	18095A0315	5	21	26	57	83	79.34	91.74	71.16	79.34
123	18095A0316	5	21	26	54	80	76.50	88.29	68.92	76.50
124	18095A0317	5	23	28	59	87	83.12	96.16	74.82	83.12
125	18095A0318	5	19	24	43	67	64.19	73.52	58.54	64.19
126	18095A0319	4	16	20	40	60	57.41	66.11	51.88	57.41
127	18095A0320	5	20	25	37	62	59.45	67.68	55.14	59.45
128	18095A0321	5	20	25	59	84	80.29	92.99	71.57	80.29
129	18095A0322	5	21	26	42	68	65.13	74.49	59.96	65.13
130	18095A0323	5	21	26	47	73	69.86	80.24	63.69	69.86
131	18095A0324	5	22	27	45	72	68.91	79.00	63.28	68.91
132	18095A0325	5	17	22	18	40	38.62	42.64	37.71	38.62
133	18095A0326	5	16	21	36	57	54.73	62.30	50.06	54.73
134	18095A0327	5	18	23	41	64	61.35	70.16	55.96	61.35
135	18095A0328	5	21	26	38	64	61.34	69.88	56.97	61.34
136	18095A0329	5	18	23	40	63	60.41	69.01	55.22	60.41
137	18095A0330	4.5	21	25	47	72	68.84	79.31	62.57	68.84
138	18095A0331	5	19	24	46	70	67.03	76.97	60.78	67.03
139	18095A0332	5	18	23	34	57	54.72	62.11	50.74	54.72
140	18095A0333	5	21	26	50	76	72.71	83.69	65.93	72.71
141	18095A0334	5	23	28	51	79	75.54	86.96	68.85	75.54
142	18095A0335	5	21	26	48	74	70.81	81.39	64.44	70.81
143	18095A0336	5	19	24	47	71	67.98	78.13	61.52	67.98
144	18095A0337	4	20	24	50	74	70.65	81.84	63.68	70.65
145	18095A0338	5	20	25	41	66	63.24	72.28	58.13	63.24
146	18095A0339	5	20	25	53	78	74.61			

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147	18095A0340	5	18	23	39	62	59.46	67.86	54.47	59.46
148	18095A0341	5	19	24	39	63	60.40	68.92	55.55	60.40
149	18095A0342	5	19	24	38	62	59.45	67.77	54.81	59.45
150	18095A0343	4.5	22	26	46	72	68.83	79.22	62.90	68.83
151	18095A0344	4	19	23	47	70	66.87	77.33	60.35	66.87
152	18095A0345	5	16	21	34	55	52.84	60.00	48.57	52.84
153	18095A0346	4	20	24	42	66	63.07	72.64	57.71	63.07
154	18095A0347	4.5	22	26	42	68	65.04	74.62	59.92	65.04
155	18095A0348	5	18	23	37	60	57.56	65.56	52.98	57.56
156	18095A0349	5	19	24	37	61	58.50	66.62	54.06	58.50
157	18095A0350	4	16	20	39	59	56.46	64.96	51.13	56.46
158	18095A0351	4	18	22	41	63	60.24	69.37	54.79	60.24
159	18095A0352	5	19	24	46	70	67.03	76.97	60.78	67.03
160	18095A0353	5	17	22	49	71	67.99	78.31	60.85	67.99

- **Attainment Value of COs= ((NUMBER OF STUDENTS SCORED >=50*3)+(NUMBER OF STUDENTS SCORED 30% < SCORE < 50% *2)+ NUMBER OF STUDENTS SCORED<30%=1))/Total Number of Students**

1. **PERCENTAGE OF CO1= (NUMBER OF STUDENTS SCORED >=50/ Total Number of Students)*100**
2. **PERCENTAGE OF CO2= (NUMBER OF STUDENTS SCORED30% < SCORE < 50%/ Total Number of Students)*100**
3. **PERCENTAGE OF CO3= (NUMBER OF STUDENTS SCORED30% < SCORE < 50%/ Total Number of Students)*100**
4. **PERCENTAGE OF CO4= (NUMBER OF STUDENTS SCORED<30% / Total Number of Students)*100**

Table 5. CO attainment Matrix

CO Attainment Matrix								
	CO1	**Grading**	**C02**	**Grading**	**CO3**	**Grading**	**CO4**	**Grading**
SCORE >=50%=3	119	3	139	3	105	3	121	3
30% < SCORE < 50%=2	35	2	16	2	49	2	33	2
SCORE <30%=1	6	1	5	1	6	1	6	1
Total students	160		160		160		160	
% of Attainment		**74.38**		**86.88**		**65.63**		**75.63**
Attainment value		**2.706**		**2.838**		**2.619**		**2.719**

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Table 6. Attainment Status

Course outcome	% of student attained	Attained or not
CO1	74.38	Y
CO2	86.88	Y
CO3	65.63	Y
CO4	75.63	Y

- **PO ATTAINMENT CALCULATION**

1. **PO ATTAINMENT= ((CO1 ATTAINMENT VALUE* CORRESPONDING PO GRADING)+ (CO2 ATTAINMENT VALUE* CORRESPONDING PO GRADING) + (CO3 ATTAINMENT VALUE* CORRESPONDING PO GRADING) + (CO4 ATTAINMENT VALUE* CORRESPONDING PO GRADING)) / AVERAGE PO VALUE**

Table 7. PO Attainment Matrix

CO/PO Mapping	CO Attainment Value	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PSO1	PSO2	PSO3	PSO4
CO1	2.70625	3	3	2	2	1			-	-	-	2	3	2	1	-	1
CO2	2.8375	2	2		2	1	1		-	-	-		2	2		-	1
CO3	2.61875	3	2	3		2		2	-	-	-	2		2		-	
CO4	2.71875	3	2	3	2	3	3		-	-	-			2		-	1
PO Attainment		2.71	2.72	2.68	2.75	2.70	2.75	2.62				2.66	2.76	2.72	2.71		2.75
PO Result		Y	Y	Y	Y	Y	Y	Y				Y	Y	Y	Y		Y

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