KANDULA SRINIVASA REDDY MEMORIAL COLLEGE OF ENGINEERING (AUTONOMOUS)

KADAPA-516003. AP

(Approved by AICTE, Affiliated to JNTUA, Ananthapuramu, Accredited by NAAC)

(An ISO 9001-2008 Certified Institution)

DEPARTMENT OF CIVIL ENGINEERING

VALUE ADDED COURSE

ON

"COMPUTER AIDED STEEL STRUCTURES"

Resource Person:

A. Anil Kumar, Assistant Professor, Dept. of CE, KSRMCE

Course Coordinator:

P. V. Vara Rathna Kumar, Assistant Professor, Dept. of CE, KSRMCE

Duration: 02/07/2018 to 28/07/2018

K.S.R.M. COLLEGE OF ENGINEERING

(UGC-AUTONOMOUS)

Kadapa, Andhra Pradesh, India– 516 003

Approved by AICTE, New Delhi & Affiliated to JNTUA, Ananthapuramu.

An ISO 14001:2004 & 9001: 2015 Certified Institution

Lr./KSRMCE/CE/2018-19/ Date: 27-06-2018

To
The Principal,
KSRMCE,
Kadapa.

Sub: Permission to Conduct Value Added Course on "Computer Aided Steel Structures" from 02/07/2018 to 28/07/2018–Req- Reg.

Respected Sir,

The Department of Civil Engineering is planning to offer a Value Added Course on "Computer Aided Steel Structures" to B. Tech. students. The course will be conducted from 02/07/2018 to 28/07/2018. In this regard, I kindly request you to grant permission to conduct the value added course.

Thanking you,

Yours faithfully

P. V. Vara Rathna Kumar

(Assistant Professor, CED)

Forwarded to Principal Sir
27/06/18

Permitted
V. S. S. Murthy

K.S.R.M. COLLEGE OF ENGINEERING
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Cr./KSRMCE/CE/2018-19/ Date: 27/06/2018

Circular

The Department of Civil Engineering is offering a Value Added Course on "Computer Aided Steel Structures" from 02/07/2018 to 28/07/2018 to B.Tech students. In this regard, interested students are requested to register their names for the Value Added Course with following registration link.

https://docs.google.com/forms/d/e/1FAIpQLSdEtH1Fv9-tw6Q_xEIkvIATVwaVBeRLFGZ4imtCfGLurWb4kQ/viewform

For further information, contact Course Coordinator.

Course Coordinator:
P. V. Vara Rathna Kumar,
Assistant Professor,
Department of Civil Engineering,
KSRMCE.

HOD

Dept. of Civil Engineering

Cc to:

IQAC-KSRMCE

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DEPARTMENT OF CIVIL ENGINEERING

List of students registered for Value Added Course on "Computer Aided Steel Structures" from 02/07/2018 to 28/07/2018

Sl. No.	Roll Number	Name of the student	Semester	Branch
1	169Y5A0101	Ambu Sreemantha Reddy	VII	CIVIL
2	169Y5A0102	Animala Sudhakar	VII	CIVIL
3	169Y5A0105	Beedagani Sarankumar	VII	CIVIL
4	169Y5A0106	Bhunasane Charan Kumar Reddy	VII	CIVIL
5	169Y5A0107	Bommisetty Sreenivasulu	VII	CIVIL
6	169Y5A0108	Boreddy Siva Sankar Reddy	VII	CIVIL
7	169Y5A0109	Chandragiri Sreenivas Kumar	VII	CIVIL
8	169Y5A0110	Chenchureddy Jayalakshmi	VII	CIVIL
9	169Y5A0111	Chintakunta Shaik Mansoor	VII	CIVIL
10	169Y5A0114	Gaajulapalle Pavan Kumar Reddy	VII	CIVIL
11	169Y5A0115	Gaddam Sai Priyanka	VII	CIVIL
12	169Y5A0119	Indla Sai Venkatesh	VII	CIVIL
13	169Y5A0120	Jonna Mahesh	VII	CIVIL
14	169Y5A0121	Kadapa Satish Kumar Reddy	VII	CIVIL
15	169Y5A0122	Kalluru Srinivas	VII	CIVIL
16	169Y5A0123	Kandukuru Uday Kumar	VII	CIVIL
17	169Y5A0124	Kothakota Sreekanth	VII	CIVIL
18	169Y5A0125	Kovvuru Ramkumar	VII	CIVIL
19	169Y5A0126	Kuppam Swetha	VII	CIVIL
20	169Y5A0127	Kuraku Vengaiah	VII	CIVIL
21	169Y5A0128	Kuruva Bata Anil Kumar	VII	CIVIL
22	169Y5A0129	Kuruva Parandamudu	VII	CIVIL
23	169Y5A0130	Kuruva Sunkanna	VII	CIVIL
24	169Y5A0131	Madisetti Dineshkumar	VII	CIVIL
25	169Y5A0132	Mettapalli Eragam Reddy	VII	CIVIL
26	169Y5A0133	Mettupalli Agraharam Akhil Kumar Reddy	VII	CIVIL
27	169Y5A0134	Mulla Mahaboob Basha	VII	CIVIL
28	169Y5A0135	Mungamuri Gangadhar	VII	CIVIL
29	169Y5A0136	Nallamekala Harendra	VII	CIVIL
30	169Y5A0137	P J Siddartha	VII	CIVIL
31	169Y5A0138	Padma Vinathi	VII	CIVIL
32	169Y5A0139	Palempalli Maheswar Reddy	VII	CIVIL
33	169Y5A0140	Pattikonda Suresh	VII	CIVIL
34	169Y5A0141	Pendluru Sivaramaiah	VII	CIVIL
35	169Y5A0144	Putta Satish Kumar Reddy	VII	CIVIL

36	169Y5A0146	Renati Venkata Siva Reddy	VII	CIVIL
37	169Y5A0147	Sanivarapu Vamsidhar Reddy	VII	CIVIL
38	169Y5A0148	Sattakari Tarun Saikumar	VII	CIVIL
39	169Y5A0149	Shaik Abdul Amanulla	VII	CIVIL
40	169Y5A0150	Shaik Dadagari Yunus Hussain	VII	CIVIL
41	169Y5A0151	Shaik Mahammad Ali	VII	CIVIL
42	169Y5A0152	Shaik Saddam	VII	CIVIL
43	169Y5A0154	Shampuri Suman	VII	CIVIL
44	169Y5A0155	Siddamreddy Sainatha Reddy	VII	CIVIL
45	169Y5A0156	Talari Suresh	VII	CIVIL
46	169Y5A0157	Thellakula Ganesh	VII	CIVIL
47	169Y5A0158	Thoka Ganesh Yadav	VII	CIVIL
48	169Y5A0159	Tupili Bharadwaj	VII	CIVIL
49	169Y5A0161	Vallapu Kiran Kumar	VII	CIVIL
50	169Y5A0162	Varada Vishnu Teja	VII	CIVIL
51	169Y5A0163	Varikunta Muni Sai Priyanth Raju	VII	CIVIL
52	169Y5A0164	Yellaturu Amruth Kumar	VII	CIVIL

Coordinator

HOD

Head
Department of Civil Engineering
K.S.R.M. College of Engineering
(Autonomous)
KADAPA - 516 003. (A.P.)

Registration for Value Added Course on "Computer Aided Steel Structures" From 02/07/2018 to 28/07/2018

vvrkce@ksrmce.ac.in (not shared) Switch account

* Required

Roll Number *

Your answer

Name of the Student *

Your answer

B.Tech Semester *

- I SEM
- II SEM
- III SEM
- IV SEM
- V SEM
- VI SEM
- VII SEM
- VIII SEM

Branch *

- CIVIL
- EEE
- MECH
- ECE
- CSE

Email ID *

Your answer

Submit

Clear form

Never submit passwords through Google Forms.

Syllabus of Value Added Course

Course Name: Computer Aided Steel Structures

Course Objectives:

- Gain a comprehensive understanding of steel as a construction material, its properties, and its applications in structural engineering.
- Learn to analyze steel structures for various types of loads and boundary conditions, using both manual calculations and computer-aided tools.
- Develop proficiency in using computer-aided design (CAD) software for creating detailed drawings and 3D models of steel structures.
- Acquire skills in using structural analysis software to model and analyze steel structures, interpreting the results effectively

Course Outcomes: Upon completing the course students will be able to:

- Perform structural analysis of steel structures using both manual methods and structural analysis software, ensuring structural stability and safety.
- Create detailed 2D and 3D models of steel structures using CAD software, facilitating effective communication and visualization of designs.
- Design steel structures in compliance with relevant design codes and standards, accounting for factors such as load combinations and safety margins.
- Analyze and design steel connections, ensuring their integrity and efficiency in transferring loads.

Contents

Module 1:

Introduction to Steel Structures: Overview of steel as a construction material, Types of steel structures, Structural elements and connections, Safety considerations in steel construction, Static equilibrium and loads on structures, Analysis of simple steel structures using hand calculations, Introduction to structural analysis software

Module 2:

Introduction to Computer-Aided Design (CAD) Software: Overview of CAD software for steel structures, Drawing basic steel structural elements, Creating 2D and 3D models of steel structures

Module 3:

Structural Analysis Software: Introduction to structural analysis software, Input data and analysis settings, Analyzing and interpreting results for steel structures.

Module 4:

Structural Design Codes and Standards: Overview of relevant design codes, Load combinations and safety factors, Design criteria for steel structures.

Textbooks:

- "Structural Steel Design" by Jack C. McCormac and Stephen F. Csernak (2016)
- "Steel Design" by William T. Segui (2017)
- "Computer Analysis & Reinforced Concrete Design of Beams" by Fady R. S. Rostom (2017)

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SCHEDULE

Department of Civil Engineering

Value Added Course on "Computer Aided Steel Structures" from 02/07/2018 to 28/07/2018

Date	Timing	Resource Person	Topic to be covered
02/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Overview of steel as a construction material
03/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Types of steel structures, Structural elements and connections
04/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Safety considerations
05/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Static equilibrium and loads on structures
06/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Analysis of simple steel structures
07/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Analysis of simple steel structures
09/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	hand calculations methods
10/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	hand calculations methods
11/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Introduction to structural analysis software
12/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Overview of CAD software for steel structures
13/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Drawing basic steel structural elements
14/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Creating 2D and 3D models of steel structures
16/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Creating 2D and 3D models of steel structures
17/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Introduction to structural analysis software
18/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Input data and analysis settings
19/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Input data and analysis settings
20/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Analyzing and interpreting results for steel structures
21/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Analyzing and interpreting results for steel structures
23/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Analyzing and interpreting results for steel structures
24/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Overview of relevant design codes
25/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Overview of relevant design codes
26/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Load combinations and safety factors
27/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Design criteria for steel structures
28/07/2018	4 PM to 6 PM	Sri. A. Anil Kumar	Design criteria for steel structures

Resource Person(s) | Coordinator(s) | HOD

Head
Department of Civil Engineering
K.S.R.M. College of Engineering
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DEPARTMENT OF CIVIL ENGINEERING

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ESTD: 1980

Value Added Course

on

"Computer Aided Steel Structures"

Resource Person

Sri. A. Anil Kumar
Assistant Professor
Department of Civil Engineering

Date

From 02/07/2018
to 28/07/2018

Coordinator

P. V. V. Rathna Kumar,
Department of Civil Engineering

Venue

CADD LAB,
Department of Civil Engg.

K.S.R.M. COLLEGE OF ENGINEERING

(UGC-AUTONOMOUS)

Kadapa, Andhra Pradesh, India– 516 003

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Report of

Value Added Course on "Computer Aided Steel Structures"

From 02/07/2018 to 28/07/2018

Target Group	:	**B. Tech. Students**
Details of Participants	:	**52 Students**
Co-coordinator(s)	:	**P. V. Vara Rathna Kumar**
Resource Person(s)	:	**A. Anil Kumar**
Organizing Department	:	**Civil Engineering**
Venue	:	**CADD Lab, Department of Civil Engineering**

Description:

A Value Added Course on "Computer Aided Steel Structures" was offered by the Department of Civil Engineering from July 2 through July 28, 2018. P. V. Vara Rathna Kumar, Assistant Professor, Department of Civil Engineering, KSRMCE, served as the course coordinator. Sri. A. Anil Kumar, Assistant Professor, Department of Civil Engineering, taught the course.

Computer-Aided for a number of compelling reasons, steel structures are of utmost significance in the field of structural engineering and construction. They first introduce previously unheard-of efficiency and accuracy to steel structure design and analysis. Engineers can methodically simulate complicated steel structures thanks to sophisticated software packages, which lowers the possibility of mistakes and ensures accuracy in calculations and blueprints. This improves the structures' strength and safety while also optimizing resource use, cutting down on both time and expense during construction. Second, using computer-aided tools enables engineers to easily handle complex geometries. Steel buildings frequently contain complex and asymmetrical designs that are difficult to handle physically. Using CAD software makes it easier to model and visualize these geometries, which makes it easier to realize creative and visually beautiful designs. Additionally, it encourages improved collaboration across interdisciplinary teams and makes it possible for stakeholders to more fully visualize the finished product, leading to better project results and decision-making. In essence, computer-aided steel structures are a game-changing development that are promoting efficiency, accuracy, and innovation in the field of structural engineering and construction.

Advances in Computer-Aided Design (CAD) and structural analysis software have revolutionized the field of steel structure engineering. These advancements have led to more efficient and precise design processes. CAD tools enable engineers to create intricate steel structures with greater accuracy and speed, allowing for complex and innovative designs. Finite Element Analysis (FEA) software has become indispensable, enabling engineers to simulate real-world stresses and strains on steel components, optimizing their performance and safety. Additionally, integration with Building Information Modeling (BIM) systems streamlines the entire construction process, enhancing collaboration between architects, engineers, and contractors. With these technological advances, the design and construction of steel structures have become more cost-effective, sustainable, and adaptable to meet evolving architectural and engineering challenges.

Photos:

The picture taken during the course is given below:

Introduction to Computer Aided Steel Structures by A. Anil Kumar

Coordinator(s)

HoD

Head
Department of Civil Engineering
K.S.R.M. College of Engineering
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Attendance sheet of Value Added Course on "Computer Aided Steel Structures"

Sl. No.	Roll No.	Name	02/07/2018	03/07/2018	04/07/2018	05/07/2018	06/07/2018	07/07/2018	09/07/2018	10/07/2018	11/07/2018	12/07/2018	13/07/2018	14/07/2018	16/07/2018	17/07/2018	18/07/2018	19/07/2018	20/07/2018	21/07/2018	23/07/2018	24/07/2018	25/07/2018	26/07/2018	27/07/2018	28/07/2018
1	169Y5A0101	Ambu Sreemantha Reddy	[illegible]	a	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	a	[illegible]	[illegible]	[illegible]	[illegible]
2	169Y5A0102	Animala Sudhakar	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3	169Y5A0105	Beedagani Sarankumar	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	a	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4	169Y5A0106	Bhunasane Charan Kumar Reddy	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	a	[illegible]	[illegible]	[illegible]	a	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5	169Y5A0107	Bommisetty Sreenivasulu	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6	169Y5A0108	Boreddy Siva Sankar Reddy	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva	B.Siva
7	169Y5A0109	Chandragiri Sreenivas	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	a	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

		Kumar																						a		
8	169Y5A0110	Chenchureddy Jayalakshmi							a																	
9	169Y5A0111	Chintakunta Shaik Mansoor											a													
10	169Y5A0114	Gaajulapalle Pavan Kumar Reddy														a										
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20	169Y5A0127	Kuraku Vengaiah																			a					
21	169Y5A0128	Kuruva Bata Anil Kumar																								

22	169Y5A0129	Kuruva Parandamudu	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]
23	169Y5A0130	Kuruva Sunkanna	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]
24	169Y5A0131	Madisetti Dineshkumar	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	a	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]
25	169Y5A0132	Mettapalli Eragam Reddy	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]
26	169Y5A0133	Mettupalli Agraharam Akhil Kumar Reddy	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	a	[signature]
27	169Y5A0134	Mulla Mahaboob Basha	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	a	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]
28	169Y5A0135	Mungamuri Gangadhar	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]
29	169Y5A0136	Nallamekala Harendra	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]
30	169Y5A0137	P J Siddartha	[signature]	[signature]	[signature]	a	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]
31	169Y5A0138	Padma Vinathi	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	a	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]
32	169Y5A0139	Palempalli Maheswar Reddy	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]
33	169Y5A0140	Pattikonda Suresh	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]
34	169Y5A0141	Pendluru Sivaramaiah	a	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	a	[signature]	[signature]	[signature]
35	169Y5A0144	Putta Satish Kumar Reddy	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]	[signature]

36	169Y5A0146	Renati Venkata Siva Reddy																								
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49	169Y5A0161	Vallapu Kiran Kumar																							o	
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51	169Y5A0163	Varikunta Muni Sai Priyanth Raju																								
52	169Y5A0164	Yellaturu Amruth Kumar						a				a														

Coordinator(s)

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Head
Department of Civil Engineering
K.S.R.M. College of Engineering
(Autonomous)
KADAPA - 516 003. (A.P.)

Feedback form on Value Added Course "Computer Aided Steel Structures" from **2/7/2018 to 28/7/2018**

vvrkce@ksrmce.ac.in (not shared) Switch account

* Required

Roll Number *

Your answer

Name of the Student *

Your answer

The objectives of the Value Added Course were met*

- Excellent
- Good
- Satisfactory
- Poor

The content of the course was organized and easy to follow*

- Excellent
- Good
- Satisfactory
- Poor

The Resource Person was well prepared and able to answer any question *

- Excellent
- Good
- Satisfactory
- Poor

The exercises/role play were helpful and relevant *

- Excellent
- Good
- Satisfactory
- Poor

The Value Added Course satisfy my expectation as a value added Programme *

- Excellent
- Satisfactory
- Good
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Feedback of Value Added Course on "Computer Aided Steel Structures"

Sl. No.	Roll No.	Name	The objectives of the Value Added Course were met	The content of the course was organized and easy to follow	The Resource Person was well prepared and able to answer any question	The exercises/role play were helpful and relevant	The Value Added Course satisfy my expectation as a value added Programme
1	169Y5A0101	Ambu Sreemantha Reddy	Excellent	Excellent	Good	Excellent	Excellent
2	169Y5A0102	Animala Sudhakar	Excellent	Good	Excellent	Excellent	Excellent
3	169Y5A0105	Beedagani Sarankumar	Good	Excellent	Good	Good	Excellent
4	169Y5A0106	Bhunasane Charan Kumar Reddy	Good	Excellent	Excellent	Excellent	Good
5	169Y5A0107	Bommisetty Sreenivasulu	Excellent	Excellent	Excellent	Excellent	Excellent
6	169Y5A0108	Boreddy Siva Sankar Reddy	Excellent	Good	Good	Excellent	Excellent
7	169Y5A0109	Chandragiri Sreenivas Kumar	Excellent	Excellent	Excellent	Good	Good
8	169Y5A0110	Chenchureddy Jayalakshmi	Good	Excellent	Good	Excellent	Good
9	169Y5A0111	Chintakunta Shaik Mansoor	Excellent	Good	Excellent	Good	Good
10	169Y5A0114	Gaajulapalle Pavan Kumar Reddy	Good	Good	Excellent	Good	Excellent

11	169Y5A0115	Gaddam Sai Priyanka	Excellent	Satisfactory	Good	Good	Excellent
12	169Y5A0119	Indla Sai Venkatesh	Excellent	Excellent	Excellent	Excellent	Excellent
13	169Y5A0120	Jonna Mahesh	Excellent	Good	Excellent	Excellent	Good
14	169Y5A0121	Kadapa Satish Kumar Reddy	Good	Excellent	Excellent	Excellent	Excellent
15	169Y5A0122	Kalluru Srinivas	Excellent	Good	Good	Good	Excellent
16	169Y5A0123	Kandukuru Uday Kumar	Good	Excellent	Excellent	Excellent	Excellent
17	169Y5A0124	Kothakota Sreekanth	Good	Excellent	Excellent	Excellent	Good
18	169Y5A0125	Kovvuru Ramkumar	Good	Good	Excellent	Excellent	Good
19	169Y5A0126	Kuppam Swetha	Excellent	Excellent	Excellent	Excellent	Excellent
20	169Y5A0127	Kuraku Vengaiah	Excellent	Excellent	Good	Good	Excellent
21	169Y5A0128	Kuruva Bata Anil Kumar	Excellent	Excellent	Excellent	Excellent	Good
22	169Y5A0129	Kuruva Parandamudu	Good	Good	Excellent	Good	Excellent
23	169Y5A0130	Kuruva Sunkanna	Excellent	Excellent	Good	Excellent	Good
24	169Y5A0131	Madisetti Dineshkumar	Excellent	Good	Excellent	Good	Excellent
25	169Y5A0132	Mettapalli Eragam Reddy	Good	Excellent	Good	Excellent	Good
26	169Y5A0133	Mettupalli Agraharam Akhil Kumar Reddy	Excellent	Excellent	Good	Good	Excellent
27	169Y5A0134	Mulla Mahaboob Basha	Good	Excellent	Good	Good	Excellent

28	169Y5A0135	Mungamuri Gangadhar	Excellent	Excellent	Excellent	Excellent	Excellent
29	169Y5A0136	Nallamekala Harendra	Excellent	Excellent	Good	Good	Excellent
30	169Y5A0137	P J Siddartha	Good	Excellent	Excellent	Excellent	Good
31	169Y5A0138	Padma Vinathi	Excellent	Good	Excellent	Good	Excellent
32	169Y5A0139	Palempalli Maheswar Reddy	Good	Excellent	Good	Excellent	Good
33	169Y5A0140	Pattikonda Suresh	Excellent	Excellent	Excellent	Excellent	Good
34	169Y5A0141	Pendluru Sivaramaiah	Good	Good	Excellent	Good	Good
35	169Y5A0144	Putta Satish Kumar Reddy	Good	Excellent	Good	Excellent	Excellent
36	169Y5A0146	Renati Venkata Siva Reddy	Good	Good	Good	Good	Excellent
37	169Y5A0147	Sanivarapu Vamsidhar Reddy	Good	Excellent	Good	Good	Excellent
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51	169Y5A0163	Varikunta Muni Sai Priyanth Raju	Excellent	Good	Excellent	Good	Excellent
52	169Y5A0164	Yellaturu Amruth Kumar	Good	Excellent	Excellent	Good	Excellent

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This certificate is presented to

A. Sudhakar (Reg. No. 169Y5A0102), Student of KSRM College of Engineering (Autonomous) for successful completion of value added course on "COMPUTER AIDED STEEL STRUCTURES " offered by Department of Civil Engineering, KSRMCE-Kadapa.

Course Duration: 48 Hours;
From: 02/07/2018 to 28/07/2018

Course Instructor:
Sri. A. Anil Kumar, Assistant Professor,
CED-KSRMCE-Kadapa

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Chapter 1

Introduction

The development of mankind has depended on the ability to modify and shape the material that nature has made available, in ways to provide them their basic needs, and security and comfort required for their survival and advancement. They have devised tools for hunting, implements for agriculture, shelter for safeguard against the vagaries of nature, and wheels for transportation, an invention mankind has always been proud of. Much of the aforementioned *design* accomplishments have resulted even before mankind may have learnt to count. The then trial-and-error and/or empirical design procedures have been systematized to a great extent using the human understanding of the laws of physics (on force, motion and/or energy transfer) with concepts from mathematics. An idea to fulfill a need and then translating the idea into an implement forms the core of activities in design. *Design and manufacture is innate to the growth of human civilization.*

1.1 Engineering Design

Design is an activity that facilitates the realization of new products and processes through which technology satisfies the needs and aspirations of the society. Engineering design of a product may be conceived and evolved in four steps:

1. *Problem definition:* Extracting a coherent appreciation of *need* or *function* of an engineering part from a fuzzy mix of facts and myths that result from an initial ill-posed problem. The data collection can be done via *observation* and/or a *detailed survey*.
2. *Creative process:* Synthesizing *form*, a design solution to satisfy the need. Multiple solutions may result (and are sought) as the creative thought process is aided by the designers' vast experience and knowledge base. *Brainstorming* is usually done in groups to arrive at various forms which are then evaluated and selected into a set of a few workable solutions.
3. *Analytical process: Sizing* the components of the designed *forms*. Requisite functionality, strength and reliability analysis, feasible manufacturing, cost determination and environmental impact may be some design goals that could be improved optimally by altering the components' dimensions and/or material. This is an iterative process requiring design changes if the analysis shows inadequacy, or scope for further improvement of a particular design. Multiple solutions may be evaluated simultaneously or separately and the *best* design satisfying most or all functional needs may be chosen.
4. *Prototype development and testing:* Providing the ultimate check through physical evaluation under, say, an actual loading condition before the design goes for production. Design changes are

needed in the step above in case the prototype fails to satisfy a set of needs in step 1. This stage forms an interface between design and manufacture. Many groups encourage prototype failure as many times as possible to quickly arrive at a successful design.

1.2 Computer as an Aid to the Design Engineer

Machines have been designed and built even before the advent of computers. During World War-II, ships, submarines, aircrafts and missiles were manufactured on a vast scale. In the significant era (19th and 20th century) of industrial revolution, steam engines, water turbines, railways, cars and power-driven textile mills were developed. The method of representing three-dimensional solid objects was soon needed and was formalized through orthographic projections by a French mathematician Gaspard Monge (1746-1818). After the military kept it a secret for nearly half a century, the approach was made available to engineers, in general, towards the end of nineteenth century.

The inception of modern computers lies in the early work by Charles Babbage (1822), punched card system developed for the US census by Herman Hollerith (1890), differential analyzer at MIT (1930), work on programmable computers by Allan Turing (1936), program storage concept and re-programmable computers by John von Neumann (1946) and micro-programmed architecture by Maurice Wilkes (1951).

The hardware went through a revolution from electronic tubes, transistors (1953), semi-conductors (1953), integrated circuits (1958) to microprocessors (1971). The first 8-bit microcomputer was introduced in 1976 with the Intel 8048 chip and subsequently 16 and 32-bit ones were introduced in 1978 and 1984. Currently, 32 bit and 64 bit PCs are used. Tremendous developments have taken place in hardware, especially in the microprocessor technology, storage devices (20 to 80 GB range), memory input/output devices, compute speed (in GHz range) and enhanced power of PCs and workstations, enabling compactness and miniaturization. The display technology has also made significant advances from its bulky Cathode Ray Tube (CRT) to Plasma Panel and LCD flat screen forms.

Interactive Computer Graphics (ICG) was developed during the 1960s. Sutherland (1962) devised the Sketchpad system with which it was possible to create simple drawings on a CRT screen and make changes interactively. By mid 1960s, General Motors (GM), Lockheed Aircraft and Bell Laboratories had developed DAC-1, CADAM and GRAPHIC-1 display systems. By late 1960s, the term Computer Aided Design (CAD) was coined in literature. During 1970s, graphics standards were introduced with the development of GKS (Graphics Kernel System), PHIGS (Programmer's Hierarchical Interface for Graphics) and IGES (Initial Graphics Exchange Specification). This facilitated the graphics file and data exchange between various computers. CAD/CAM software development occurred at a fast rate during late 1970s (GMSolid, ROMULUS, PADL-2). By 1980s and 1990s, CAD/CAM had penetrated virtually every industry including Aerospace, Automotive, Construction, Consumer products, Textiles and others. Software has been developed over the past two decades for interactive drawing and drafting, analysis, visualization and animation. A few widely used products in Computer Aided Design and drafting are Pro-Engineer™, AutoCAD™, CATIA™, IDEAS™, and in analysis are NASTRAN™, ABAQUS™, ANSYS™ and ADAMS™. Many of these softwares have/are being planned to be upgraded for potential integration of design, analysis, optimization and manufacture.

1.2.1 Computer as a Participant in a Design Team

As it stands, a computer has been rendered a major share of the design process in a man-machine team. It behooves to understand the role of a human vis-à-vis a computer in this setting:

(a) *Conceptualization*, to date, is considered still within the domain of a human designer. Product design commences with the identification of its 'need' that may be based on consumer's/market's demand. An old product may also need design revision in view of new scientific and technological developments. An expert designer or a team goes through a creative and ingenious thought process (brainstorming), mostly qualitative, to synthesize the form of a product. A computer has not been rendered the capability, as yet, to capture non-numeric, qualitative 'thought' design, though it can help a human designer by making available relevant information from its stored database.

(b) *Search, learning and intelligence* is inherent more in a human designer who can be made aware of the new technological developments useful to synthesize new products. A computer, at this time, has little learning and 'qualitative thinking' capability and is not intelligent enough to synthesize a new form on its own. However, it can passively assist a designer by making available a large set of possibilities (stored previously) from a variety of disciplines, and narrow down the search domain for the designer.

(c) *Information storage and retrieval* can be performed very efficiently by a computer that has an excellent capability to store and handle data. Human memory can fade or fail to avail appropriate information fast enough, and at the right time from diverse sources. Further, a computer can automatically create a product database in final stages of the design.

(d) *Analytical power* in a computer is remarkable in that it can perform, say, the finite element analysis of a complex mechanical part or retrieve the input/output characteristics of a designed system very efficiently, provided mathematical models are embedded. Humans usually instruct the computers, via codes or software, the requisite mathematical models employed in *geometric modeling* (modeling of curves, surfaces and solids) and *analysis* (finite element method and optimization). Geometric modeling manifests the *form* of a product that a designer has in mind (qualitatively) while analysis works towards the systematic improvement of that *form*.

(e) *Design iteration* and improvement can be performed by a computer very efficiently once the designer has offloaded his/her conception of a product via geometric modeling. Finite element analysis (or other performance evaluation routine) and optimization can be performed simultaneously with the aim to modify the dimensions/shape of a product to meet the pre-specified design goals.

(f) *Prototyping* of the optimized design can be accomplished using the tools now available for Rapid Manufacturing. The geometric information of the final product can be passed on to a manufacturing set up that would analogically *print* a three dimensional product.

Computers help in manifesting the qualitative conception of a design form a human has of a product. Further, they prove useful in iterative improvement of the design, and its eventual realization. Computers are integrated with humans in design and manufacture, and provide the scope for automation (or least human interaction) wherever needed (mainly in analysis and optimization). Computer Aided Process Planning (CAPP), scheduling (CAS), tool design (CATD), material requirement planning (MRP), tool path generation for CNC machining, flexible manufacturing system (FMS), robotic systems for assembly and manufacture, quality inspection, and many other manufacturing activities also require computers.

1.3 Computer Graphics

Computer Graphics, which is a discipline within Computer Science and Engineering, provides an important mode of interaction between a designer and computer. Sutherland developed an early form of a computer graphic system in 1963. Rogers and Adams explain computer graphics as the *use* *of computers to define, store, manipulate, interrogate and present pictorial output.* Computer graphics involves the creation of two and three dimensional models, shading and rendering to bring in realism to the objects, natural scene generation (sea-shores, sand dunes or hills and mountains), animation, flight simulation for training pilots, navigation using graphic images, walk through buildings, cities and highways, and creating virtual reality. War gaming, computer games, entertainment industry and advertising has immensely benefited from the developments in computer graphics. It also forms an important ingredient in Computer-Aided Manufacturing (CAM) wherein graphical data of the object is converted into machining data to operate a CNC machine for production of a component. The algorithms of computer graphics lay behind the backdrop all through the process of virtual design, analysis and manufacture of a product. Two primary constituents of computer graphics are the *hardware* and the *software*.

1.3.1 Graphics Systems and Hardware

Hardware comprises the *input*, and *display* or *output devices*. Numerous types of graphics systems are in use; those that model one-to-many interaction and others that allow one-to-one interface at a given time. *Mainframe-based systems* use a large mainframe computer on which the software, which is usually a huge code requiring large space for storage, is installed. The system is networked to many designer stations on time-sharing basis with display unit and input devices for each designer. With this setting, intricate assemblies of engineering components, say an aircraft, requiring many human designers can be handled. *Minicomputer* or *Workstation* based systems are smaller in scale than the Mainframe systems with a limited number (one or more) of display and input devices. Both systems employ one-to-many interface wherein more than one designer can interact with a computer. On the contrary, *Microcomputer* (PC) based systems allow only one-to-one interaction at a time. Between the Mainframe, Workstation and PC based systems, the Workstation based system offers advantages of distributed computing and networking potential with lower cost compared with the mainframes.

1.3.2 Input Devices

Keyboard and *mouse* are the primary input devices. In a more involved environment, digitizers, joysticks and tablets are also used. Trackballs and input dials are used to produce complex models. Data gloves, image scanners, touch screens and light pens are some other input devices. A keyboard is used for submitting alphanumeric input, three-dimensional coordinates, and other non-graphic data in 'text' form. A mouse is a small hand held pointing device used to control the position of the cursor on the screen. Below the mouse is a ball. When the mouse is moved on a surface, the amount and direction of movement of the cursor is proportional to that of the mouse. In optical mouse, an optical sensor moving on a special mouse pad having orthogonal grids detects the movements. There are push buttons on top of the mouse beneath the fingers for signaling the execution of an operation, for selecting an object created on the screen within a rectangular area, for making a selection from the pulled down menu, for dragging an object from one part of the screen to other, or for creating drawings and dimensioning. It is an important device used to expedite the drawing operations. A special z-mouse for CAD, animation and virtual reality includes three buttons, a thumb-wheel and a track-ball on top. It gives six degrees of freedom for spatial positioning in x-y-z directions. The z-mouse is used for rotating the object around a desired axis, moving and navigating the viewing position (observer's eye) and the object through a three-dimensional scene.

Trackballs, *space-balls* and *joysticks* are other devices used to create two and three-dimensional drawings with ease. Trackball is a 2-D positioning device whereas space-ball is used for the same in 3-D. A joystick has a vertical lever sticking out of a base box and is used to navigate the screen cursor.

Digitizers are used to create drawings by clicking input coordinates while holding the device over a given 2-D paper drawing. Maps and boundaries in a survey map, for example, can be digitized to create a computer map. *Touch panels* and *light pens* are input devices interacting directly with the computer screen. With touch panels, one can select an area on the screen and observe the details pertaining to that area. They use infrared light emitting diodes (LEDs) along vertical and horizontal edges of the screen, and go into action due to an interruption of the beam when a finger is held closer to the screen. Pencil shaped *light pens* are used to select screen position by detecting the light from the screen. They are sensitive to the short burst of light emitted from the phosphor coating as the electron beam hits the screen. *Scanners* are used to digitize and input a two-dimensional photographic data or text for computer storage or processing. The gradations of the boundaries, gray scale or color of the picture is stored as data arrays which can be used to edit, modify, crop, rotate or scale to enhance and make suitable changes in the image by software designed using geometric transformations and image processing techniques.

FaroArm®, a 3-D coordinate measuring device, is a multi-degree of freedom precision robotic arm attached to a computer. At the tip of the end-effector is attached a fine roller-tipped sensor. The tip can be contacted at several points on a curved surface to generate a point data cloud. A 3-D surface can then be fitted through the data cloud to generate the desired surface. A non-contact 3-D digitizer, Advanced Topometric Sensor (ATOS) uses optical measuring techniques. It is material independent and can scan in three-dimensions any arbitrary object such as moulds, dies, and sculptures. It is a high detailed resolution and precision machine. It uses adhesive retro targets stuck on the desired surface. Digital reflex cameras then record the positions of these retro targets from different views. The images consisting of the coordinates of targets are transferred from the digital camera to the computer. The image coordinates are then converted to the object coordinates by calculating the intersection of the rays from different camera positions. Finally, the required object surface is generated. Techniques for scanning objects in three-dimensions are very useful in reverse engineering, rapid prototyping of existing objects with complex surfaces such as sculptures and other such applications.

1.3.3 Display and Output Devices

Three types of display devices are in use: Cathode ray tube (*CRT*), Plasma Panel Display (PPD) and Liquid Crystal Display (LCD). CRT is a popular display device in use for its low cost and high-resolution color display capabilities. It is a glass tube with a front rectangular panel (screen) and a cylindrical rear tube. A cathode ray gun, when electrically heated, gives out a stream of electrons, which are then focused on the screen by means of positively charged electron-focusing lenses. The position of the focused point is controlled by orthogonal (horizontally and vertically deflecting) set of amplifiers arranged in parallel to the path of the electron beam. A popular method of CRT display is the Raster Scan. In raster scan, the entire screen is divided into a matrix of picture cells called *pixels*. The distance between pixel centers is about 0.25 mm. The total number of pixel sets is usually referred to as *resolution*. Commonly used CRTs are those with resolution of 640×480 (VGA), 1024×768 (XGA) and 1280×1024 (SXGA). With higher resolution, the picture quality is much sharper. As the focused electron beam strikes a pixel, the latter emits light, i.e. the pixel is 'on' and it becomes bright for a small duration of time. The electron beam is made to scan the entire screen line-by-line from top to bottom (525 horizontal lines in American system and 625 lines in European system) at 63.5 microseconds per scan line. The beam keeps on retracing the path. The *refresh rate* is 60Hz, implying that the screen is completely scanned in $1/60^{th}$ of a second (for European system, it is $1/50^{th}$ of a second). In a black and white display, if the pixel intensity is '0', the pixel appears black, and when '1', the pixel is bright. As the electron beam scans through the entire screen, it switches off those pixels which are supposed to be black thus creating a pattern on the screen. For the electron beam to know precisely which pixels are to be kept 'off' during scans, a *frame buffer* is used that is a hardware programmable memory. At least one memory bit ('0' or '1') is needed for each pixel, and there are as many bits allocated in the memory as the number of pixels on display. The entire memory required for displaying all the pixels is called a *bit plane* of the frame buffer.

One bit plane would create only a 'black' and 'white' image, but for a realistic picture, one would need *gray levels* or shades between black and white as well. To control the intensity (or shade) of a pixel one has to use a number of bit planes in a frame buffer. For example, if one uses 3 bit planes in single frame buffer, one can create 8 (or 2^3) combinations of intensity levels (or shades) for the same pixel- 000 (black)-001-010- 011-100-101-110-111(white). The intermediate values will control the intensity of the electron beam falling on the pixel. To have an idea about the amount of memory required for a black and white display with 256 × 256 (or 2^{16}) pixels, every bit plane will require a memory of 2^{16} = 65,536 bits. If there are 3 bit planes to control the gray levels, the memory required will be 1,96,608 bits! Since memory is a digital device and the raster action is analog, one needs digital-to-analog converters (DAC). A DAC takes the signal from the frame buffer and produces an equivalent analog signal to operate the electron gun in the CRT.

For *color display*, all colors are generated by a proper combination of 3 basic colors, viz. red, green, and blue. If we assign '0' and '1' to each color in the order given, we can generate 8 colors: black (000), red (100), green (010), blue (001), yellow (110), cyan (011), magenta (101) and white (111). The frame buffer requires a minimum of 3 bit planes—one for each RGB color; this can generate 8 different colors. If more colors are desired, one needs to increase the number of bit planes for each color. For example, if each of the RGB colors has 8 bit planes (a total of 24 bit planes in the frame buffer with three 8-bit DAC), the total number of colors available for picture display would be 2^{24} = 1,67,77,216! To further enhance the color capabilities, each 8-bit DAC is connected to a color look up memory table. Various methods are employed to decrease the access and display time and enhance the picture sharpness.

CRT displays are popular and less costly, but very bulky and suitable only for desktop PCs. Flat Panel Displays (FPD) are gaining popularity with laptop computers and other portable computers and devices. FPD belongs to one of the following two classes: (a) active FPD devices, which are primarily light emitting devices. Examples of active FPD are flat CRT, plasma gas discharge, electroluminescent and vacuum fluorescent displays. (b) Passive FPD devices are based on light modulating technologies. Liquid Crystal (LC) and Light Emitting Diodes (LED) are some examples.

Plotters and *printers* constitute the output devices. Line printers are the oldest succeeded by 9-pin and 24-pin *dot matrix plotters* and printers. *Ink jet plotters*, *laser plotters* and *thermal plotters* are used for small and medium sized plots. For large plots, *pen and ink plotters* of the flat bed, drum and pinch roller types are used.

1.4 Graphics Standards and Software

Till around 1973, software for producing graphics was mostly device dependent. Graphics software written for one type of hardware system was not portable to another type, or it became useless if the hardware was obsolete. Graphics standards were set to solve portability issues to render the application software device independent. Several standards have been developed; most popular among them are GKS (Graphics Kernel System), PHIGS (Programmer's Hierarchical Interactive Graphics System), DXF (Drawing Exchange Format), and IGES (Initial Graphics Exchange Specification).

For designing mechanical components and systems, one requires 3-D graphics capabilities for which GKS 3-D, PHIGS and DXF are suitable. For 3-D graphics and animation, PHIGS is used.

It provides high interactivity, hierarchical data structuring, real time graphic data modification, and support for geometric transformations. These standards provide the core of graphics including basic graphic primitives such as line, circle, arc, poly-lines, poly-markers, line-type and line-width, text, fill area for hatching and shading, locators for locating coordinates, valuators for real values for dimensioning, choice options and strings. Around such standard primitives, almost all standard software for CAD is written. They also include the device drivers for standard plotters and display devices.

Another comprehensive standard is IGES to enable the exchange of model databases among CAD/CAM systems. IGES contains more geometric entities such as, curves, surfaces, solid primitives, and Boolean (for Constructive Solid Geometry) operations. Wire-frame, surface modeling and solid modeling software can all be developed around IGES. It can transmit the property data associated with the drawings which helps in preparing, say, the bill of materials. Though these standards appear veiled or at the *back end*, they play a crucial role in creation of the application software.

1.5 Designer-Computer Interaction

A CAD/CAM software is designed to be primarily interactive, instructive and user-friendly wherein a designer can instruct a computer to perform a sequence of tasks ranging from designing to manufacture of an engineering component. The front end of a software is a graphical user interface or GUI while the back end comprises computation and database management routines. The front end is termed so as a user can visually observe the design operations being performed. However, computation and data storage routines are not very apparent to a designer, which is why they may be termed collectively as the back end of the software. In most CAD software, the GUI is divided into two parts (or windows) that appear on the display device or screen (Figure 1.1): (i) the visual manifestation or the

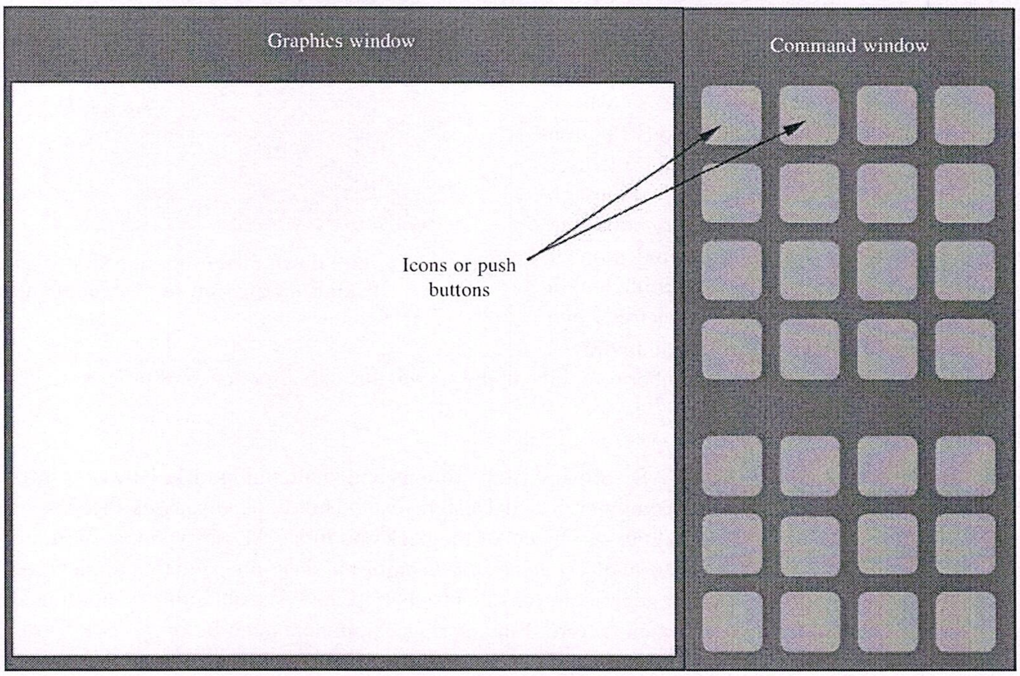


Figure 1.1 Generic appearance of the Front end of a CAD software

Graphics Window and (ii) the Command window. The Graphics window provides the visual feedback to the user detailing desired information about an object being designed. One can manipulate the position (through translation/rotation) of an object relative to another or a fixed coordinate system and visualize the changes in the Graphics window. In essence, all design operations involving transformations, curve design, design of surfaces and solids, assembly operations pertaining to relative positioning of two or more components, drafting operations that provide the engineering drawings, analysis operations that yield results pertaining to displacements and stresses, optimization operations that involve sequential alterations in design, and many others can be visualized through the Graphics window.

The design instructions are given through a user-friendly Command Window that is subdivided into several *push buttons* or *icons*. To accommodate numerous applications in CAD and to allow a guided user interface, the icons appear in groups. For instance, icons pertaining to the design of curves would be grouped in the Command window. Push buttons pertaining to curve trimming, extension, intersection and other such actions would be combined. Icons used in surface and solid design would appear in two different groups. Options under transformations, analysis, optimization and manufacture would also be clustered respectively. A user may make a design choice by clicking on an icon using the mouse. There may be many ways to design a curve, for instance. To accommodate many such possibilities, a CAD GUI employs the *pull down menus* (Figure 1.2). That is, when an icon on curve segment design is clicked on, a menu would drop down prompting the user to choose between, say, the Ferguson, Bézier or B-spline options. Similarly, for a surface patch design, a pull down menu may have choices ranging between the analytical patches, tensor product surfaces, Coon's patches, rectangular or triangular patches, ruled or lofted patches and many others. For solid modeling, a user may have to choose between Euler operations or Boolean sequences. After a design operation is chosen using a push button and from a respective pull down menu, the user would be prompted to enter further choices through *pop up* menus. For instance, if a user chooses to sketch a line, a pop up window may appear expecting the user to feed in the start point, length and orientation of the line. Note that for a two dimensional case, a much easier option to draw a curve segment may be to select a number of points on the screen through a sequence of mouse clicks.

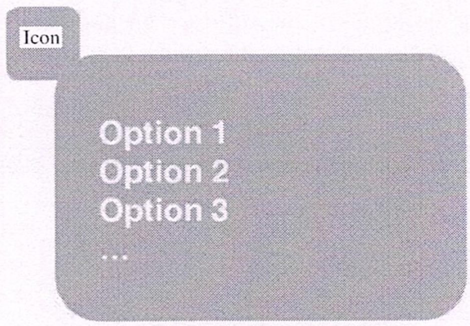


Figure 1.2 A pull down menu that appears when clicking on an icon in the command window

1.6 Motivation and Scope

Developing the front end GUI of a CAD software is an arduous and challenging task. However, it is the back end wherein the core of Computer Aided Design rests. This book discusses the design concepts based on which various modules or objects of the back end in a CAD software are written. The concepts emerge as an amalgamation of *geometry*, *mathematics* and *engineering* that renders the software the capability of *free-form* or generic design of a product, its analysis, obtaining its optimized form, if desired, and eventually its manufacture. Engineering components can be of various forms (sizes and shapes) in three-dimensions. A Solid can be thought of as composed of a simple *closed connected surface* that encloses a finite volume. The closed surface may be conceived as an interweaved

Chapter 2

Transformations and Projections

Geometric transformations provide *soul* or *life* to *virtual objects* created through geometric modeling discussed in later chapters. It is using transformations that one can manoeuver an object, view it from different angles, create multiple copies, create its reflected image, re-shape or scale an object, position an object with respect to the other, and much more. Projections, like orthographic and perspective on the other hand, help comprehend an object for purpose of its fabrication. Transformations have many uses, mainly pertaining *motion*, such as manipulating the relative positions of two objects in solid modeling to create a complex entity, displaying motion of mechanisms, animating an assembly to demonstrate its working or imparting motion to a virtual human for a walk through a virtual city or a building. Motion simulators for aircrafts, tanks and motor vehicles extensively employ geometric transformations.

Transformations may be employed to perform *rigid-body motion* wherein an object may be moved from one position to another without altering its shape and size. Typical rigid body transformations involve *translation*, *rotation* and *reflection*, the latter being a combination of the first two. Transformations may also cause *deformations* like *shear*, *scaling* and *morphing* wherein the object is altered in size and/or shape. For special effects, *free-form* deformation may be used where a geometric model is embedded inside a grid of control points, and transformations are applied to these control points to distort the object in a desired manner.

When dealing with transformations, an engineer would require a full description of the object, its position relative to a fixed point called *origin*, and a specified set of coordinate axes. An object may

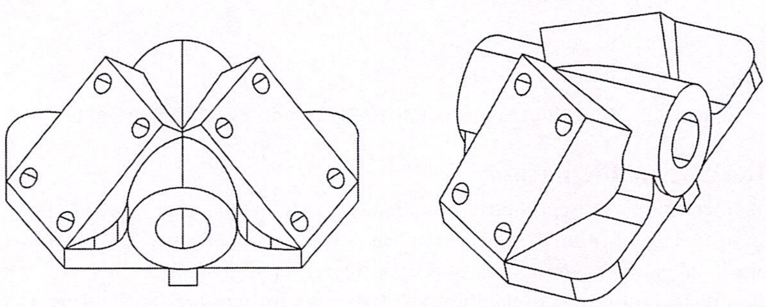
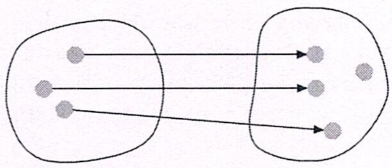


Figure 2.1 Use of transformation to view an object from different angles

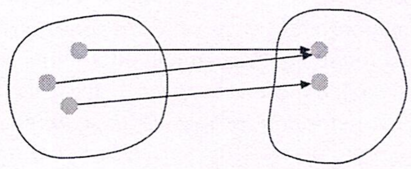
be treated as an assemblage of finitely many points arranged in a non-arbitrary manner in space. The origin and coordinate axes may or may not be a part of the object. If the coordinate frame is attached to the object, it is called the *local frame* of reference. For coordinate frame not a part of the object, it is called *global frame*. Usually, since there are many objects to manoeuver at a given time, the user prefers a fixed global coordinate frame for all objects and one local coordinate system for each object. Geometric transformations may then involve: (a) moving all points of an object to a new location with respect to the global coordinate system or (b) relocating the local coordinate frame of an object to a new position without changing the object's position in the global frame. Transformations, in this chapter, are regarded as *time independent* in that the motion of an object from one position to another is *instantaneous* and does not follow a specified path in space. In other words, there can be more than one ways to manoeuver an object from its current location to a specified one.

2.1 Definition

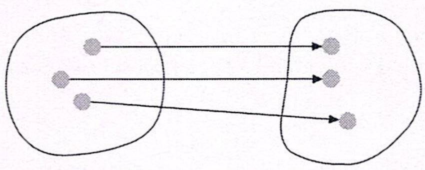
A geometric transformation may be considered as a mapping function between a set of points both in the domain and range. The points may belong to the object or the coordinate system to be relocated. The function needs to be *one-to-one* in that any and all points in the domain (initial location) should have the corresponding images in the range (final location). Thus, if $T(\mathbf{P}_1)$ and $T(\mathbf{P}_2)$ represent the final locations of points $\mathbf{P}_1$ and $\mathbf{P}_2$ belonging to the object where T is a transformation function, then, if $\mathbf{P}_1 \neq \mathbf{P}_2$, $T(\mathbf{P}_1) \neq T(\mathbf{P}_2)$. In addition, the transformation should be *onto* in that for every final location $T(\mathbf{P})$, there must exist its pre-image $\mathbf{P}$ corresponding to the initial position of the object. In other words, any point in the newly located object must be associated with only one point belonging to the object in its original location. Thus, a one-to-one and onto map makes it possible to perform *inverse transformation*, that is, to move the object from its final to original location.



(a) One-to-one and not onto



(b) Onto and not one-to-one



(c) One-to-one and onto

Figure 2.2 Nature of geometric transformation as a function map

2.2 Rigid Body Transformations

In rigid body transformations, the geometric model stays undeformed, that is, the points constituting the model maintain the same relative positions with respect to each other. A solid model may be conceived to consist of points, curves and surfaces which should not get distorted under a rigid-body trans-formation. Rotation and translation are two transformations that can be grouped under this category. First, rotation and translation are discussed in two-dimensions. Vectors and matrices are most convenient to represent such motions. The *homogenous coordinate system*, which has some distinct advantages, is also introduced to unify the two transformations.

2.2.1 Rotation in Two-Dimensions

Consider a rigid body S packed with points P_i ($i = 1, \ldots, n$) and let a point $P_j(x_j, y_j)$ on S be rotated about the z-axis to $P_j^*(x_j^*, y_j^*)$ by an angle θ. From Figure 2.3, 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

$$\begin{bmatrix} x_j^* \\ y_j^* \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x_j \\ y_j \end{bmatrix} \Rightarrow \mathbf{P}_j^* = \mathbf{R}\mathbf{P}_j \qquad (2.1)$$

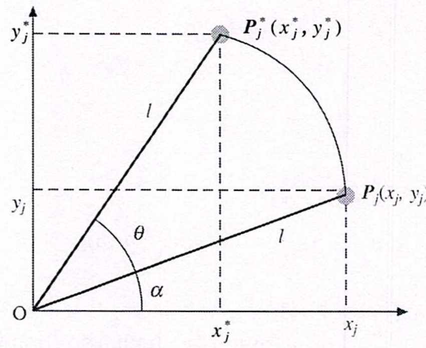


Figure 2.3 Rotation in a plane

where $\mathbf{R} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$ is the two-dimensional *rotation matrix*. For S to be rotated by an angle θ, transformation in Eq. (2.1) must be performed simultaneously for all points P_i ($i = 1, \ldots, n$) such that the entire rigid body reaches the new destination S^*.

Example 2.1 A trapezoidal lamina $ABCD$ lies in the x-y plane as shown with $A(6, 1)$, $B(8, 1)$, $C(10, 4)$ and $D(3, 4)$. The lamina is to be rotated about the z-axis by 90°. Determine the new position $A^*B^*C^*D^*$ after rotation (Figure 2.4(a)).

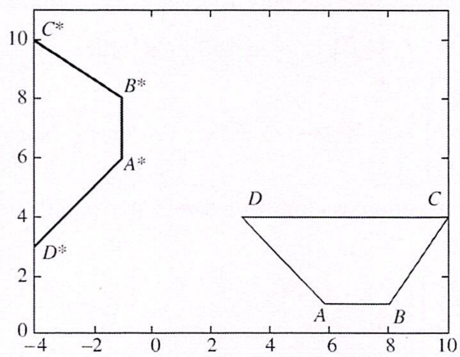


Figure 2.4 (a) Lamina rotation in Example 2.1

The transformation matrix **R** is given by Eq. (2.1) with $\theta = 90°$. Thus,

$$\begin{bmatrix} A^* \\ B^* \\ C^* \\ D^* \end{bmatrix}^T = \mathbf{R} \begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix}^T = \begin{bmatrix} \cos 90° & -\sin 90° \\ \sin 90° & \cos 90° \end{bmatrix} \begin{bmatrix} 6 & 1 \\ 8 & 1 \\ 10 & 4 \\ 3 & 4 \end{bmatrix}^T$$

$$= \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 6 & 1 \\ 8 & 1 \\ 10 & 4 \\ 3 & 4 \end{bmatrix}^T = \begin{bmatrix} -1 & 6 \\ -1 & 8 \\ -4 & 10 \\ -4 & 3 \end{bmatrix}^T$$

2.2.2 Translation in Two-Dimensions: Homogeneous Coordinates

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

$$x_j^* = x_j + p, \quad y_j^* = y_j + q \Rightarrow \begin{bmatrix} x_j^* \\ y_j^* \end{bmatrix} = \begin{bmatrix} x_j \\ y_j \end{bmatrix} + \begin{bmatrix} p \\ q \end{bmatrix} \Rightarrow \mathbf{P}_j^* = \mathbf{P}_j + \mathbf{v} \qquad (2.2)$$

Example 2.2 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 $\mathbf{v} = \begin{bmatrix} 8 \\ 5 \end{bmatrix}$. Eq. (2.2) yields

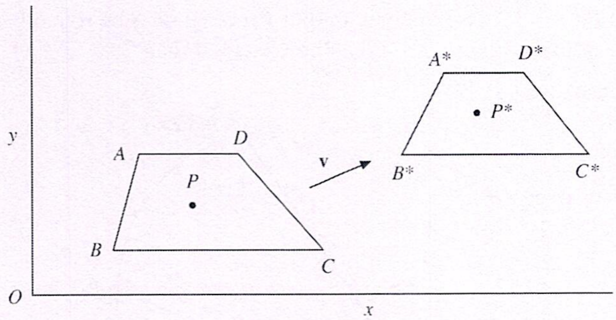


Figure 2.4 (b)

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

We may note that like rotation, translation as in Eq. (2.2) does not work out to be a matrix multiplication. Instead, it is the addition of a point (position vector) and a (free) vector. One may attempt to represent translation also in the matrix multiplication form to unify the procedure for rigid body transformations. Consider Eq. (2.2) rewritten as

$$\begin{bmatrix} x_j^* \\ y_j^* \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & p \\ 0 & 1 & q \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_j \\ y_j \\ 1 \end{bmatrix} = \begin{bmatrix} x_j + p \\ y_j + q \\ 1 \end{bmatrix} \tag{2.3}$$

Here, the first two rows provide the translation information while the third row gives the dummy result 1 = 1. Note also that the definition of position vector $\boldsymbol{P}_j \begin{bmatrix} x_j \\ y_j \end{bmatrix}$ is altered from an ordered pair in the two-dimensional space to an ordered triplet $\begin{bmatrix} x_j \\ y_j \\ 1 \end{bmatrix}$ which are termed as the *homogenous coordinates* of $\boldsymbol{P}_j$. We may use this new definition of position vectors to express translation in Eq. (2.3) as $\mathbf{P}_j^* = \mathbf{TP}_j$ where

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

The rotation relation in Eq. (2.1) can be modified as well to express the result in terms of the homogeneous coordinates, that is

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

where
$$\mathbf{R} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.4}$$

Rigid body translation and rotation thus get unified as *matrix multiplication* operations only, involving no addition or subtraction of matrices and vectors. Further, one can *concatenate* a sequence of transformations, for instance, translation of an object followed by its rotation. If one can identify the matrices for each of these transformations in the multiplication form, it becomes much easier to track the intermediate positions as well as to predict the final transformed position of the rigid body.

2.2.3 Combined Rotation and Translation

Consider a point P $(x, y, 1)$ in the x-y plane to be rotated by an angle θ about the z-axis to a position P_1 $(x_1, y_1, 1)$ followed by a translation by $\mathbf{v}$ (p, q) to a position P_2 $(x_2, y_2, 1)$. Using Eqs. (2.3) and (2.4), we may write

$$\mathbf{P}_1 = \mathbf{RP}, \begin{bmatrix} x_1 \\ y_1 \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

and
$$\mathbf{P}_2 = \mathbf{TP}_1, \begin{bmatrix} x_2 \\ y_2 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & p \\ 0 & 1 & q \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & p \\ 0 & 1 & q \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \mathbf{TRP}$$

Thus,
$$\mathbf{P}_2 = \begin{bmatrix} \cos\theta & -\sin\theta & p \\ \sin\theta & \cos\theta & q \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{2.5}$$

On the contrary, if translation by $\mathbf{v}$ is followed by rotation about the z-axis by an angle θ to reach P_2^*, then

$$\mathbf{P}_2^* = \mathbf{RTP} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & p \\ 0 & 1 & q \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & p\cos\theta - q\sin\theta \\ \sin\theta & \cos\theta & p\sin\theta + q\sin\theta \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{2.6}$$

We observe from Eqs. (2.5) and (2.6) that the final positions P_2 and P_2^* are not identical. From above we can arrive at two important conclusions: (a) the homogeneous coordinate system helps to unify translation and rotation as multiplicative transformations and (b) transformations are not commutative. The sequence in which the transformations are performed is significant and must be maintained while concatenating the respective matrices. Otherwise a different orientation or position of the object is reached. If $T_1, T_2, \ldots, T_n$ are the transformations to be performed in the order, the combined transformation matrix T is given as $T = T_n\, T_{n-1}\, T_{n-2} \ldots\, T_2\, T_1$.

Example 2.3. Lamina *ABCD* with an inner point *P* with coordinates (4, 3), (3, 1), (8, 1), (7, 4) and (5, 2) respectively is first rotated through 60° and then translated by (5, 4). In another sequence, the trapezoid is first translated by (5, 4) and then rotated through 60°. The lamina acquires different positions and orientations given and shown below for the two sequences of transformations.

For rotation and then translation using Eq. (2.5), we have

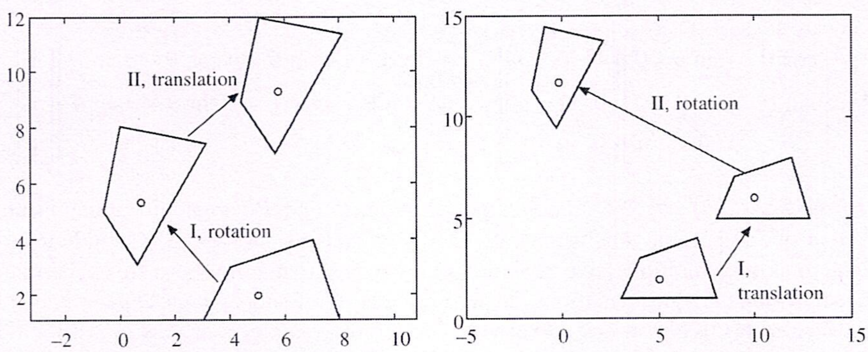
$$\begin{bmatrix} A' \\ B' \\ C' \\ D' \\ P' \end{bmatrix}^T = \begin{bmatrix} \cos 60° & -\sin 60° & 5 \\ \sin 60° & \cos 60° & 4 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 4 & 3 & 1 \\ 3 & 1 & 1 \\ 8 & 1 & 1 \\ 7 & 4 & 1 \\ 5 & 2 & 1 \end{bmatrix}^T = \begin{bmatrix} 4.43 & 8.96 & 1 \\ 5.63 & 7.09 & 1 \\ 8.13 & 11.42 & 1 \\ 5.03 & 12.06 & 1 \\ 5.76 & 9.33 & 1 \end{bmatrix}^T$$

For translation and then rotation, Eq. (2.6) gives

$$\begin{bmatrix} A^* \\ B^* \\ C^* \\ D^* \\ P^* \end{bmatrix}^T = \begin{bmatrix} \cos 60° & -\sin 60° & 5\cos 60° - 4\sin 60° \\ \sin 60° & \cos 60° & 5\cos 60° + 4\sin 60° \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 4 & 3 & 1 \\ 3 & 1 & 1 \\ 8 & 1 & 1 \\ 7 & 4 & 1 \\ 5 & 2 & 1 \end{bmatrix}^T$$

$$= \begin{bmatrix} -1.56 & 11.30 & 1 \\ -.33 & 9.43 & 1 \\ 2.17 & 13.76 & 1 \\ -.93 & 14.40 & 1 \\ -0.19 & 11.66 & 1 \end{bmatrix}^T$$

The two different laminar positions and orientations are shown in Figure 2.5.



(a) Rotation before translation

(b) Translation before rotation

Figure 2.5 An example depicting the significance of order in transformations

2.2.4 Rotation of a Point Q (x_q, y_q, 1) about a Point P (p, q, 1)

Since the rotation matrix **R** about the z-axis and translation matrix **T** in the x-y plane are known from Eqs. (2.4) and (2.3) respectively, rotation of Q about P can be regarded as translating P to coincide with the origin, followed by rotation about the z-axis by an angle θ, and lastly, placing P back to its original position (Figure 2.6). These transformations can be concatenated as

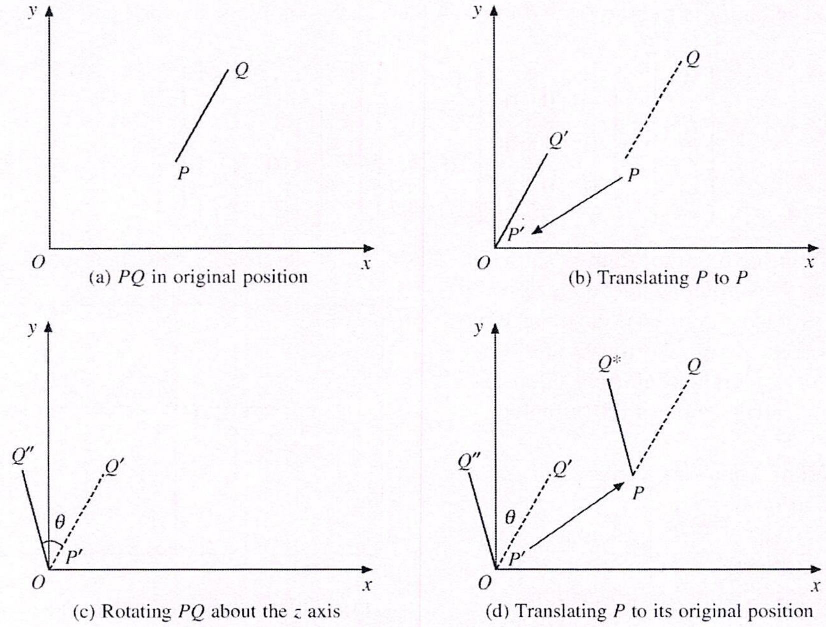


Figure 2.6 Steps to rotate point Q about point P

$$Q^* = \begin{bmatrix} x_q^* \\ y_q^* \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & p \\ 0 & 1 & q \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & -p \\ 0 & 1 & -q \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_q \\ y_q \\ 1 \end{bmatrix} \tag{2.7}$$

2.2.5 Reflection

In 2-D, reflection of an object can be obtained by rotating it through 180° about the axis of reflection. For instance, if an object S in the x-y plane is to be reflected about the x-axis ($y = 0$), reflection of a point (x, y, 1) in S is given by (x^*, y^*, 1) such that

$$\begin{bmatrix} x^* \\ y^* \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ -y \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \mathbf{R}_{fx} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{2.8}$$

Similarly, reflection about the y-axis is described as

$$\begin{bmatrix} x^* \\ y^* \\ 1 \end{bmatrix} = \begin{bmatrix} -x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \mathbf{R}_{fy} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{2.9}$$

Example 2.4. Consider a trapezium $ABCD$ with $A = (6, 1, 1)$, $B = (8, 1, 1)$, $C = (10, 4, 1)$ and $D = (3, 4, 1)$. The entity is to be reflected through the y-axis. Applying $\mathbf{R}_{fy}$ in Eq. (2.9) results in

$$\begin{bmatrix} A^* \\ B^* \\ C^* \\ D^* \end{bmatrix}^T = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 6 & 1 & 1 \\ 8 & 1 & 1 \\ 10 & 4 & 1 \\ 3 & 4 & 1 \end{bmatrix}^T = \begin{bmatrix} -6 & 1 & 1 \\ -8 & 1 & 1 \\ -10 & 4 & 1 \\ -3 & 4 & 1 \end{bmatrix}^T$$

The new position for the trapezium is shown as $A^*B^*C^*D^*$ in Figure 2.7. Note that identical result may be obtained by rotating the trapezium by 180° about the y axis. As expected there is no distortion in the shape of the trapezium. Since reflection results by combining translation and/or rotation, it is a rigid body transformation.

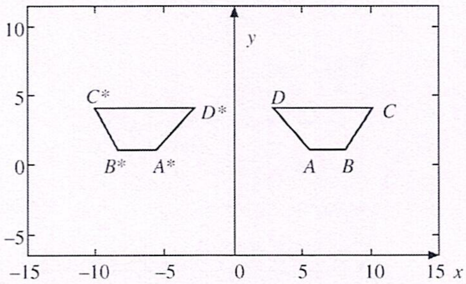


Figure 2.7 Reflection about the *y*-axis

2.2.6 Reflection About an Arbitrary Line

Let D be a point on line L and S be an object in two-dimensional space. It is required to reflect S about L. This reflection can be obtained as a sequence of the following transformations:

(a) Translate point D $(p, q, 1)$ to coincide with the origin O, shifting the line L parallel to itself to a translated position L^*.
(b) Rotate L^* by an angle θ such that it coincides with the y-axis (new position of the line is L^{**}, say).
(c) Reflect S about the y-axis using Eq. (2.9).
(d) Rotate L^{**} through $-\theta$ to bring it back to L^*.
(e) Translate L^* to coincide with its original position L.

The schematic of the procedure is shown in Figure 2.8. The new image S^* is the reflection of S about L and the transformation is given by

$$\begin{bmatrix} 1 & 0 & p \\ 0 & 1 & q \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} 1 & 0 & -p \\ 0 & 1 & -q \\ 0 & 0 & 1 \end{bmatrix} = \mathbf{T_{OD}R}(-\theta)\mathbf{R}_{fy}\mathbf{R}(\theta)\mathbf{T_{DO}} \tag{2.10}$$

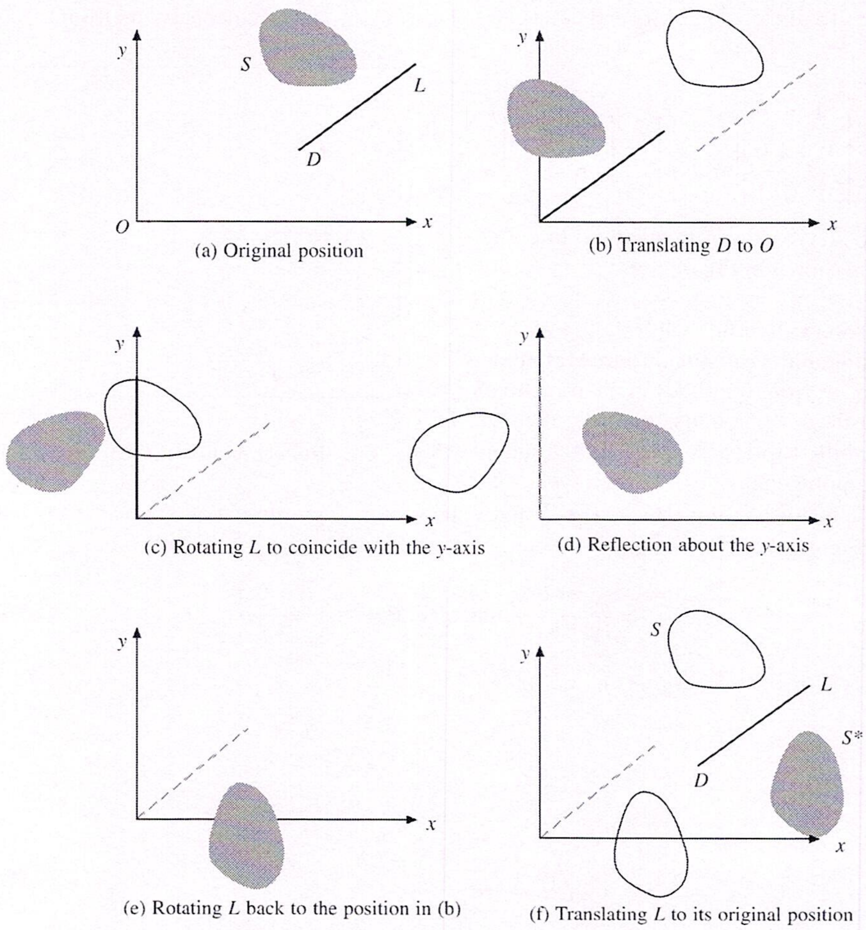


Figure 2.8 Reflection about an arbitrary line

In Eq. (2.10), $\mathbf{T}_{PQ}$ represents translation from point **P** to **Q**. The above procedure is not unique in that the steps (b), (c) and (d) above can be altered so that L is made to coincide with the x-axis by rotating it through an angle α, reflection is performed about the x-axis, and the line is rotated back by $-\alpha$.

2.2.7 Reflection Through a Point

A point P $(x, y, 1)$ when reflected through the origin is written as P^* $(x^*, y^*, 1) = (-x, -y, 1)$ or

$$\begin{bmatrix} x^* \\ y^* \\ 1 \end{bmatrix} = \begin{bmatrix} -x \\ -y \\ 1 \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \mathbf{R}_{fo} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{2.11}$$

For reflection of an object about a point P_r, we would require to shift P_r to the origin, perform the above reflection and then transform P_r back to its original position.

Example 2.5. To reflect a line with end points P (2, 4) and Q (6, 2) through the origin, from Eq. (2.11), we have

$$\begin{bmatrix} P^* \\ Q^* \end{bmatrix}^T = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 2 & 4 & 1 \\ 6 & 2 & 1 \end{bmatrix}^T = \begin{bmatrix} -2 & -4 & 1 \\ -6 & -2 & 1 \end{bmatrix}^T$$

Joining P^*Q^* gives the reflection of line PQ through O as shown in Figure 2.9.

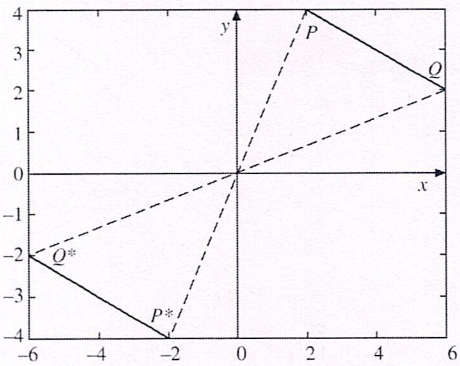


Figure 2.9 Reflection of a line through the origin

2.2.8 A Preservative for Angles! Orthogonal Transformation Matrices

We must ensure for rigid-body transformations that if for instance a polygon is rotated, reflected or linearly shifted to a new location, the angle between the polygonal sides are preserved, that is, there is no distortion in its shape. Let $\mathbf{v}_1$ and $\mathbf{v}_2$ be vectors representing any two adjacent sides of a polygon (Figure 2.10). The angle between them is given by

$$\cos\theta = \frac{\mathbf{v}_1 \cdot \mathbf{v}_2}{|\mathbf{v}_1||\mathbf{v}_2|} \quad \text{and} \quad \sin\theta = \frac{(\mathbf{v}_1 \times \mathbf{v}_2)\cdot \mathbf{k}}{|\mathbf{v}_1||\mathbf{v}_2|} \tag{2.12}$$

where $\mathbf{v}_1 = [v_{1x} \;\; v_{1y} \;\; 0]$ and $\mathbf{v}_2 = [v_{2x} \;\; v_{2y} \;\; 0]$.

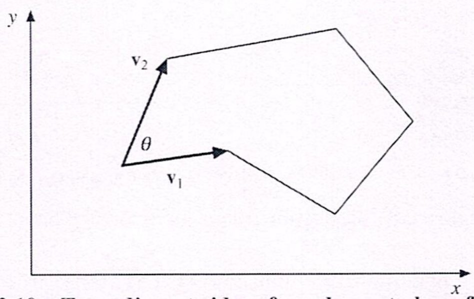


Figure 2.10 Two adjacent sides of a polygon to be reflected, rotated or translated to a new location

Note the way the vectors are expressed as homogenous coordinates. For position vectors of points A and B as $[x_1, y_1, 1]^T$ and $[x_2, y_2, 1]^T$, the vector **AB** can be expressed as

$$\mathbf{AB} = \begin{bmatrix} x_2 \\ y_2 \\ 1 \end{bmatrix} - \begin{bmatrix} x_1 \\ y_1 \\ 1 \end{bmatrix} = \begin{bmatrix} x_2 - x_1 \\ y_2 - y_1 \\ 0 \end{bmatrix}$$

Thus in homogenous coordinates, free vectors have 0 as their last element. With (**i**, **j**, **k**) as unit vectors along the coordinate axes x, y and z, respectively, applying any generic transformation **A** yields

$$\begin{bmatrix} v_1^* \\ v_2^* \end{bmatrix}^T = \mathbf{A}\begin{bmatrix} v_1 \\ v_2 \end{bmatrix}^T = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}\begin{bmatrix} v_{1x} & v_{1y} & 0 \\ v_{2x} & v_{2y} & 0 \end{bmatrix}^T$$

$$= \begin{bmatrix} a_{11}v_{1x} + a_{12}v_{1y} & a_{21}v_{1x} + a_{22}v_{1y} & a_{31}v_{1x} + a_{32}v_{1y} \\ a_{11}v_{2x} + a_{12}v_{2y} & a_{21}v_{2x} + a_{22}v_{2y} & a_{31}v_{2x} + a_{32}v_{2y} \end{bmatrix}^T$$

Thus,

$$\mathbf{v}_1^* \cdot \mathbf{v}_2^* = \left|\mathbf{v}_1^*\right|\left|\mathbf{v}_2^*\right|\cos\theta^*$$

$$= (a_{11}v_{1x} + a_{12}v_{1y})(a_{11}v_{2x} + a_{12}v_{2y}) + (a_{21}v_{1x} + a_{22}v_{1y})(a_{21}v_{2x} + a_{22}v_{2y})$$
$$+ (a_{31}v_{1x} + a_{32}v_{1y})(a_{31}v_{2x} + a_{32}v_{2y})$$
$$= (a_{11}^2 + a_{21}^2 + a_{31}^2)v_{1x}v_{2x} + (a_{12}^2 + a_{22}^2 + a_{32}^2)v_{1y}v_{2y}$$
$$+ (a_{11}a_{12} + a_{21}a_{22} + a_{31}a_{32})(v_{1x}v_{2y} + v_{1y}v_{2x}) \quad (2.13)$$

Also,

$$\mathbf{v}_1^* \times \mathbf{v}_2^* = \left|\mathbf{v}_1^*\right|\left|\mathbf{v}_2^*\right|\mathbf{k}\sin\theta^*$$

$$= (a_{11}v_{1x} + a_{12}v_{1y})(a_{21}v_{2x} + a_{22}v_{2y})\mathbf{k} - (a_{11}v_{1x} + a_{12}v_{1y})(a_{31}v_{2x} + a_{32}v_{2y})\mathbf{j}$$
$$- (a_{21}v_{1x} + a_{22}v_{1y})(a_{11}v_{2x} + a_{12}v_{2y})\mathbf{k} + (a_{21}v_{1x} + a_{22}v_{1y})(a_{31}v_{2x} + a_{32}v_{2y})\mathbf{i}$$
$$+ (a_{31}v_{1x} + a_{32}v_{1y})(a_{11}v_{2x} + a_{12}v_{2y})\mathbf{j} - (a_{31}v_{1x} + a_{32}v_{1y})(a_{21}v_{2x} + a_{22}v_{2y})\mathbf{i} \quad (2.14)$$

The angle between the original vectors $\mathbf{v}_1$ and $\mathbf{v}_2$ are given by

$$|\mathbf{v}_1||\mathbf{v}_2|\cos\theta = (v_{1x}\mathbf{i} + v_{1y}\mathbf{j}) \cdot (v_{2x}\mathbf{i} + v_{2y}\mathbf{j}) = (v_{1x}v_{2x} + v_{1y}v_{2y})$$
$$|\mathbf{v}_1||\mathbf{v}_2|\mathbf{k}\sin\theta = (v_{1x}\mathbf{i} + v_{1y}\mathbf{j}) \times (v_{2x}\mathbf{i} + v_{2y}\mathbf{j}) = (v_{1x}v_{2y} - v_{1y}v_{2x})\mathbf{k} \quad (2.15)$$

For no change in magnitude or angle, $\left|\mathbf{v}_1^*\right|\left|\mathbf{v}_2^*\right|\cos\theta^* = |\mathbf{v}_1||\mathbf{v}_2|\cos\theta$ and also $\mathbf{v}_1^* \times \mathbf{v}_2^* = \mathbf{v}_1 \times \mathbf{v}_2$. On comparing results, we obtain

$$(v_{1x}v_{2x} + v_{1y}v_{2y}) = (a_{11}^2 + a_{21}^2 + a_{31}^2)v_{1x}v_{2x} + (a_{12}^2 + a_{22}^2 + a_{32}^2)v_{1y}v_{2y}$$
$$+ (a_{11}a_{12} + a_{21}a_{22} + a_{31}a_{32})(v_{1x}v_{2y} + v_{1y}v_{2x}) \quad (2.16)$$

and

$$(v_{1x}v_{2y} - v_{1y}v_{2x})\mathbf{k} = (a_{11}v_{1x} + a_{12}v_{1y})(a_{21}v_{2x} + a_{22}v_{2y})\mathbf{k} - (a_{11}v_{1x} + a_{12}v_{1y})(a_{31}v_{2x} + a_{32}v_{2y})\mathbf{j}$$
$$- (a_{21}v_{1x} + a_{22}v_{1y})(a_{11}v_{2x} + a_{12}v_{2y})\mathbf{k} + (a_{21}v_{1x} + a_{22}v_{1y})(a_{31}v_{2x} + a_{32}v_{2y})\mathbf{i}$$
$$+ (a_{31}v_{1x} + a_{32}v_{1y})(a_{11}v_{2x} + a_{12}v_{2y})\mathbf{j} - (a_{31}v_{1x} + a_{32}v_{1y})(a_{21}v_{2x} + a_{22}v_{2y})\mathbf{i} \quad (2.17)$$

We can work out Eq. (2.17) and compare the coefficients of **i**, **j** and **k** and further, compare the terms corresponding to $v_{1y}\,v_{2x}$ and $v_{1x}\,v_{2y}$. Finally, after comparison from Eqs. (2.16) and (2.17), we would get

$$(a_{11}^2 + a_{21}^2 + a_{31}^2) = 1 \qquad (a_{11}a_{13} + a_{21}a_{23} + a_{31}a_{33}) = 0$$

$$(a_{12}^2 + a_{22}^2 + a_{32}^2) = 1 \qquad (a_{13}a_{12} + a_{23}a_{22} + a_{33}a_{32}) = 0$$

$$(a_{11}a_{12} + a_{21}a_{22} + a_{31}a_{32}) = 0 \qquad (a_{11}a_{12} + a_{21}a_{22} + a_{31}a_{32}) = 0$$

$$(a_{11}a_{22} - a_{12}a_{21}) = 1$$

which suggests that **A** must be orthogonal having the property $\mathbf{A}^{-1} = \mathbf{A}^{\mathrm{T}}$ so that $\mathbf{A}\mathbf{A}^{\mathrm{T}} = \mathbf{A}^{\mathrm{T}}\mathbf{A} = \mathbf{I}$, where **I** is the identity matrix of the same size as **A**. Further, $(a_{11}a_{22} - a_{12}a_{21}) = 1$ implies that the determinant of **A** should be 1. In pure rotation, the above conditions are completely met where for **R** in Eq. (2.4), $a_{13} = a_{23} = a_{31} = a_{32} = 0$, and $a_{33} = 1$. In reflection, the determinant of the transformation matrix is –1; hence, although the matrix is orthogonal, the angle is not preserved and that it changes to $(2\pi - \theta)$ though the absolute angle between the adjacent sides of the polygon remains θ. The magnitudes of the vectors are preserved. The angle between the intersecting vectors is also preserved in case of translation, that is

$$\begin{bmatrix} v_1^* \\ v_2^* \end{bmatrix}^T = \begin{bmatrix} 1 & 0 & p \\ 0 & 1 & q \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}^T = \begin{bmatrix} 1 & 0 & p \\ 0 & 1 & q \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_{1x} & v_{1y} & 0 \\ v_{2x} & v_{2y} & 0 \end{bmatrix}^T = \begin{bmatrix} v_{1x} & v_{1y} & 0 \\ v_{2x} & v_{2y} & 0 \end{bmatrix}^T = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}^T$$

which implies that the translation does not alter vectors.

2.3 Deformations

Previous sections dealt with transformations wherein the object was relocated and/or reoriented without the change in its shape or size. In this section, one would deal with transformations that would alter the size and/or shape of the object. Examples involve those of *scaling* and *shear*.

2.3.1 Scaling

A point $\boldsymbol{P}$ $(x, y, 1)$ belonging to the object S can be scaled to a new position vector $\boldsymbol{P}^*$ $(x^*, y^*, 1)$ using factors μ_x and μ_y such that

$$x^* = \mu_x x \text{ and } y^* = \mu_y y$$

Or in matrix form

$$\begin{bmatrix} x^* \\ y^* \\ 1 \end{bmatrix} = \begin{bmatrix} \mu_x & 0 & 0 \\ 0 & \mu_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \mathbf{SP} \tag{2.18}$$

where $\mathbf{S} = \begin{bmatrix} \mu_x & 0 & 0 \\ 0 & \mu_y & 0 \\ 0 & 0 & 1 \end{bmatrix}$ is the scaling matrix. Scale factors μ_x and μ_y are always non-zero and positive. For both μ_x and μ_y less than 1, the geometric model gets *shrunk*. In case of *uniform scaling* when $\mu_x = \mu_y = \mu$, the model gets changed uniformly in size (Figure 2.11) and there is no distortion.

Consider a curve, for instance, defined by $\mathbf{r}(u) = x(u)\mathbf{i} + y(u)\mathbf{j}$, where parameter u varies in the interval [0, 1]. The curve after scaling becomes $\mathbf{r}^*(u) = x^*(u)\mathbf{i} + y^*(u)\mathbf{j} = \mu_x x(u)\mathbf{i} + \mu_y y(u)\mathbf{j}$ and the tangent to any point on this curve is obtained by differentiating $\mathbf{r}^*(u)$ with respect to u, that is,

$$\dot{\mathbf{r}}^*(u) = \mu_x \dot{x}(u)\,\mathbf{i} + \mu_y \dot{y}(u)\,\mathbf{j}$$

Hence

$$\frac{dy}{dx} = \frac{(dy/du)}{(dx/du)} = \frac{\mu_y \dot{y}(u)}{\mu_x \dot{x}(u)} \tag{2.19}$$

Thus, non-uniform scaling changes the tangent vector proportionally while the slope remains unaltered in uniform scaling for $\mu_x = \mu_y$.

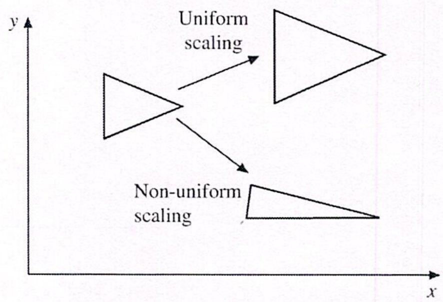


Figure 2.11 Uniform and non-uniform scaling

2.3.2 Shear

Consider a matrix $\mathbf{Sh}_x = \begin{bmatrix} 1 & sh_x & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$ which when applied to a point $\boldsymbol{P}$ $(x, y, 1)$ results in

$$\begin{bmatrix} x^* \\ y^* \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & sh_x & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} x + sh_x y \\ y \\ 1 \end{bmatrix} \tag{2.20}$$

which in effect shears the point along the x axis. Likewise, application of $\mathbf{Sh}_y = \begin{bmatrix} 1 & 0 & 0 \\ sh_y & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$ on $\boldsymbol{P}$ yields

$$\begin{bmatrix} x^* \\ y^* \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ sh_y & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ sh_y x + y \\ 1 \end{bmatrix} \tag{2.21}$$

that is, the new point gets sheared along the y direction.

Example 2.6. For a rectangle with coordinates (3, 1), (3, 4), (8, 4) and (8, 1), respectively, applying shear along the y direction (Figure 2.12) with a factor $sh_y = 1.5$ yields the new points as

$$\begin{bmatrix} P_1^* \\ P_2^* \\ P_3^* \\ P_4^* \end{bmatrix}^T = \begin{bmatrix} 1 & 0 & 0 \\ 1.5 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 3 & 1 & 1 \\ 3 & 4 & 1 \\ 8 & 4 & 1 \\ 8 & 1 & 1 \end{bmatrix}^T = \begin{bmatrix} 3 & 5.5 & 1 \\ 3 & 8.5 & 1 \\ 8 & 16 & 1 \\ 8 & 13 & 1 \end{bmatrix}^T$$

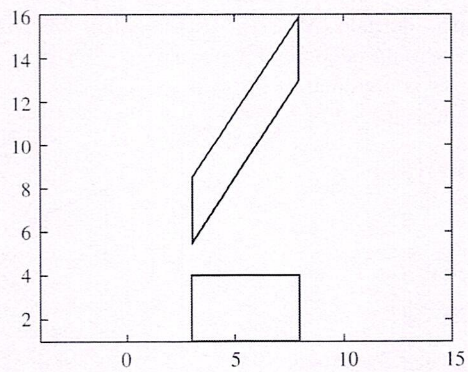


Figure 2.12 Shear along the *y* direction

2.4 Generic Transformation in Two-Dimensions

Observing the transformation matrices developed previously for translation, rotation, reflection, scaling and shear, we may realize that the matrices may be expressed generically in the partitioned form as

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & | & a_{13} \\ a_{21} & a_{22} & | & a_{23} \\ — & — & — & — \\ a_{31} & a_{32} & | & a_{33} \end{bmatrix} \tag{2.22}$$

The top left 2 × 2 sub-matrix represents: (a) rotation when the elements are the sine and cosine terms of the rotation angle about the z-axis, (b) reflection when the diagonal elements are +1 or –1, and the off diagonal terms are zero, (c) scaling when the diagonal elements are positive μ_x and μ_y with the off diagonal terms as zero and (d) shear when the off diagonal elements are non-zero and diagonal elements are 1. The second top-right partition of 2 × 1 sub-matrix represents translation. The bottom-left partition of 1 × 2 sub-matrix represents perspective transformation discussed later and the bottom right matrix, the diagonal element $a_{33} = 1$ represents the homogeneous coordinate scalar. Like a point in the x-y plane is represented as (x, y, 1) using the homogenous system, in a three-dimensional space, the representation can be extended to (x, y, z, 1). Accordingly, the matrix **A** in Eq. (2.22) gets modified to

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & | & a_{14} \\ a_{21} & a_{22} & a_{23} & | & a_{24} \\ a_{31} & a_{32} & a_{33} & | & a_{34} \\ — & — & — & | & — \\ a_{41} & a_{42} & a_{43} & | & a_{44} \end{bmatrix} \tag{2.23}$$

The partitions now consist of 3 × 3, 3 × 1, 1 × 3, and 1 × 1 sub-matrices having the same role as discussed for the respective partitions above for a two-dimensional case.

2.5 Transformations in Three-Dimensions

Matrices developed for transformations in two-dimensions can be modified as per the schema in Eq. (2.23) for use in three-dimensions. For instance, the translation matrix to move a point and thus an object, e.g. in Figure 2.13, by a vector (p, q, r) may be written as

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & p \\ 0 & 1 & 0 & q \\ 0 & 0 & 1 & r \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2.24}$$

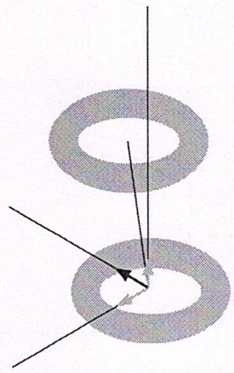


Figure 2.13 Translation of a donut along an arbitrary vector

2.5.1 Rotation in Three-Dimensions

The rotation matrix in Eq. (2.4) can be modified to accommodate the three-dimensional homogenous coordinates. For rotation by angle θ about the z-axis (the z coordinate does not change), we get

$$\mathbf{R}_z = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2.25}$$

Further, using the cyclic rule for the right-handed coordinate axes, rotation matrices about the x- and y-axis for angles ψ and ϕ can be written, respectively, by inspection as

$$\mathbf{R}_x = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\psi & -\sin\psi & 0 \\ 0 & \sin\psi & \cos\psi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{and} \quad \mathbf{R}_y = \begin{bmatrix} \cos\phi & 0 & \sin\phi & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\phi & 0 & \cos\phi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2.26}$$

Rotation of a point by angles θ, ϕ and ψ (in that order) about the z-, y- and x-axis, respectively, is a useful transformation used often for rigid body rotation. The combined rotation is given as

$$\mathbf{R} = \mathbf{R}_x(\psi)\mathbf{R}_y(\phi)\mathbf{R}_z(\theta) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\psi & -\sin\psi & 0 \\ 0 & \sin\psi & \cos\psi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\phi & 0 & \sin\phi & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\phi & 0 & \cos\phi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2.27}$$

We may as well multiply the three matrices to derive the composite matrix though it is easier to express the transformation in the above form for the purpose of depicting the order of transformations. Also, it is easier to remember the individual transformation matrices than the composite matrix. We may need to rotate an object about a given line. For instance, to rotate an object in Figure 2.14 (a) by 45° about the line $L \equiv y = x$. One way is to rotate the object about the z-axis such that L coincides with the x-axis, perform rotation about the x-axis and then rotate L about the z-axis to its original location. The combined transformation would then be

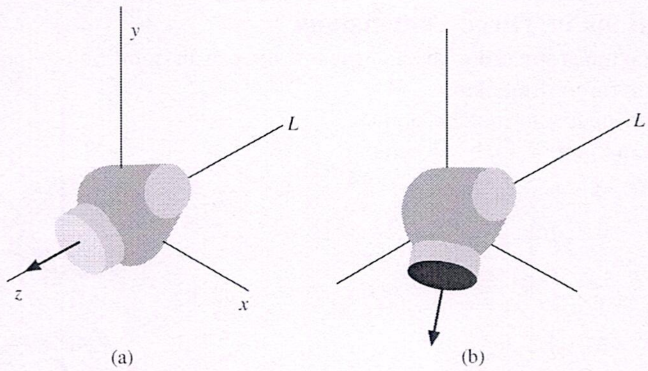


Figure 2.14 Rotation of an object: (a) about the line $y-x = 0$ and (b) rotated result

$$\mathbf{R} = \mathbf{R}_z(45°)\mathbf{R}_x(45°)\mathbf{R}_z(-45°)\begin{bmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 & 0 \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\ -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

and the result is shown in Figure 2.14 (b). An alternate way is to rotate the line about the z-axis to coincide with the y-axis, perform rotation about the y-axis and then rotate L back to its original location. Apparently, transformation procedures may not be unique though the end result would be the same if a proper transformation order is followed.

To rotate a point **P** about an axis L having direction cosines $\mathbf{n} = [n_x\ n_y\ n_z\ 0]$ that passes through a point **A** $[p\ q\ r\ 1]$, we may observe that **P** and its new location **P*** would lie on a plane perpendicular to L and the plane would intersect L at **Q** (Figure 2.15(a)). Transformations may be composed stepwise as follows:

(i) Point **A** on L may be translated to coincide with the origin O using the transformation $\mathbf{T}_A$. The new line L' remains parallel to L.

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

(ii) The unit vector **OU** (along L) projected onto the x-y and y-z planes, makes the traces OU_{xy} and OU_{yz}, respectively (Figure 2.15(b)). The magnitude of OU_{yz} is $d = \sqrt{(n_y^2 + n_z^2)} = \sqrt{(1 - n_x^2)}$. OU_{yz} makes an angle ψ with the z-axis such that

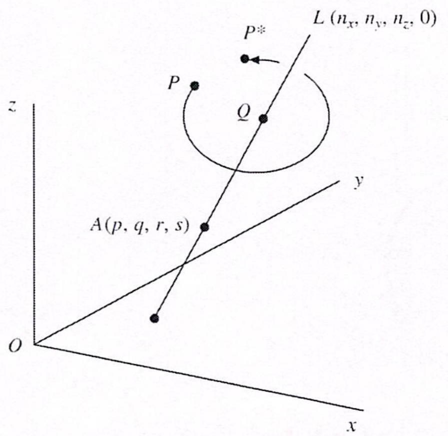


Figure 2.15(a) Rotation of *P* about a line *L*

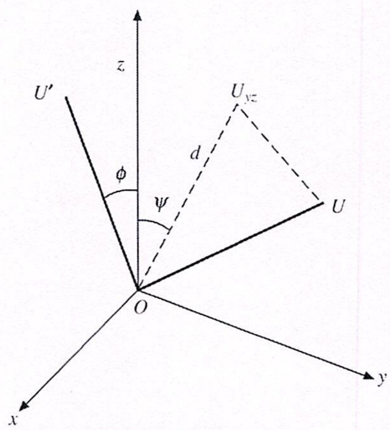


Figure 2.15(b) Computing angles from the direction cosines

$$\cos\psi = \frac{n_z}{d}, \quad \sin\psi = \frac{n_y}{d}$$

Rotate OU about the x-axis by ψ to place it on the x-z plane (OU') in which case OU_{yz} will coincide with the z-axis. OU' makes angle ϕ with the z-axis such that $\cos\phi = d$ and $\sin\phi = n_x$. Rotate OU' about the y-axis by $-\phi$ so that in effect, OU coincides with the z-axis. The two rotation transformations are given by

$$\mathbf{R}_x = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\psi & -\sin\psi & 0 \\ 0 & \sin\psi & \cos\psi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{and} \quad \mathbf{R}_y = \begin{bmatrix} \cos(-\phi) & 0 & \sin(-\phi) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(-\phi) & 0 & \cos(-\phi) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(iii) The required rotation through angle α is then performed about the z-axis using

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

(iv) Eventually, OU or line L is placed back to its original location by performing inverse transformations. The complete rotation transformation of point P about L can now be written as

$$\mathbf{R} = \mathbf{T}_A^{-1}\,\mathbf{R}_x^{-1}(\psi)\,\mathbf{R}_y^{-1}(-\phi)\,\mathbf{R}_z(\alpha)\,\mathbf{R}_y(-\phi)\,\mathbf{R}_x(\psi)\,\mathbf{T}_A \tag{2.28}$$

Figure 2.16 shows, as an example, the rotation of a disc about its axis placed arbitrarily in the coordinate system. Note that all matrices being orthogonal, $\mathbf{R}_y^{-1}(-\phi) = \mathbf{R}_y(\phi)$, $\mathbf{R}_x^{-1}(\psi) = \mathbf{R}_x(-\psi)$ and $\mathbf{T}_A^{-1}(-\mathbf{v}) = \mathbf{T}_A(\mathbf{v})$, where $\mathbf{v} = [p\ q\ r]^T$.

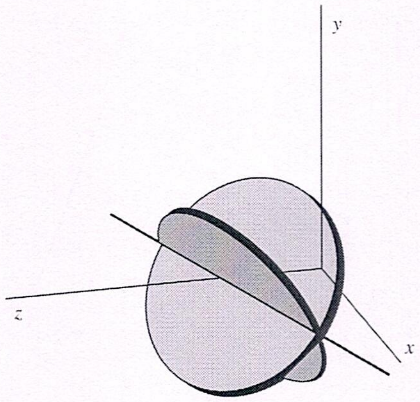


Figure 2.16 Rotation of a disc about its axis

2.5.2 Scaling in Three-Dimensions

The scaling matrix can be extended from that in a two-dimensional case (Eq. 2.18) as

$$\mathbf{S} = \begin{bmatrix} \mu_x & 0 & 0 & 0 \\ 0 & \mu_y & 0 & 0 \\ 0 & 0 & \mu_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2.29}$$

where μ_x, μ_y and μ_z are the scale factors along x, y and z directions, respectively. For uniform overall scaling, $\mu_x = \mu_y = \mu_z = \mu$.

Alternatively,

$$\mathbf{S}_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & s \end{bmatrix}$$

has the same uniform scaling effect as that of Eq. (2.29). To observe this, we may write

$$\begin{bmatrix} x^* \\ y^* \\ z^* \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & s \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \\ s \end{bmatrix} \equiv \begin{bmatrix} \frac{x}{s} \\ \frac{y}{s} \\ \frac{z}{s} \\ 1 \end{bmatrix} = \begin{bmatrix} \frac{1}{s} & 0 & 0 & 0 \\ 0 & \frac{1}{s} & 0 & 0 \\ 0 & 0 & \frac{1}{s} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \tag{2.30}$$

comparing which with Eq. (2.29) for $\mu_x = \mu_y = \mu_z = \mu$ yields $\mu = \frac{1}{s}$. Figure 2.17 shows uniform scaling of a cylindrical primitive.

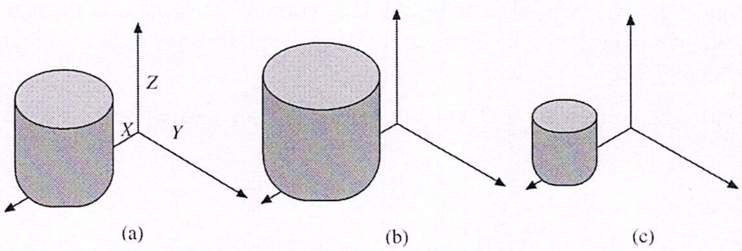


Figure 2.17 **A scaled cylinder using different factors: (a) original size, (b) twice the original size, (c) half the original size**

Eq. (2.30) uses the equivalence $[x\ y\ z\ s]^T \equiv \begin{bmatrix} \frac{x}{s} & \frac{y}{s} & \frac{z}{s} & 1 \end{bmatrix}^T$ since both vectors represent the same point in the four-dimensional homogeneous coordinate system.

2.5.3 Shear in Three-Dimensions

In the 3 × 3 sub-matrix of the general transformation matrix (2.23), if all diagonal elements including a_{44} are 1, and the elements of 1 × 3 row sub-matrix and 3 × 1 column sub-matrix are all zero, we get the shear transformation matrix in three-dimensions, similar to the two-dimensional case. The generic form is

$$\mathbf{Sh} = \begin{bmatrix} 1 & sh_{12} & sh_{13} & 0 \\ sh_{21} & 1 & sh_{23} & 0 \\ sh_{31} & sh_{32} & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2.31}$$

whose effect on point $\boldsymbol{P}$ is

$$\begin{bmatrix} x^* \\ y^* \\ z^* \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & sh_{12} & sh_{13} & 0 \\ sh_{21} & 1 & sh_{23} & 0 \\ sh_{31} & sh_{32} & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x + sh_{12}y + sh_{13}z \\ sh_{21}x + y + sh_{23}z \\ sh_{31}x + sh_{32}y + z \\ 1 \end{bmatrix}$$

Thus, to shear an object only along the y direction, the entries $sh_{12} = sh_{13} = sh_{31} = sh_{32}$ would be 0 while either sh_{21} and sh_{23} or both would be non-zero.

2.5.4 Reflection in Three-Dimensions

Generic reflections about the x-y plane (z becomes $-z$), y-z plane (x becomes $-x$), and z-x plane (y becomes $-y$) can be expressed using the following respective transformations:

$$\mathbf{Rf}_{xy} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{Rf}_{yz} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{and} \quad \mathbf{Rf}_{zx} = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2.32}$$

For reflection about a generic plane Π having the unit normal vector as $\mathbf{n} = [n_x\ n_y\ n_z\ 0]$ and for $\mathbf{A}\ [p\ q\ r\ 1]$ as any known point on it, the *modus operandi* is similar to the rotation about an arbitrary axis discussed in section 2.5.1. The steps followed are

(a) Translate Π to the new position Π′ such that point **A** coincides with the origin using

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

(b) Rotate the unit vector **n** (passing through the origin) on Π′ to coincide with the z-axis. The new position of Π′ will be Π″ and the reflecting plane will coincide with the x-y plane ($z = 0$). We would need the following transformations to acccomplish this step:

$$\mathbf{R}_x = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \dfrac{n_z}{\sqrt{1-n_x^2}} & -\dfrac{n_y}{\sqrt{1-n_x^2}} & 0 \\ 0 & \dfrac{n_y}{\sqrt{1-n_x^2}} & \dfrac{n_z}{\sqrt{1-n_x^2}} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{R}_y = \begin{bmatrix} \sqrt{1-n_x^2} & 0 & -n_x & 0 \\ 0 & 1 & 0 & 0 \\ n_x & 0 & \sqrt{1-n_x^2} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{Rf}_{xy} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(c) After reflection, the reverse order transformations need to be performed. The complete transformation would be

$$\mathbf{R} = \mathbf{T}_\mathrm{A}^{-1}\mathbf{R}_x^{-1}(\psi)\mathbf{R}_y^{-1}(-\phi)\ \mathbf{Rf}_{xy}\ \mathbf{R}_y(-\phi)\ \mathbf{R}_x(\psi)\ \mathbf{T}_\mathrm{A} \tag{2.33}$$

Example 2.7. The corners of wedge-shaped block are $A(0, 0, 2)$, $B(0, 0, 3)$, $C(0, 2, 3)$, $D(0, 2, 2)$, $E(-1, 2, 2)$ and $F(-1, 2, 3)$, and the reflection plane passes through the y-axis at 45° between $(-x)$ and z-axis. Determine the reflection of the wedge.

First, no translation of the reflecting plane is required as it passes through the origin. The direction cosines of the plane are (0.707, 0, 0.707). We may apply Eq. (2.33) directly to get the result. Alternatively, rotate the plane about the y-axis for the reflecting plane to coincide with the y-z plane. Perform reflection about the y-z plane and thereafter, rotate the plane back to its original location.

$$\mathrm{R}_y(-225°) = \begin{bmatrix} \cos(45°) & 0 & \sin(45°) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(45°) & 0 & \cos(45°) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0.707 & 0 & 0.707 & 0 \\ 0 & 1 & 0 & 0 \\ -0.707 & 0 & 0.707 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{Rf}_{yz} = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The transformations are

$$\begin{bmatrix} A^* \\ B^* \\ C^* \\ D^* \\ E^* \\ F^* \end{bmatrix}^T = \mathbf{R}_y^{-1}\mathbf{Rf}_{yz}\ \mathbf{R}_y \begin{bmatrix} A \\ B \\ C \\ D \\ E \\ F \end{bmatrix}^T = \begin{bmatrix} 0.707 & 0 & -0.707 & 0 \\ 0 & 1 & 0 & 0 \\ 0.707 & 0 & 0.707 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} 0.707 & 0 & 0.707 & 0 \\ 0 & 1 & 0 & 0 \\ -0.707 & 0 & 0.707 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} -2 & 0 & 0 & 1 \\ -3 & 0 & 0 & 1 \\ -3 & 2 & 0 & 1 \\ -2 & 2 & 0 & 1 \\ -2 & 2 & 1 & 1 \\ -3 & 2 & 1 & 1 \end{bmatrix}^T$$

and the reflected object is shown in Figure 2.18.

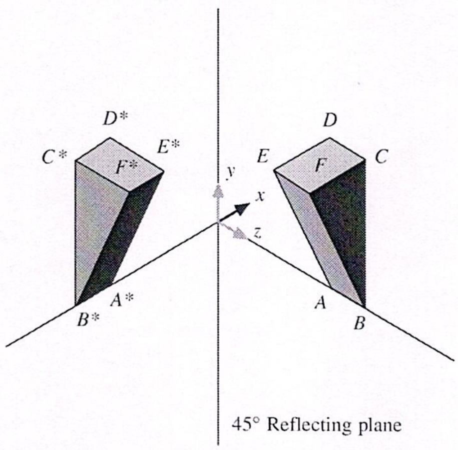


Figure 2.18 Reflection of a wedge about a plane at 45° between (– x) and z-axis.