B. TECH. PROJECT REPORT

On

PERFORMANCE ANALYSIS OF 2PRP-2PPR PLANAR PARALLEL MANIPULATOR AND ITS APPLICATION IN MILLING MACHINE.

BY

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DISCIPLINE OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY INDORE

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Performance analysis of 2PRP-2PPR planar parallel manipulator and its application in milling machine.

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

of

BACHELOR OF TECHNOLOGY

in

MECHANICAL ENGINEERING

Submitted by:

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December 2016

CANDIDATE'S DECLARATION

We hereby declare that the project entitled **"Performance analysis of a 2PRP-2PPR planar parallel manipulator and its application in milling machine."** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in 'Mechanical' completed under the supervision of **Dr. M. Santhakumar, Asst. Professor, Dept. of Mechanical engineering, Dr. E. Anil Kumar, Associate professor, Dept. of Mechanical engineering** IIT Indore is an authentic work.

Further, we declare that we have not submitted this work for the award of any other degree elsewhere.

Signature and name of the student(s) with date

G. Manideep **G. Chaitanya Kumar** **Y. Sri Yeshwanth**

CERTIFICATE by BTP Guide(s)

It is certified that the above statement made by the students is correct to the best of my/our knowledge.

Signature of BTP Guide(s) with dates and their designation

Dr. M. Santhakumar
Asst. Prof. Mechanical Engg.

Dr. E. Anil Kumar
Associate professor, Mechanical Engg.

Preface

This report on "Performance analysis of a 2PRP-2PPR planar parallel manipulator and its application in milling machine " is prepared under the guidance of Dr.M.santhakumar, Dr.E.Anil Kumar. Through this report we tried to give a detailed (theoretical and experimental) result for using 2PRP-2PPR planar parallel manipulator as a platform for milling operation. We have designed prototypes to study the motion of platform and to show the design is technically sound and feasible for milling and other numerous applications.

We have tried to best of our abilities and knowledge to explain the content in more informative, illustrative and lucid manner. We have added 3D CAD model as well as certain figures of experimental setup to explain the mechanism. Equations of motion, Simulation results and Experimental results are given in the respective section.

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And at last we would like to thank all of our friends Anirudh, Prem, Sandeep, Veerendra Manish, and 2013 batch for standing with us at all times.

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Abstract

This report analyses various aspects of 2PRP-2PPR parallel plane manipulator which has 3 degrees of freedom, singularity free workspace, and having 4 manipulator legs. Out of those 4, 3 legs have active prismatic joints and the 4^{th} leg is added for better compliance and better rigidity and carries a passive prismatic joint. All these 4 legs connect to the moving plate (end-effector).This 2PRP-2PPR parallel plane manipulator is used as a platform for milling machine. Static analysis and dynamic analysis are performed for that platform using Ansys and Adams. Both Forward and Inverse Kinematic equations have been obtained. The z- axis motion is given by one more actuator which is assembled perpendicular to the platform. The fixture along z-axis holds the milling spindle. The prismatic joint in the z-direction provides the necessary motion to change the depth of cut. Actuators are controlled by a micro controller and a PID controller to give the desired motion. The exact shape to be milled on a surface is given to the system using MATLAB and Mach3 software packages.

Experiments to check milling capability of the assembly were performed on Wood and Soft Aluminium. Results of the experiments were obtained from Coordinate Measuring Machine (CMM).

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CHAPTER 1

INTRODUCTION

Robotics is a field of modern technology that crosses traditional engineering boundaries. Understanding the complexity of robots and their applications requires knowledge of mechanical engineering, electrical engineering, systems and industrial engineering, computer science, economics, and mathematics. An official definition for a robot comes from the Robot Institute of America (RIA): A robot is a reprogrammable multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks.

According to the Kinematic structure robots are classified into two types. A robot is said to be a serial robot or serial (open-loop) manipulator if its kinematic structure takes the form of an open loop-chain, a parallel manipulator if it is made of a closed-loop chain, and hybrid manipulator if it is consists of both open and closed-loop chains.

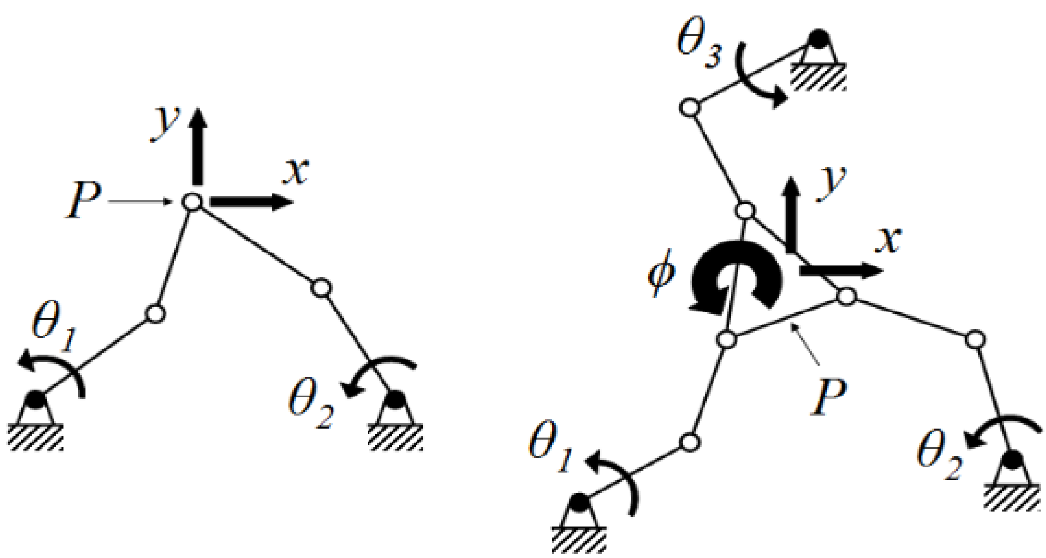

Figure 1.1 Serial and Parallel manipulators

1.1. Comparison between Serial and Parallel Manipulators:

Feature	Serial Robot	Parallel Robot
Workspace	Large	Small
Solving Forward and Inverse Kinematics	Easy	Difficult

Position Error	Accumulates	Averages
Force Error	Averages	Accumulates
Maximum Force	Limited by minimum actuator force	Summation of all actuator forces
Stiffness	Low	High
Modeling and solving dynamics	Relatively Simple	Complex
Inertia	Large	Small
Payload/weight ratio	Low	High
Accuracy	Low	High
Uniformity of Components	Low	High
Calibration	Relatively Simple	Complex
Workspace/robot size ratio	High	Low

Table 1

A parallel manipulator is a mechanical system that uses several computer-controlled serial chains to support a single platform, or end-effector while the serial manipulator has the end-effector connected to the base through a single platform. Parallel manipulators are extensively recognized as excellent robotic manipulators and used in many industries for their remarkable properties over serial robotic manipulators such as high payload capacity, low inertia of moving parts, high stiffness, high speed, high precision and accuracy.

So we see that parallel manipulators are mechanisms where all the links are connected to the ground and the moving platform at the same time. They possess high rigidity, load capacity, precision, structural stiffness, velocity and acceleration since the end-effector is linked to the movable plate in several points. Parallel manipulators can be classified into following categories:

1.2. Classification of Parallel Manipulators

- Symmetric
- Planar
- Spherical
- Spatial

But out of these the two fundamental categories are, spatial and planar manipulators. The first category composes of the spatial parallel manipulators that can translate and rotate in the three dimensional space. Gough-Stewart platform, one of the most popular spatial manipulator, is extensively preferred in flight simulators. The planar parallel manipulators of second category, translate along the x and y-axes, and rotate around the z-axis, only. Although planar parallel manipulators are increasingly being used in industry for micro or nano-positioning applications,(Hubbard et al., 2001),the kinematics, especially dynamics analysis of planar parallel manipulators is more difficult than their serial counterparts. Therefore selection of an efficient kinematic modelling convention is very important for simplifying the complexity of the dynamics problems in planar parallel manipulators.

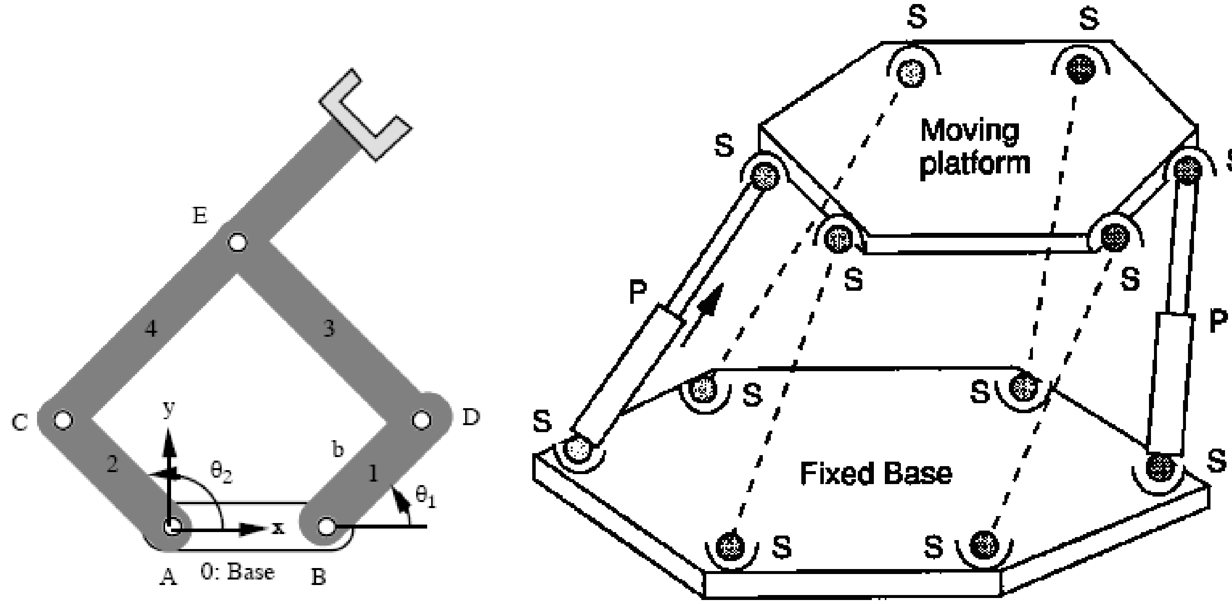

Figure 1.2 Planar and Spatial parallel manipulators

What this project is about?

Performance analysis of vertical milling machine table based on the 2PRP – 2PPR platform is presented here. The machining capabilities are tested with the help of predefined trajectories. The results are tested using CMM. They prove that the proposed manipulator offers better results than conventional milling machines. The work table of the machining system is developed based on 2PRP-2PPR configuration. Additionally, an actuator for z-axis is also included to carry the spindle which is used for Milling or Drilling operations. With the help of this additional actuator we can vary the depth of cut in an operation. This 2PRP-2PPR manipulator has 420mm X 500mm workspace. To reduce the error in the position of the joints a simple PID control is used. And Linear Potentiometers are used to track the joints and take necessary measures if necessary. The results of the experiments were given in the subsequent chapters. And it is clearly seen that Parallel plane manipulator is better than Serial manipulator.

CHAPTER 2

SYSTEM DESCRIPTION

2.1 General Description:

The manipulator has 2PRP-2PPR configuration. This configuration is being a platform for milling operation which has 3 degrees of freedom and the 4th degree of freedom is provided by an additional joint which is attached perpendicular to the existing platform.So, totally the system has 4 degrees of freedom for x, y, z and θ motions. The frame arrangement of the platform is given below in fig .Out of the 4 prismatic links 3 of them have active prismatic joint each and the last one is inactive (Passive). In each PRP, there are prismatic, revolute and prismatic joints in order with first being the active joint. In active PPR there are prismatic, prismatic and revolute in order with the first being the active joint. In passive PPR configuration has prismatic, prismatic and revolute in order and all joints are passive. All the 4 configurations are connected in a closed loop finally manipulating the square shaped mobile end-effector. All these rails are situated in XY plane. Number of active joints are three and all three are prismatic joints. And there are six passive joints and out of these six, three are revolute joints and the others are prismatic joints.

The active prismatic joints are actuated by DC motor. The platform is supported on a fixed base made of steel and an arrangement is made to support additional z-axis joint which can be seen in the figure. The joint providing the motion in z-axis is attached to the same arrangement as shown in the figure. (I think we need to add ADAMS figure here)

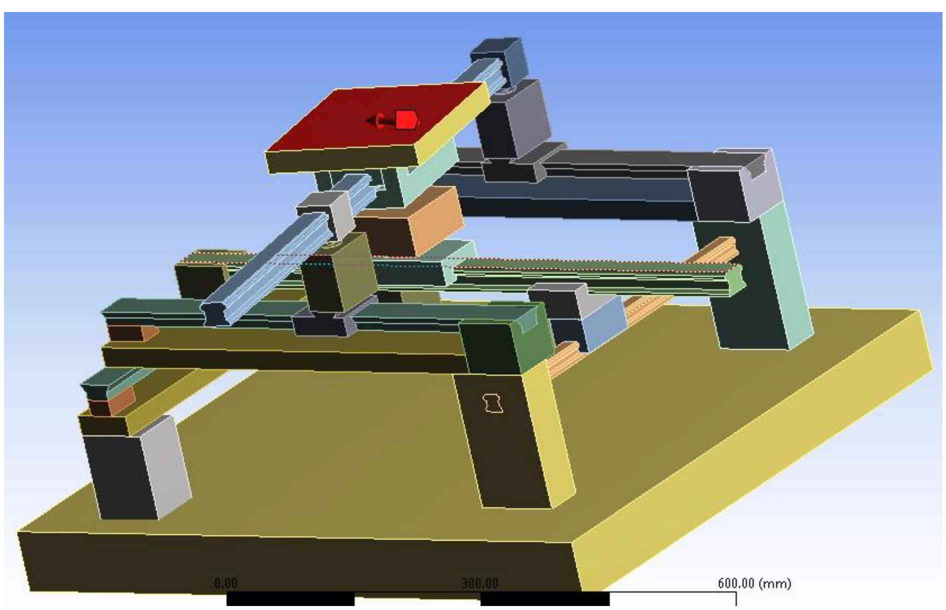

Figure 2.1 Solid model of our manipulator

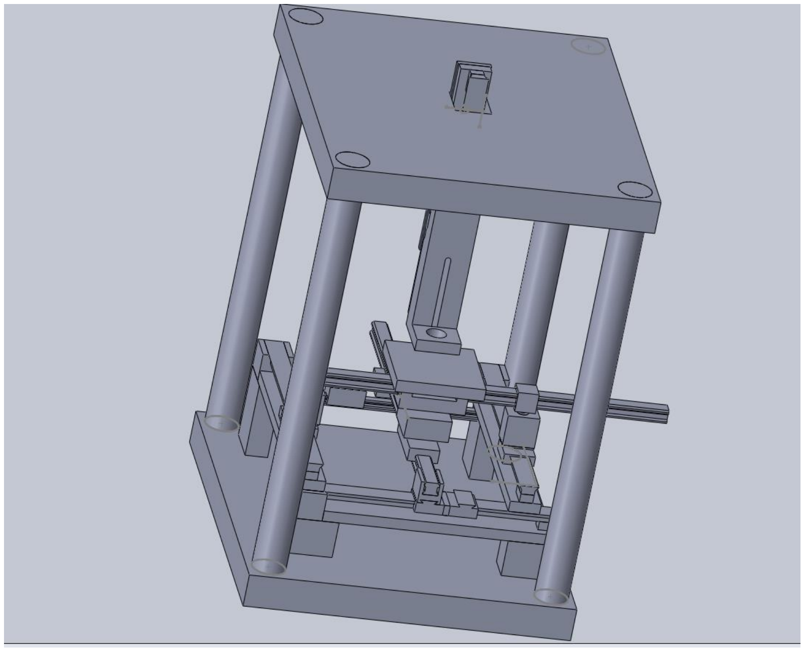

Figure 2.2 Complete Solid Model

The dimensions of the platform are 420mm X 500mm. The power supply is connected to PC and Driver with feedback which in turn supplies power to the motors. This feedback device is connected to the motors for controlling them. The feedback device gets the input from the PC through a computer program. We can give the trajectory to be followed by writing a code. All the dimensions are included in the code itself.

The schematic arrangement of links, joints and frames is given in the figure2.3. The manipulator has 4 legs which connect the mobile frame (end-effector) to the base (fixed) frame. As 3 of the 4 legs are active, r1, r2 and r3 act as inputs i.e. joint space variables. x, y, θ are the task space variables. The motion in the X-direction of the end-effector is given by r1, the motion in the Y-direction is provided by r2 and r3 together. The orientation of the end-effector is guided by equations based on r2 and r3.

To know the position of the joints, linear potentiometers are connected. These linear potentiometers are connected to the Arduino to check the position. The spindle motor is attached to the perpendicular one which can hold end mill cutters, drill bits necessary for machining. The spindle has six different speeds.

2.2 Kinematic Modeling:

To obtain information on the position of each component within the mechanical system, we need to perform kinematic analysis. Kinematic analysis refers to the development of relation between the task space variables and joint space variables. The position and the orientation of the end-effector are known as task space variables which are *x, y,* θ_z. The distances of prismatic joints that is translational inputs of the system are known as joint space variables which are r1, r2, r3. Kinematic analysis is done in two steps: Forward kinematics and Inverse Kinematics. Forward kinematics refers to the use of kinematic equations of a manipulator to compute the position and orientation of the end-effector from specified values of Joint space variables. The reverse process that computes joint space parameters that achieve a specified position of the end-effector is known as inverse kinematics.

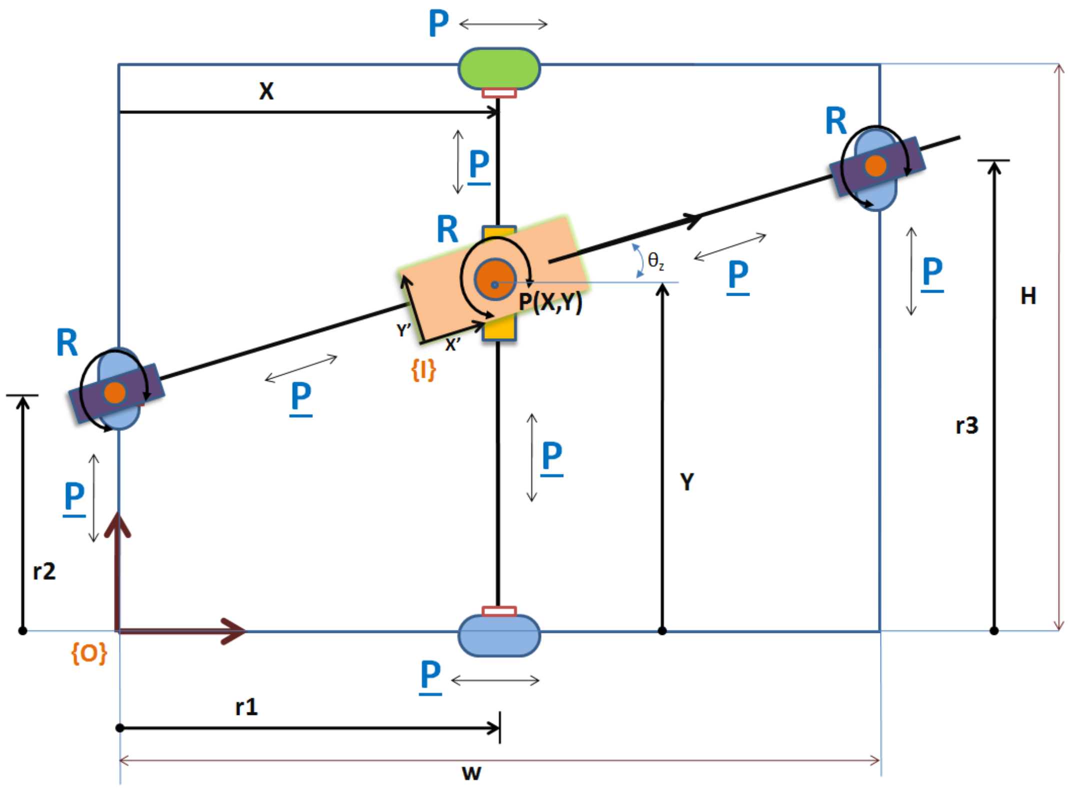

Figure 2.3 Frame arrangement

$P(x, y)$: Position of End effector,

θ_z: Orientation of the end effector,

r1: Distance of prismatic joint located on X-axis from Y-axis of Base frame,

r2, r3: Distances of prismatic joints located on Y-axis from X-axis of Base frame

O: Base frame,

I: End effector frame,

P: Prismatic joint,

R: Revolute joint,

H: span along Y-axis = 42cm,

W: span along X-axis = 50cm.

Forward Kinematics:

Forward kinematics refers to use of kinematic equations of the manipulator to determine the position $P(x, y)$ and the orientation (θz) of the end-effector from the base frame O(0, 0) using the joint space parameters (*r1*, *r2* and *r3*). Thus the resulting forward kinematic equations for the proposed manipulator are:

$$x = r_1;$$

$$y = r_2 + \frac{r1(r3-r2)}{w};$$

$$\theta_z = \tan^{-1} \frac{r1(r3-r2)}{w};$$

$$\mu = \begin{bmatrix} x \\ y \\ \theta z \end{bmatrix} = \begin{bmatrix} r1 \\ r2 + (r1(r3 - r2))/w \\ \tan^{-1}((r3 - r2)/w) \end{bmatrix} = \text{function}(q)$$

where r_1, r_2 and r_3 are the displacements of the prismatic joints, and w is the Horizontal span.

$\mu = [\,x \;\; y \;\; \theta_z]^T$ is the vector of Cartesian (task space) of the manipulator. $q = [r1 \quad r2 \quad r3]^T$ is the vector of the active prismatic joint (joint space) displacements of the manipulator.

Inverse Kinematics:

Inverse kinematics refers to the use of the kinematics equations of a robot to determine the joint parameters that provide a desired position of the end-effector. More often than not, it is easier to obtain the inverse kinematic solutions for the parallel manipulators compared to their serial counterparts. Specific to the above manipulator the inverse kinematic equations are given by the following set of equations which gives us the translational inputs required on the prismatic joints for the end-effector to reach the desired position.

$r_1 = x$

$r_2 = y - x\ (\tan\theta_z)$

$r_3 = y + (s - x)*\tan\theta_z$

q= function (μ)

2.3 Jacobian and Singularities:

Differentiating forward kinematic equations with respect to time gives us an equation of the form

$\dot{\mu} = J(q)\dot{q}$

where $\dot{\mu} = [\ \dot{x} \quad \dot{y} \quad \dot{\theta}\ ]^T$ is the Cartesian velocities of the manipulator,

$\dot{q} = [\ \dot{r}_1 \quad \dot{r}_2 \quad \dot{r}_3\ ]^T$ is the vector of the active prismatic joint velocities of the manipulator, and J(q) is the time-varying linear transformations which relates joint velocities to Cartesian velocities.

Using Jacobian Matrix we can get the Cartesian velocities using Joint velocities. Can we get the joint velocities from Cartesian velocities? Yes, if the matrix is invertible. That is if the matrix is non-singular, then the joints are free to move. Singularity is a case when there is some direction in Cartesian space along which it is impossible to move the hand of the robot, no matter what joint rates are selected.

We can observe from J(q) that when $\theta_z = 90^o$, the matrix will be singular. However, most of the operations never reach the value of 90^o, they will be far below 90^o. Hence this condition doesn't have any major consequences. So, we can assume that this manipulator doesn't have any singularities in its workspace.

$$J(q) = \begin{bmatrix} 1 & 0 & 0 \\ \frac{r_2 - r_3}{w} & 1 - \frac{r_1}{w} & \frac{r_1}{w} \\ 0 & -\frac{1}{w}(\cos\theta_z)^2 & \frac{1}{w}(\cos\theta_z)^2 \end{bmatrix}$$

2.4 What makes 2PRP-2PPR better?

Our configuration is almost similar to 2PRP-PPR in which necessary changes are made. In 2PRP-PPR configuration, we have a link hanging in the air which may produce a cantilever effect in some situations. To counter that effect and for better structural rigidity, here we add a passive leg which acts as a support for that leg hanging in the air. Doing this reduces the error also. Therefore the added PPR leg makes the 2PRP-PPR configuration into 2PPR- 2PPR, which used as the Milling platform.

Specifications of Fixed Base Plate, Cylinder, Fixture Plate

Fixed Base Plate	
Length x width x thickness	800 mm x 800 mm x 50 mm
Cylinder	
Length x outer diameter x inner diameter	1000 mm x 70 mm x 40 mm
Fixture Plate	
Length x width x thickness	100 mm x 100 mm x 15 mm
Threaded holes size	M5

Table 2

Specifications of Linear Guide & Carriage Dimensions

Guide & Carriage Dimensions	
Width of the rail [mm]	23 mm
Height of the rail [mm]	22 mm
Length of the rail [mm]	800 mm
Pitch of the rail [mm]	60 mm
Dynamic load rating [kN]	28.1 kN
Static load rating [kN]	42.4 kN
Static moment rating [kN-m]	0.48 kN-m
Weight of the carriage [kg]	0.62 kg
Weight of the rail [kg/m]	34 kg/m
Width of the carriage [mm]	70 mm
Width of the carriage [mm]	36 mm
Length of the carriage [mm]	81.6 mm

Table 3

Specifications of DC Motor with Ball-screw Arrangement

DC Motor with Ball-screw Arrangement	
Travel distance [mm]	420 mm
Size of the face of the slider block	80 mm x 80 mm
Feed Ball screw [Dia. and lead]	16 mm and 5 mm
Weight [kg]	7 kg
Resolution	100 micrometer
Max. speed [mm/sec]	300 mm/s
Load capacity	1000 N
Operating voltage and max. current	24 V and 5 A
Moment rigidity [Pitching; Yawing; Rolling]	[0.005; 0.008; 0.003] / Ncm

Table 4

Specifications of Linear Potentiometer (Rod less)

Linear Potentiometer (Rod less)	
Mechanical stroke [mm]	400 mm
Total Length [mm]	550 mm
Linearity	$\pm$% 0.05
Resolution	10 micrometer
Load Resistance [Kohm]	Min. 100 Kohm
Repeatability	$\pm$% 0.01
Resistance output [Kohm]	20 Kohm
Displacement speed [m/s]	$\pm$% 5 m/s

Table 5

Specifications of Spindle Motor (tool holder and Z axis)

Spindle Motor (tool holder and Z axis)	
Input power [Watt]	800 W
Output power [Watt]	420 W
Operating voltage [V]	230 V
Idle speed [rpm]	1000- 10,000 rpm
Max. tool shaft dia. [mm]	10 mm
Clamping collar dia. [mm]	43 mm
Weight [kg]	1.4 kg
Dimensions	267 mm x 73 mm

Table 6

CHAPTER 3

ANALYSIS OF THE SYSTEM

During machining some forces are developed on the end-effector due to forces applied on the work piece. We studied the deformation of the platform when the forces are applied on the end-effector in different directions using Ansys software. And the model we developed is using Solid Works for analysis in Ansys. We analyzed system in two different ways:-

1. Static Analysis
2. Dynamic Analysis

3.1. STATIC ANALYSIS:

In static analysis we considered our platform as a rigid body, that is all the prismatic joints present in platform are considered as immovable joints. Here we analysed the maximum deformation of platform when forces are applied along X, Y, Z axes. In this analysis we applied forces varying from -100N to 100N in magnitude and in all three directions that is along X,Y,Z axes. Here, T**able 7** is representing the forces along axis in left column and maximum deformation in right column. And **Figure 3.1** represents the forces along x-axis in x-axis and maximum deformation along y axis.

Force x(N)	Maximum Deformation(mm)
-100	0.00078828
-75	0.00059121
-50	0.00039414
-25	0.00019707
0	0
25	0.00019707
50	0.00039414
75	0.00059121
100	0.00078828

Table7

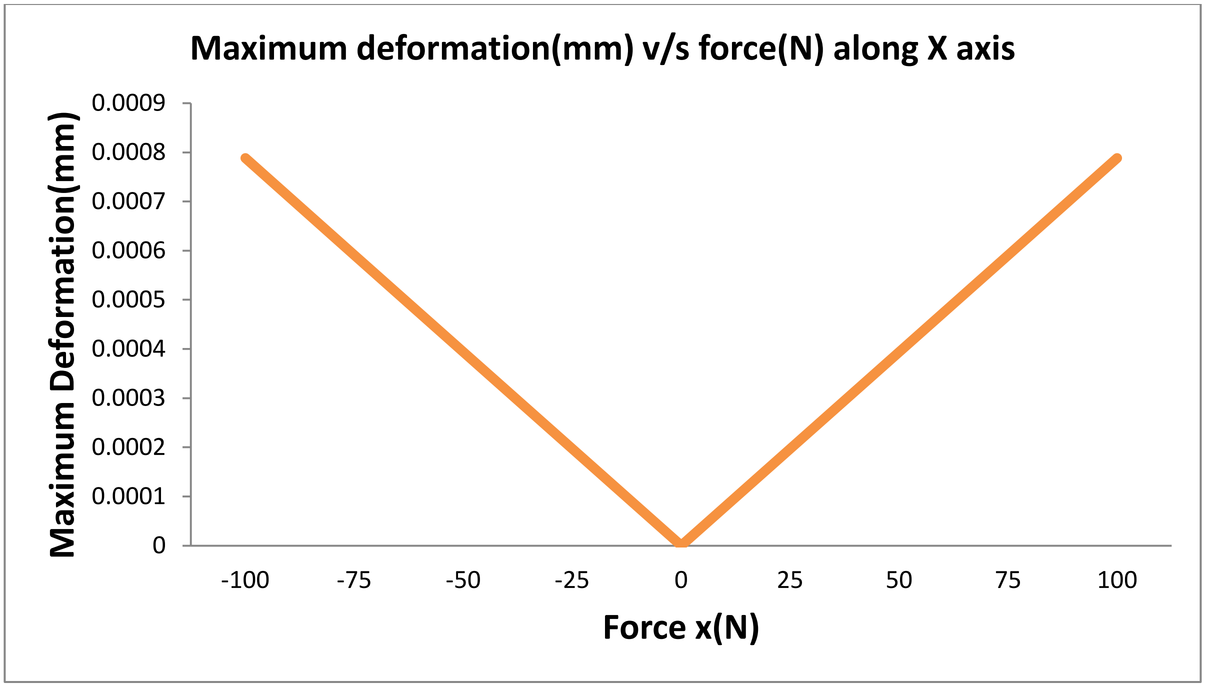

Figure 3.1

Here, **Table 8** represents the forces along axis in left column and maximum deformation in right column. And **Figure 3.2** represents the forces along Y-axis in x-axis and maximum deformation along y axis.

Force y(N)	Maximum Deformation(mm)
-100	0.0017903
-75	0.0013427
-50	0.00089516
-25	0.00044758
0	0
25	0.00044758
50	0.00089516
75	0.0013427
100	0.0017903

Table 8

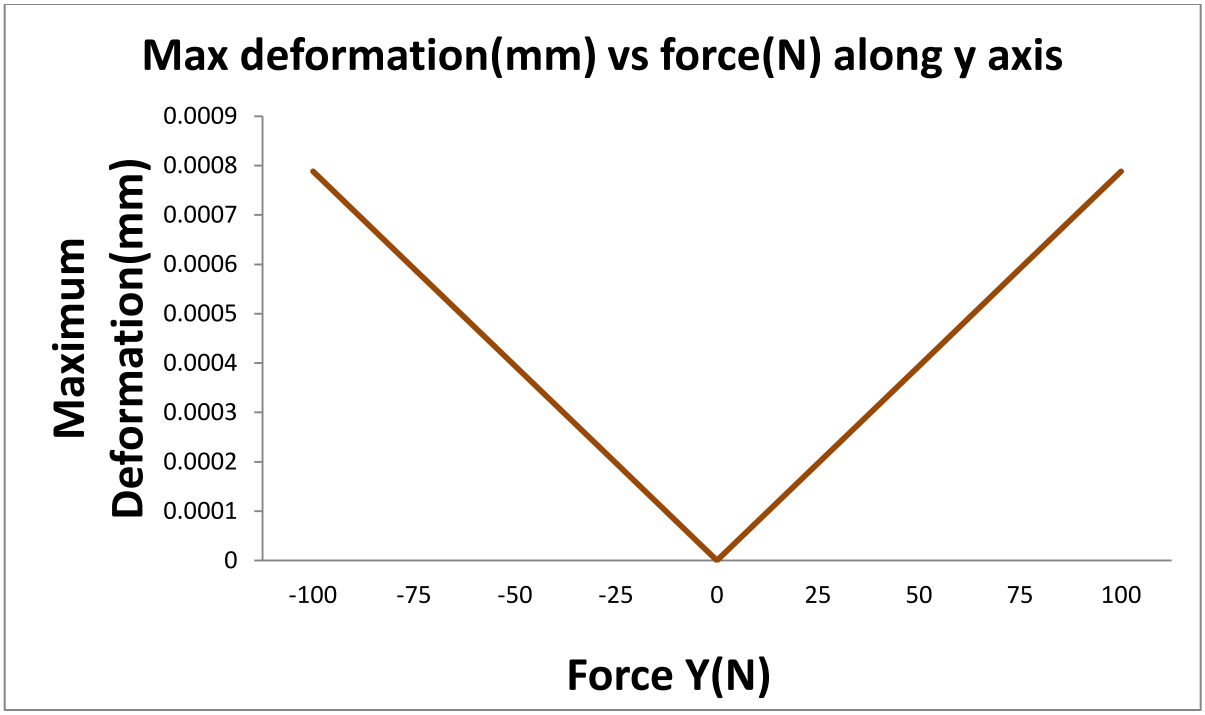

Figure 3.2

Here, **Table 9** represents the forces along axis in left column and maximum deformation in right column. And **Figure 3.3** represents the forces along Z-axis in x-axis and maximum deformation along y axis.

Force z(N)	Maximum Deformation(mm)
-100	0.00080563
-75	0.00060422
-50	0.00040282
-25	0.00020141
0	0
25	0.00020141
50	0.00040282
75	0.00060422
100	0.00080563

Table 9

Detailed deformation pattern of Static analysis for different forces along X.Y,Z are presented in Appendix 1 pictorially.

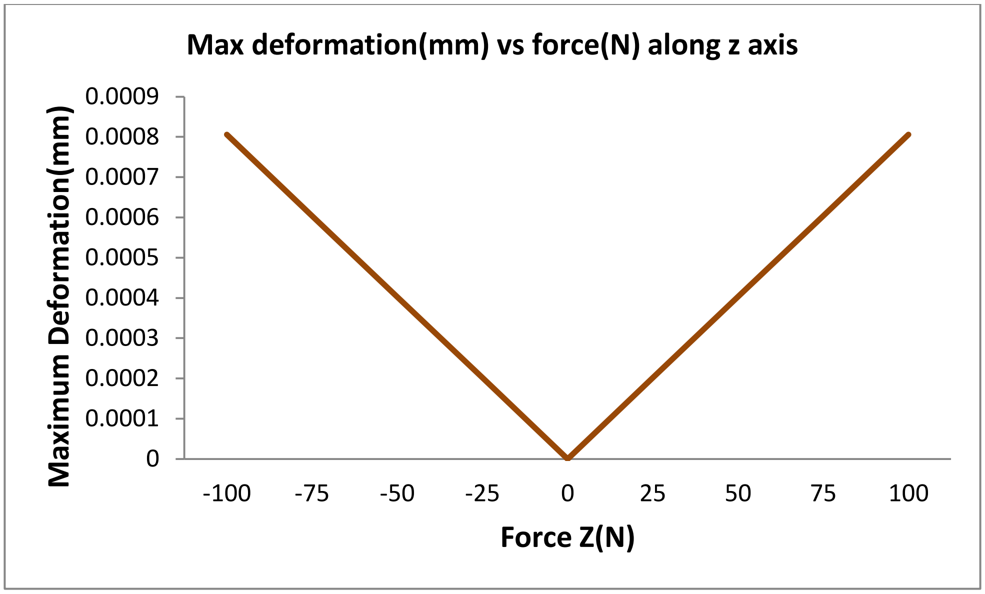

Figure 3.3

3.2. DYNAMIC ANALYSIS:

In Dynamic analysis we considered our platform as system consisting multi body which are rigid that is all the prismatic joints present in platform are considered as free movable joints. Here we analysed the maximum deformation of platform when forces are applied along X–axis and moment about Z-axis. Here, **Table 10** represents the forces along X-axis in left column and maximum deformation in right column for given moment about Z-axis. And **Figure 3.4** represents the forces along X-axis in x-axis and maximum deformation along y axis, in this case moment about z-axis is 0N-mm.

Force x(N)	Maximum Deformation(mm)
-20	184.91
-15	138.68
-10	92.452
-5	46.225
0	0
5	46.225
10	92.452
15	138.68
20	184.91

Table 10

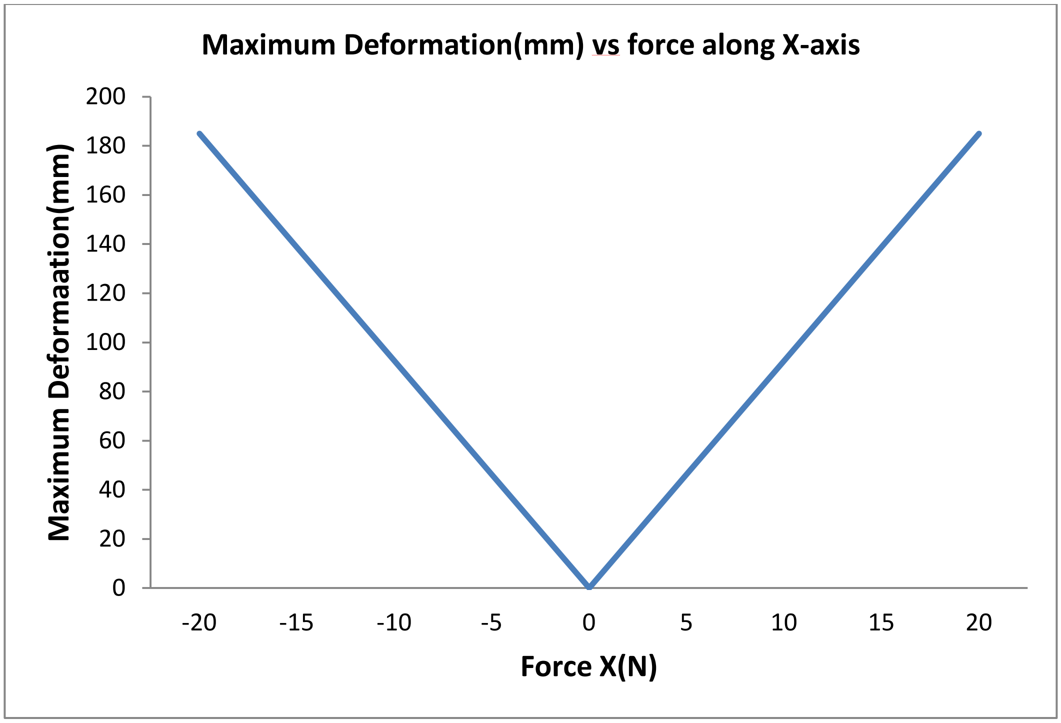

Figure 3.4

Here, **Table 11** represents the Moment about Z-axis in left column and maximum deformation in right column. And **Figure 3.5** represents the moment about Z-axis in x-axis and maximum deformation along y axis.

Moment z (N.mm)	Maximum Deformation(mm)
-20	3.0566
-15	2.3384
-10	1.5832
-5	0.7881
0	0
5	0.7881
10	1.5832
15	2.3384
20	3.0566

Table 11

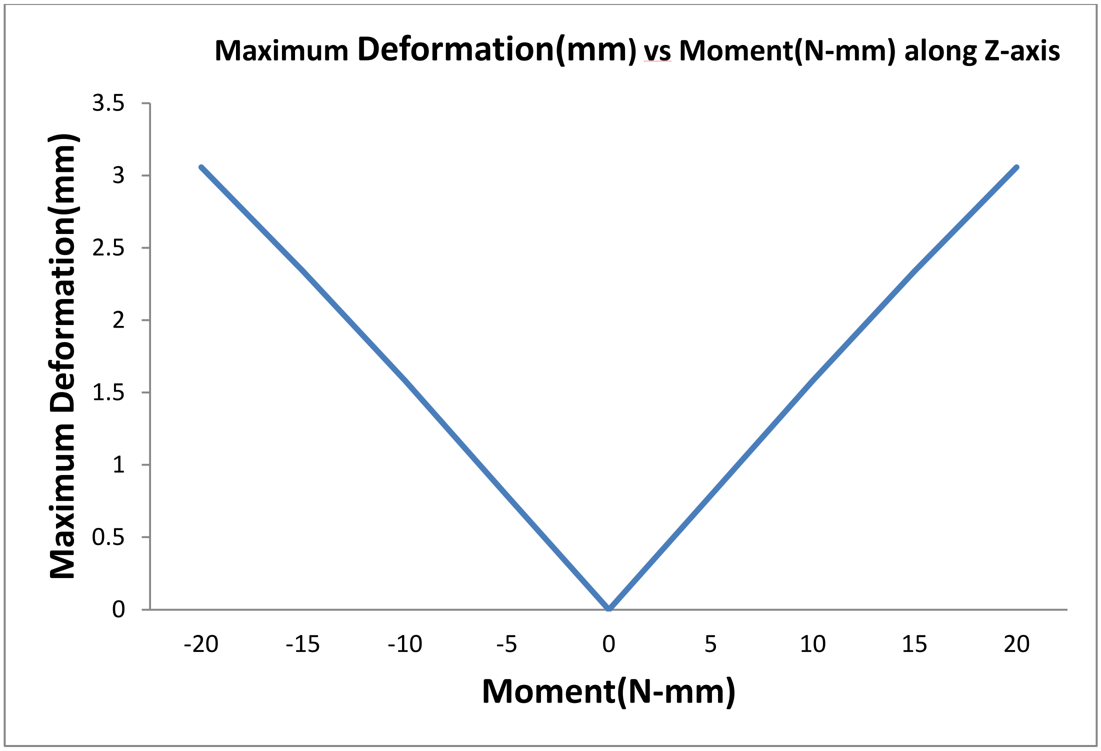

Figure 3.5

Here, **Table 12** represents for forces along X-axis in left column and maximum deformation in right column for given moment about Z-axis. And a **Figure 3.6** represents the forces along X-axis in x-axis and maximum deformation along y axis, in this case moment about z-axis is -20N-mm.

Force x(N)	Maximum Deformation(mm)
-20	186.78
-15	140.62
-10	94.461
-5	48.31
0	3.0566
5	49.383
10	95.691
15	141.95
20	188.34

Table 12

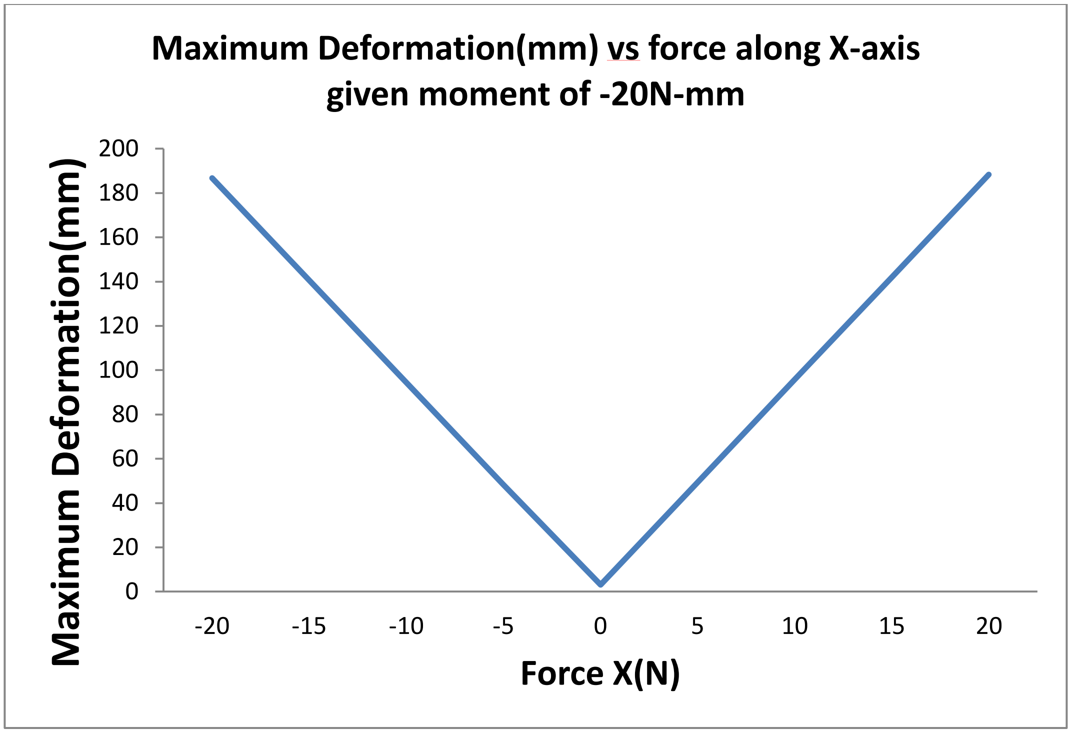

Figure 3.6

Here, **Table 13** represents for forces along X-axis in left column and maximum deformation in right column for given moment about Z-axis. And **Figure 3.7** represents the forces along X-axis in x-axis and maximum deformation along y axis, in this case moment about Z-axis is 5N-mm.

Force x(N)	Maximum Deformation(mm)
-20	185.36
-15	139.15
-10	92.948
-5	46.743
0	0.7881
5	46.981
10	93.198
15	139.42
20	185.63

Table 13

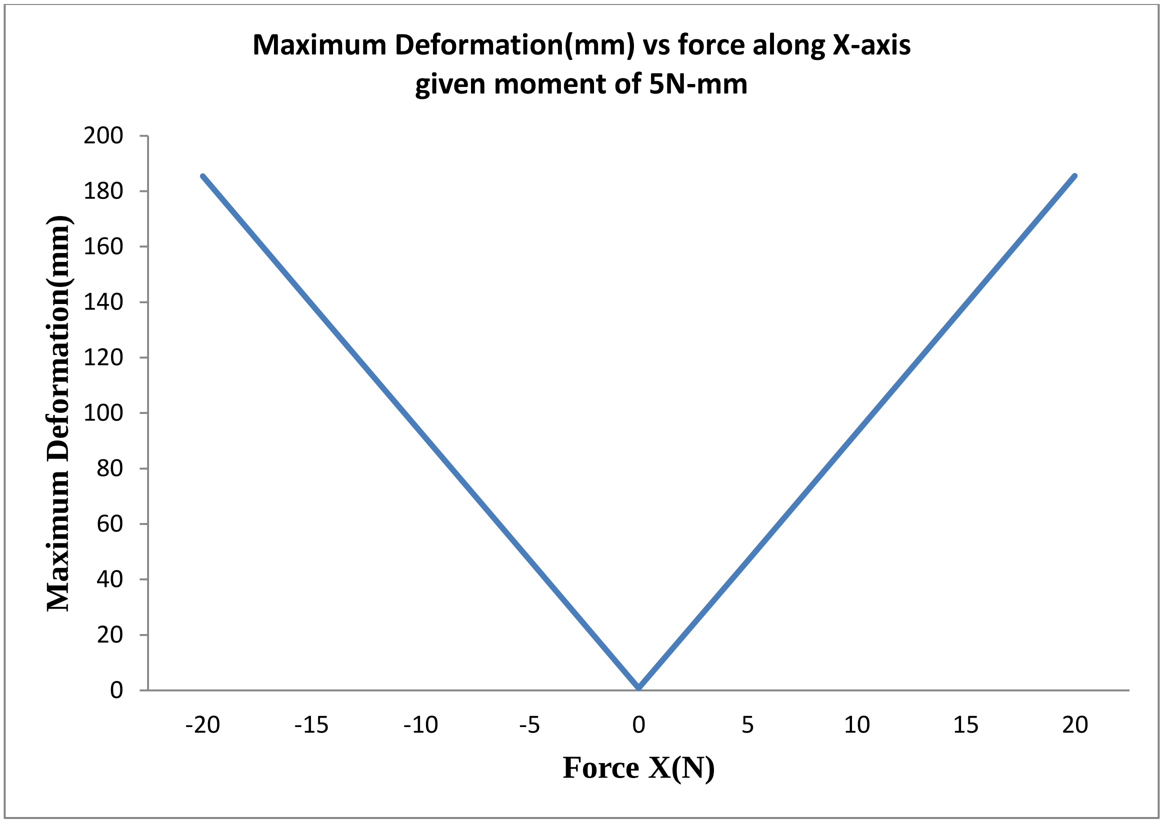

Figure 3.7

Here, **Table 14** represents the forces along X-axis in left column and maximum deformation in right column for given moment about Z-axis. And **Figure 3.8** represents the forces along X-axis in x-axis and maximum deformation along y axis, in this case moment about Z-axis is 20N-mm.

Force x(N)	Maximum Deformation(mm)
-20	185.36
-15	139.15
-10	92.948
-5	46.743
0	0.7881
5	46.981
10	93.198
15	139.42
20	185.63

Table 14

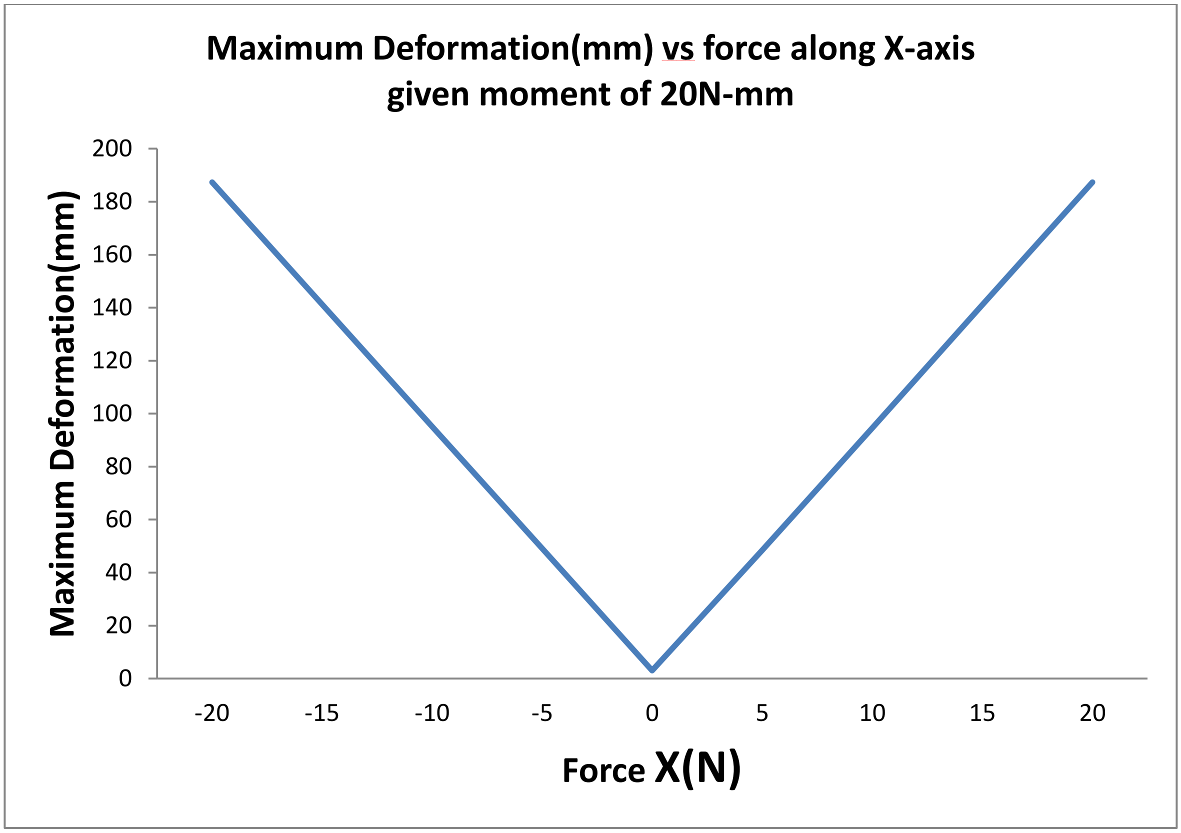

Figure 3.8

Detailed deformation pattern of Static analysis for different forces along X.Y,Z are presented in Appendix 2 pictorially.

3.3. Co-Simulations:

ADAMS/MATLAB Co-simulation:

In this chapter, a dynamic simulation methodology of our given system is presented by using ADAMS/MATLAB Co-simulation. This methodology allows simulation, development and validation of different control strategies for robotic manipulators in fast way.

Finally, this methodology was validated by constructing a simulation model of our manipulator and then implementing PID type control strategy.

Simulation is an alternative to prototype design. As a methodology tool, Simulation provides a wide view of a system behavior, enabling error detection, parameters optimization or analysis for testing results. It is possible to develop the mathematical model by analytic methods, but in certain cases there is a certain degree of complexity despite of the approximation process, thus simulation is recommended as an easy way to test the system. Simulation models allow to verify or to establish diverse features of the model such as: parameters, weight, dimensions, paths, acceleration, velocity, angles, workspace, range and limits measurement. The use of models simulation is a key asset inside this methodology. There is software available specialized on the modeling of robotic manipulators as ANSYS, ADAMS and others.

Here a co-simulation methodology is presented for our parallel planar manipulator with 3 degrees of freedom using ADAMS/MATLAB. Co-simulation is the cooperation of informatics applications in respect to the shortcomings from one of those applications in a specific circumstance.

Following steps will be observed in the process: design, simulation, co-simulation and the PID control strategy that is implemented.

ADAMS allows creating parts to model mechanical systems, to modify systems parameters and to write the codes necessary to the proper functioning and analysis of the system. Once the simulation model of the system is built, different control strategies can be implemented by using MATLAB.

CHAPTER 4

EXPERIMENTAL SETUP

4.1. Block Diagram:

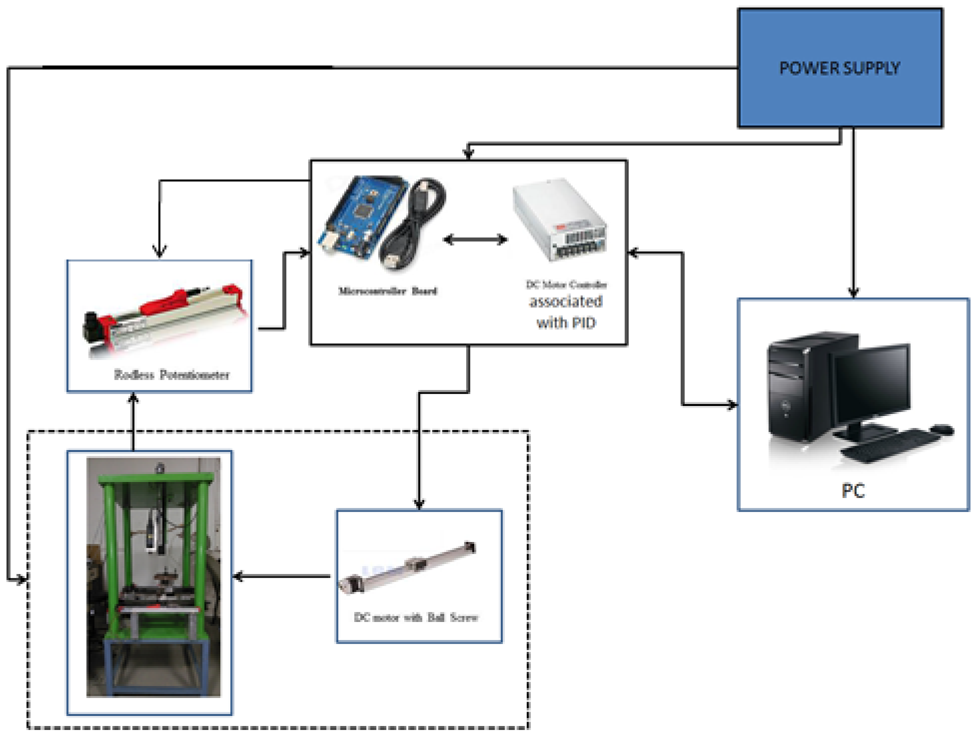

Figure 4.1 Block Diagram

The power is supplied to the PC and to the spindle in the machine. All the actuators are connected to the DC motor controller which is directly connected to the PC. A micro-controller and PID controller are built in in the DC motor controller box. The controller box actuates the motors according to the inputs given to the PC. A software package named MACH3 is installed in the PC which provides the required interface. A G-code is to be generated for the desired trajectory to be followed by the end-effector using MATLAB.

The generated code needs to be uploaded to MACH3 software and should be run. Then the code generates the desired trajectory virtually which will then be sent to the controller box and the motors are actuated according to the desired shape. The end-effector motion is solely responsible for the machining which is done on the workpiece. The end-mill cutter will be machining the surface whose arrangement is shown in the figure.

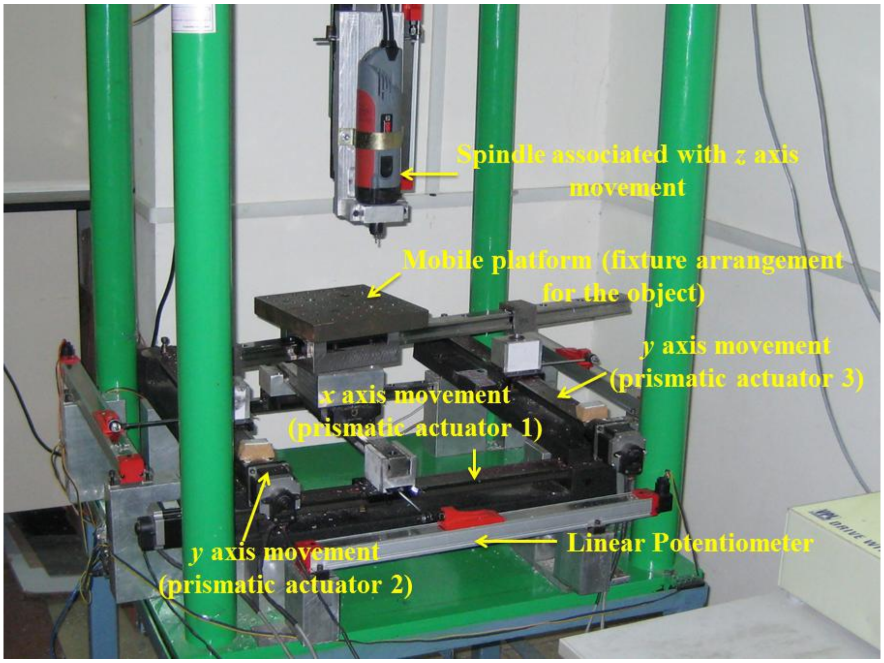

Figure 4.2 Manipulator with all arrangements

To check the joint displacements, linear potentiometers are connected parallel to the joints and those potentiometers are connected to the arduino to take the readings at a particular time.

4.2 Description:

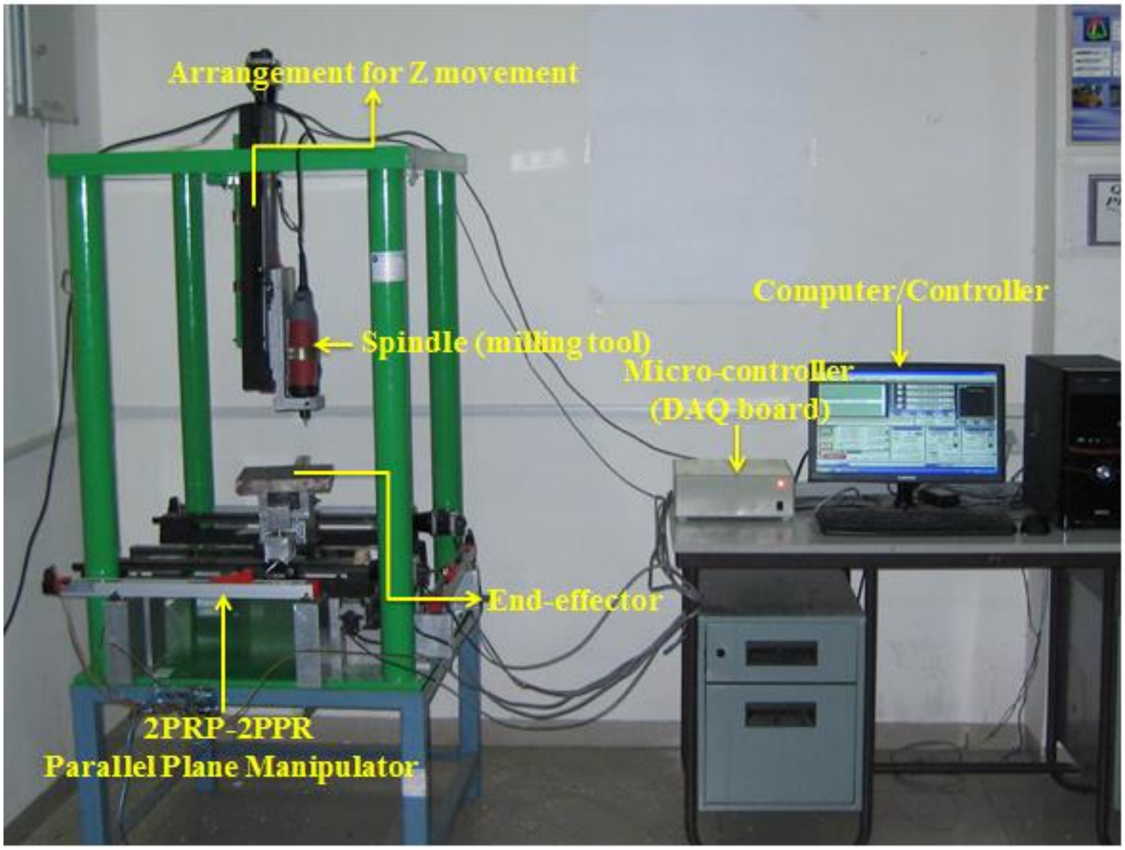

Figure 4.3 Complete Setup

4.3 Experiments Performed:

Two sets of experiments were performed to test the capabilities of the manipulator to serve as the milling platform. Particularly these shapes are chosen to check whether it can manipulate the end-effector in a curved path, if it can produce two lines which are exactly perpendicular, and to check if it can produce two lines which are perfectly parallel. The second set of experiments has a complex trajectory which is used to test several capabilities at a time.

All the codes for these trajectories were generated separately using MATLAB and then uploaded to the PC. Trajectories to test the above mentioned capabilities are:

1. Circle with a radius of 50mm.

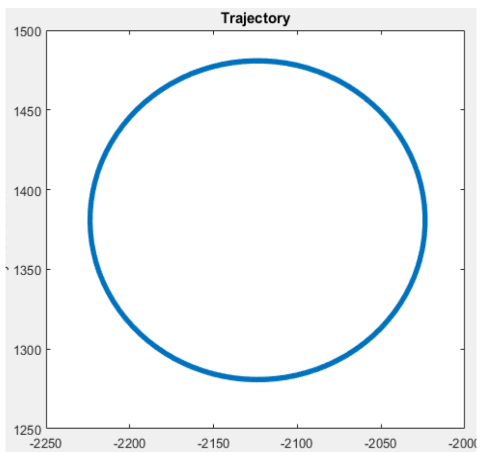

Figure 4.4 Circular trajectory

2. Rectangle with length and breadth equal to 100mm.

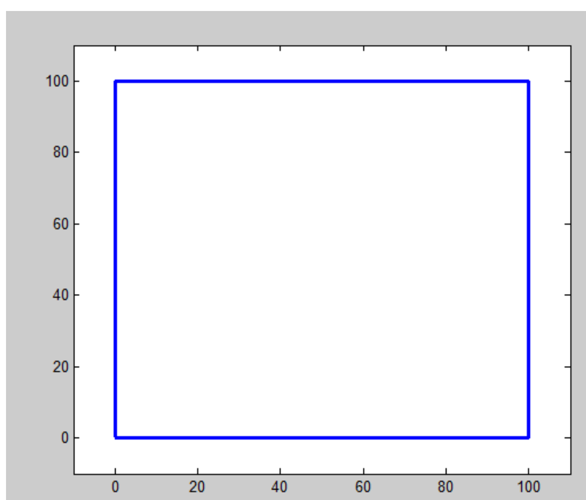

Figure 4.5 Rectangular Trajectory

3. Triangle with base = 100mm and an altitude of 85mm.

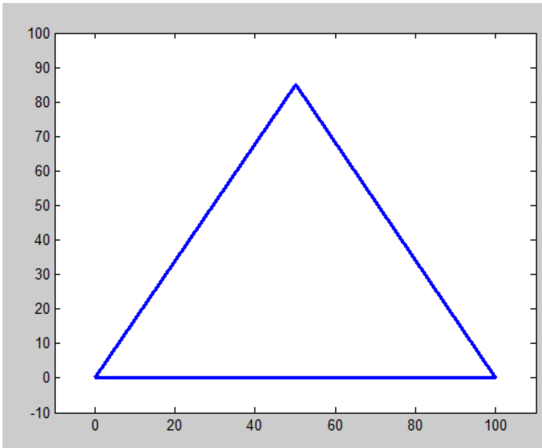

Figure 4.6 Triangular Trajectory

4. A complex shape with dimensions mentioned in the figure.

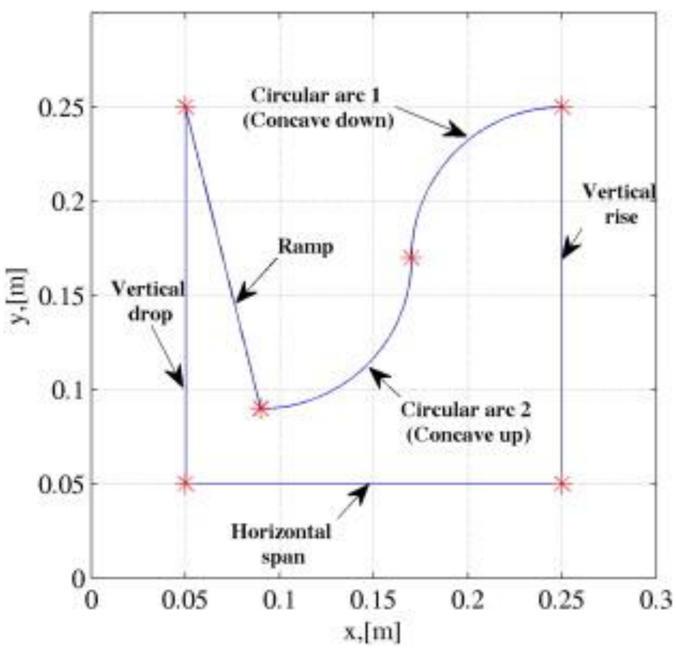

Figure 4.7 Complex Trajectory

All the experiments were conducted on Wood and Soft Aluminium with different feed rates. Water is used as a coolant when machining is being done on Aluminium. The results of all the experiments and deviations from the theoretical values are mentioned in the next chapter.

5. Random/free style trajectory

This is done just to check whether the manipulator has the ability to follow any random trajectory or not.

Figure 4.8 Random Trajectory

Generation of Trajectories using sensors:

While or after machining, to check whether the end effector is following the desired trajectory we calculated position coordinates of end effector from the joint space variables. To get those joint space variables i.e. displacements of prismatic joints, we connected linear potentiometers(rod less) to all three prismatic joints and then created a simulink model which after simulation gives the values of the displacements of the 3 prismatic joints. Simulation time should always be greater than or equal to machining time to get all the points which the joints travelled throughout the machining. Once the simulation is done, we get the displacements of all 3 joints r1,r2,r3 as 'r1.signals.values','r2.signals.values','r3.signals.values' respectively. As the readings from the sensors are in between 0 - 1023, we need to convert them to linear scale (normal scale). A new code in matlab which takes these displacements and convert them into our normal scale and in further the code will apply Forward kinematic equations to these joint space variables and calculate the position coordinates of end effector. Once the coordinates are done, it'll plot the trajectory of end effector and all 3 translational displacements versus time.

Matlab code:

```
RANGEy1 = input('RANGE on Y1 axes');
RANGEy2 = input('RANGE on Y2 axes');
RANGEx = input('RANGE on X axes');
A= r1.signals.values ;
m1a= max (A);
m1b= min(A);
m1= RANGEy1/(m1a-m1b) ;
c1= ((RANGEy1/(m1b-m1a))*m1a);
 b= (m1*A)+ c1 ;
 C= r2.signals.values ;
 m2a= max (A);
 m2b= min(A);
 m2= RANGEx/(m2a-m2b) ;
 c2= ((RANGEx/(m2b-m2a))*m2a);
 d= (m2*C)+c2;
 E= r3.signals.values ;
 m3a= max (A);
 m3b= min(A);
 m3= RANGEy2/(m3a-m3b) ;
 c3= ((RANGEy2/(m3b-m3a))*m3a);
 f= (m3*E)+c3 ;
 x=d;
 p= (f-b)/500;
 q= p*transpose(d) ;
 r=diag(q);
 y=b+r;
```

Using this code, we generate trajectories virtually in our system. The inputs needed for this code to run are taken from the Potentiometers connected to Arduino. All those virtually generated trajectories are shown in results.

CHAPTER 5

RESULTS AND DISCUSSION

Geometric Tolerances like Circularity, Straightness, Perpendicularity and Parallelism were measured using Co-ordinate Measuring Machine (CMM). Cross checking is also done using the same machine.

Specifications of the CMM:

Name: MITUTOYO

Range/Frequency: 1000mm.

Calibration Measurement Capability (±): (6 + L/100) µm, L in mm (Measurement Capability is expressed as an uncertainity (±) at a confidence probability of 95%).

Remarks: Using long guage block and dial guage by Comparison method.

Results:

5.1. Circle: Machining is done at a feed rate of 250mm/min (All the values below are in mm)

ELEM#	NOMINAL	ACTUAL	LOW_TOL	UPP_TOL	DEV	OUT_OF_TOL
Flatness	-	0.043	-	0.200	-	-
Circularity	-	0.003	-	0.200	-	-
Radius	48.5	48.184	-0.200	0.200	-0.316	-0.116

Table 15

From the above results it can be observed that Flatness and Circularity are well inside the limits. The error is radius is below 1% which can be appreciated for a human made machine.

Actual Machined Workpiece:

Figure 5.1 Machined circular trajectory

The sensor readings of all the joints and the shape followed by the end-effector is calculated from the readings of the potentiometer and is shown below

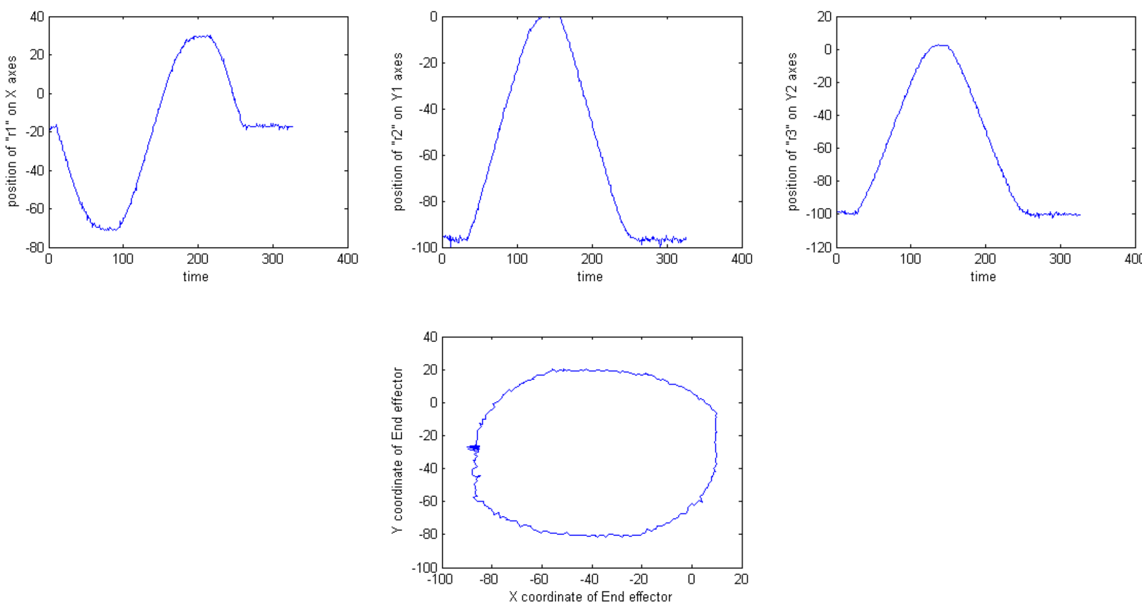

Figure 5.2 Sensors readings

5.2. Rectangle: Machining is done at a feed rate of 300 mm/min (All the values below are in mm)

ELEM#	NOMINAL	ACTUAL	LOW_TOL	UPP_TOL	DEV	OUT_OF_TOL
Flatness	-	0.013	-	0.200	-	-
Straightness (L1)	-	0.062	-	0.200	-	-

Straightness (L2)	-	0.022	-	0.200	-	-
Perpendicu-larity (L1 and L2)	-	0.044	-	0.200	-	-
Length (L1)	103.000	102.293	-0.200	0.200	-0.707	-0.507
Breadth (L2)	103.000	102.197	-0.200	0.200	-0.803	-0.603
Parallelism (L2 and L4)	-	0.001	0.010	-	-	-

Table 16

The results are very accurate with 4 of the properties well inside the tolerance zone and errors in length and breadth are less than 1%.

Actual Machined Workpiece:

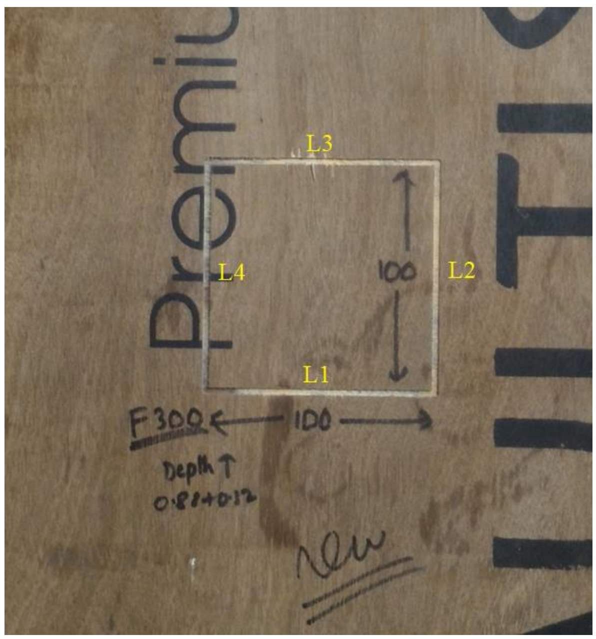

Figure 5.3 Machined Rectangular Trajectory

The sensor readings of all the joints and the shape followed by the end-effector is calculated from the readings of the potentiometer and is shown below

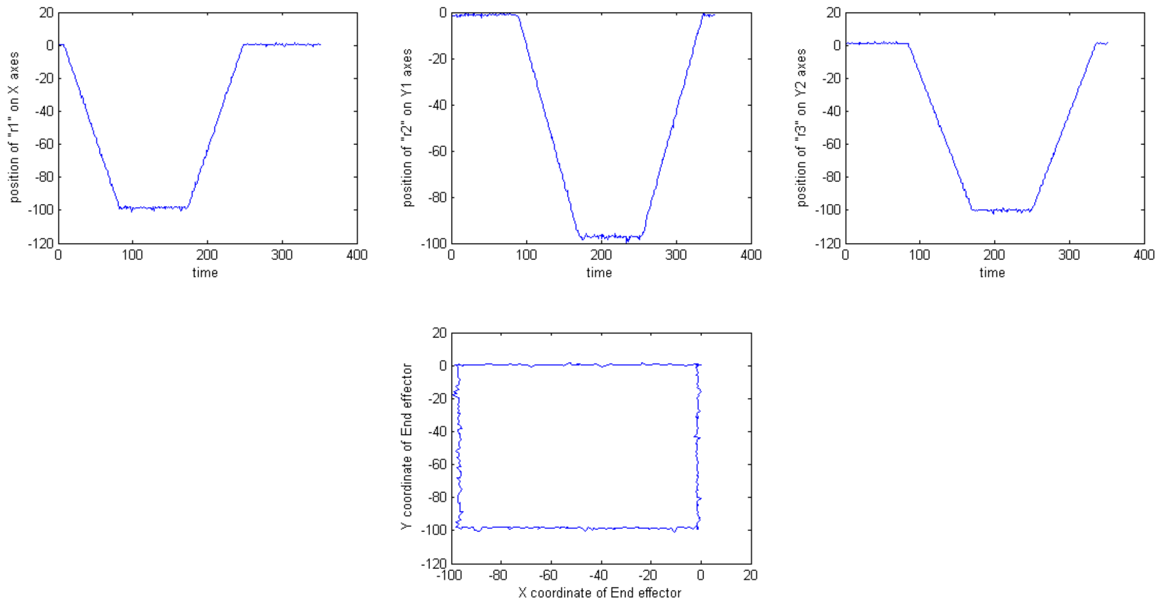

Figure 5.4 Sensor readings

5.3. Triangle: Machining is done at a feed rate of 300 mm/min (All the values below are in mm)

ELEM#	NOMINAL	ACTUAL	LOW_TOL	UPP_TOL	DEV	OUT_OF_TOL
Flatness	-	0.007	-	0.200	-	-
Straightness (L1)	-	0.000	-	0.200	-	-
Straightness (L2)	-	0.000	-	0.200	-	-
Length(Base)	100	99.490	-0.200	0.200	-0.510	-0.310
Altitude	85	84.713	-0.200	0.200	-0.287	-0.087

Table 25

The angle measured between the two sides other than the base is $60^{0}46'40''$ which is almost same as $60^{0}92'$ the original value. The errors in length and Altitude are less than 1%.

Actual Machined Workpiece:

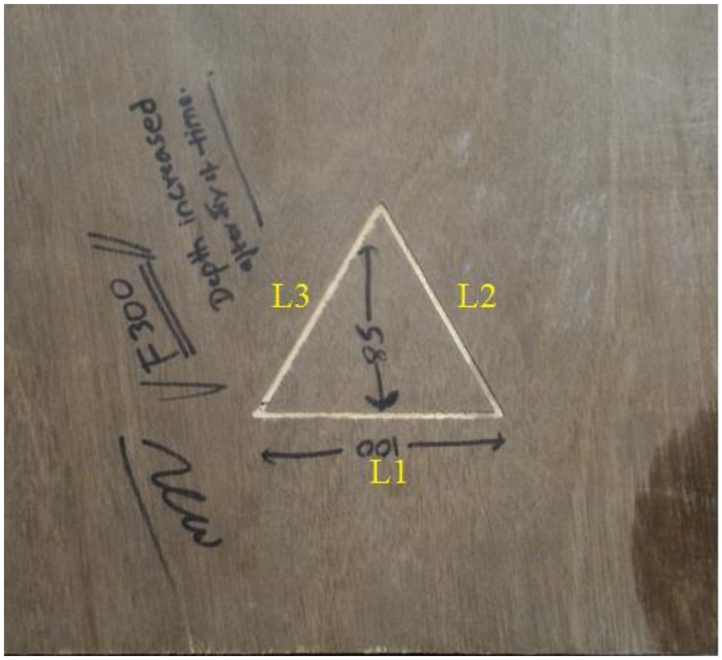

Figure 5.5 Machined Triangular Trajectory

The sensor readings of all the joints and the shape followed by the end-effector is calculated from the readings of the potentiometer and is shown below

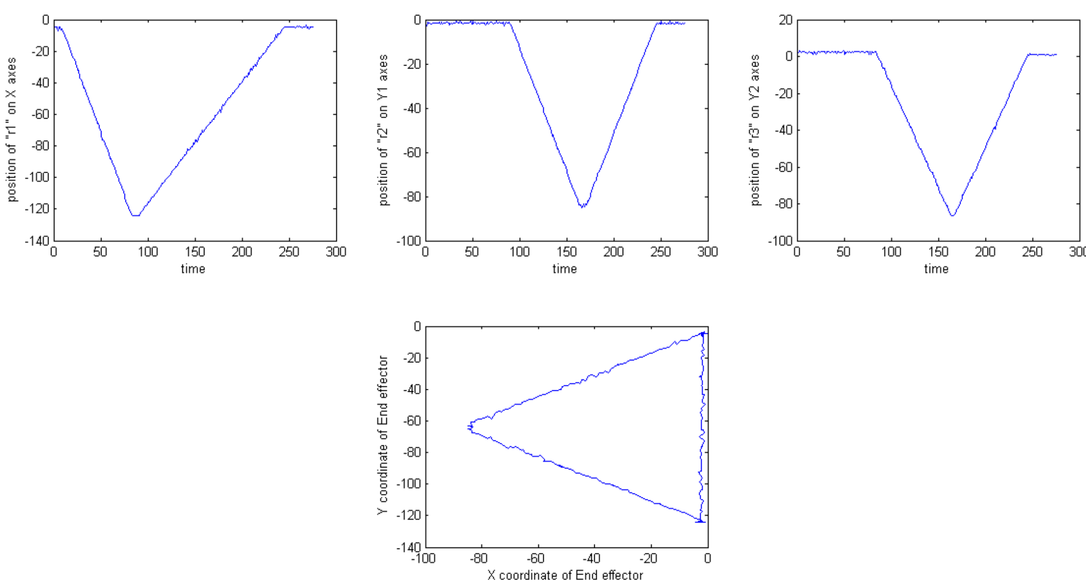

Figure 5.6 Sensor readings

5.4. Complex Shape: A complex trajectory was given to the system to follow. This part was done on Aluminium to check the capability of the machine working on Metal. Feed rate was reduced to 50 mm/min and water is used as a coolant while machining.

All the values in the table are in mm.

ELEM#	NOMINAL	ACTUAL	LOW_TOL	UPP_TOL	DEV	OUT_OF_TOL
Flatness (of the profile plane)	-	0.019	-	0.200	-	-
Parallelism (L2 and L3)	-	0.186	-	0.200	-	-
Perpendicularity (L1 and L3)	-	0.470	-	0.200	-	-
Angle (Between L2 and the curve)	15.000	14.341	-0.200	0.200	-0.659	-0.459

Table 17

Actual Machined Workpiece:

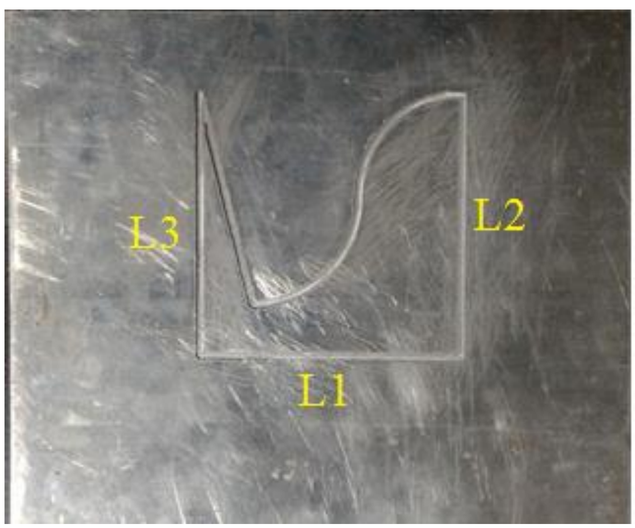

Figure 5.7 Machined Complex Trajectory

The sensor readings of all the joints and the shape followed by the end-effector is calculated from the readings of the potentiometer and is shown below

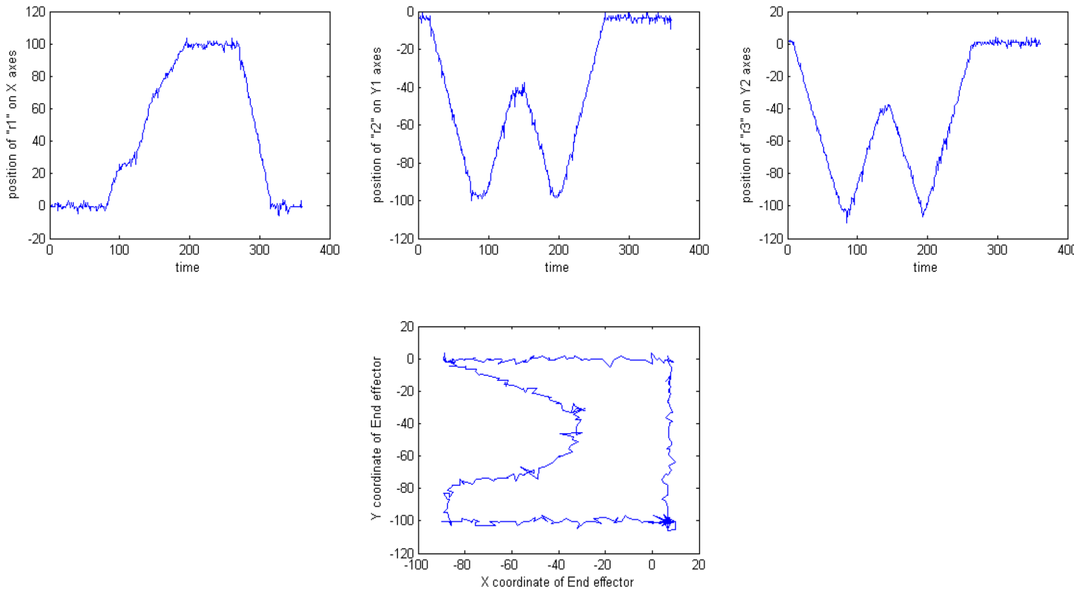

Figure 5.8 Sensor readings

From the above results we can observe that all the features of the machine are tested and the manipulator is very accurate. Errors included in the system are due to the human error while assembling or fabrication.

Actual shape machined on the workpiece tested using CMM:

The profile of the curve measured using CMM is given below. Picking every point on the machined surface we got the exact profile of the curve machined, which is very close when compared to the theoretical image. Selection of points (on actual machined surface) is random leaving some distance between two consecutive points.

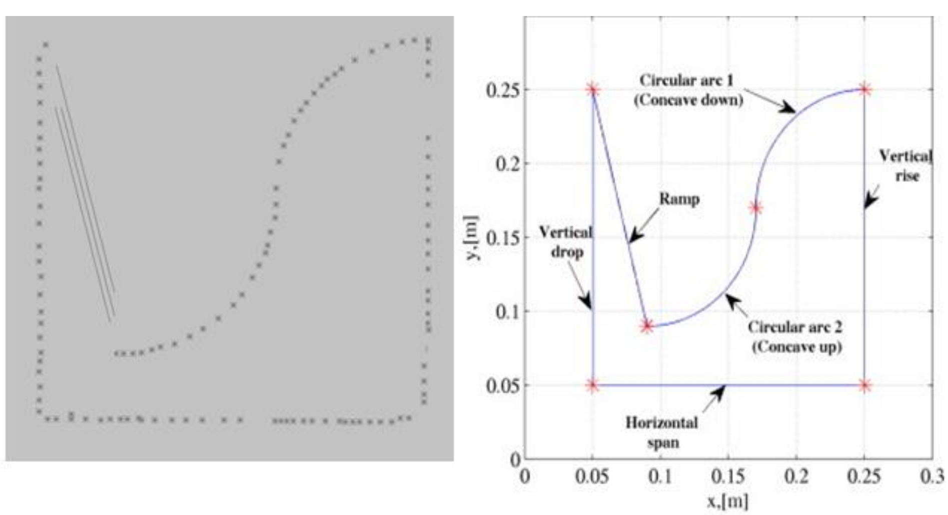

Figure 5.9 Comparison between machined and original

CHAPTER 6

CONCLUSION

Conclusion and Future Scope:

From Chapter 1, we get to know that Parallel plane manipulators are better than Serial manipulators for some of the industrial applications. Kinematic modeling is been discussed here. And the advantage of adding one extra passive leg is mentioned here. Chapter 3 gives the detailed analysis of our system when it is working. Static deflection analysis shows the deflection of the joints under particular forces. And Dynamic analysis shows the deflections and stresses on the joints when real time simulations are run (time varying loads). Chapter 4 shows the real-time machine and describes every aspect of the system. It also discusses different types of experiments which are done on the machine. This report also discusses the use of Sensors in calibration. Micro-controller Arduino is used to get the readings of the joints and MATLAB is used to generate the trajectory followed by the joint. Chapter 6 discusses all the results of the experiments and we found that the manipulator is performing very well with error percentage less than 1.

The dynamic model is verified physically (using in-house fabricated prototype). The main objective is to replace the traditional CNC or Milling machines where high accuracy, precision, higher feed rates and higher load capacity are required. The shown here prove that the manipulator is free from error accumulation and pretty accurate for Industrial applications. Workspace analysis of the system proved that the manipulator is well suitable for milling operation.

Some of the drawbacks we observed were increasing the depth of cut appreciably need the machining to be done in multiple cycles with depth of cut increasing after each cycle. And if the machining is done with a high depth of cut in a single run, then the tool may fail. The failure is mainly because of the human fabrication, this can be removed through professional fabrications.

Future Scope:

Now, as the manipulator can only be used for 2D applications, we can develop it for 3D applications. Less workspace area of the Parallel Plane Manipulator must be increased. We have faced some restrictions regarding the size of the workpiece, this can be overcome by removing unnecessary supports. If the unnecessary restrictions are removed, then we can machine on the workpiece of larger size.

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(11) Ángel, M. P. Pérez, C. Díaz-Quintero, C. Mendoza, Dynamic Systems Analysis and Control Tool

Appendix 1

Figure8.1 and Figure 8.2 represent the deformation analysis for 100N and -100N along x-axis.

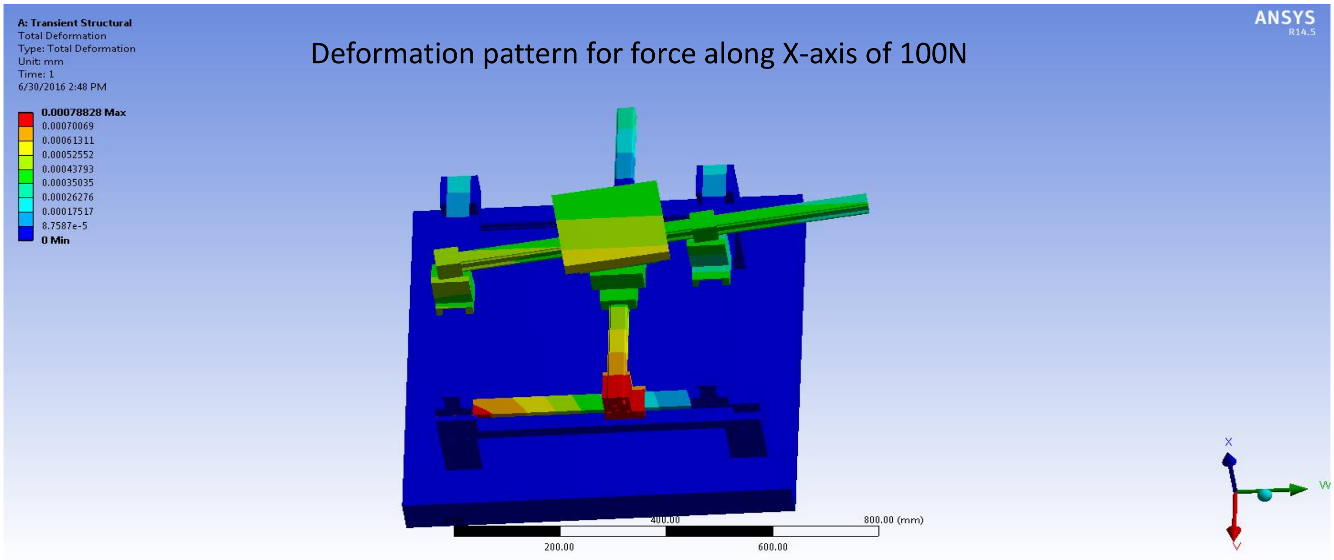

Figure 8.1

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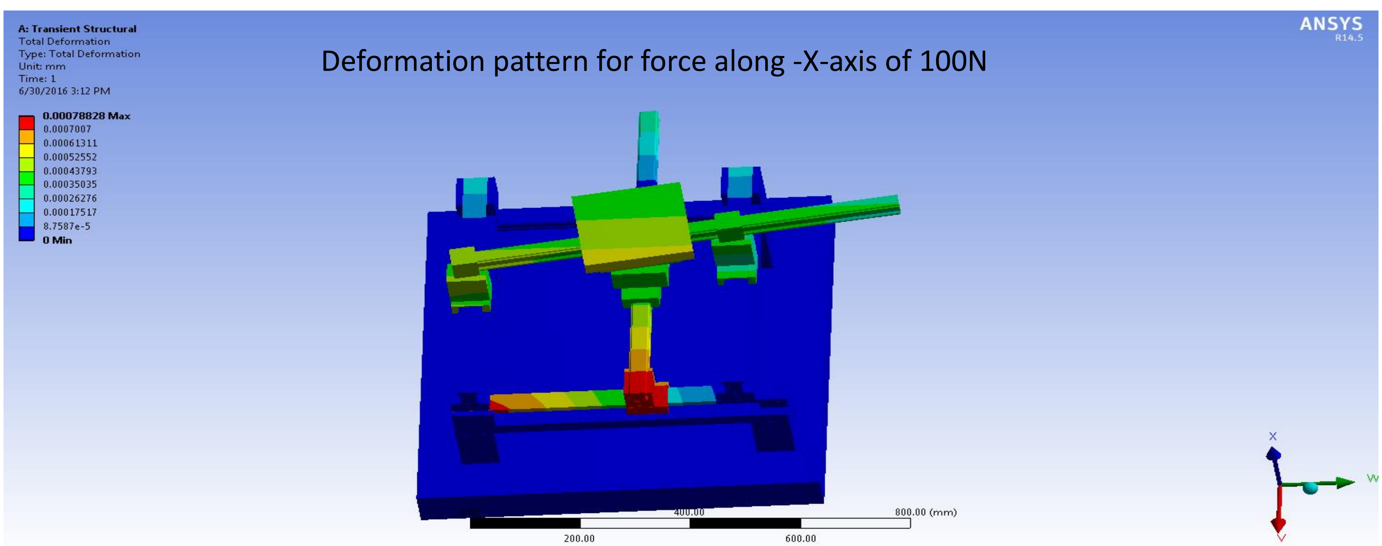


Figure8.2

Figure8.3, Figure8.4and Figure 8.5 represent the deformation analysis for 100N , -100N and 25N along Y-axis.

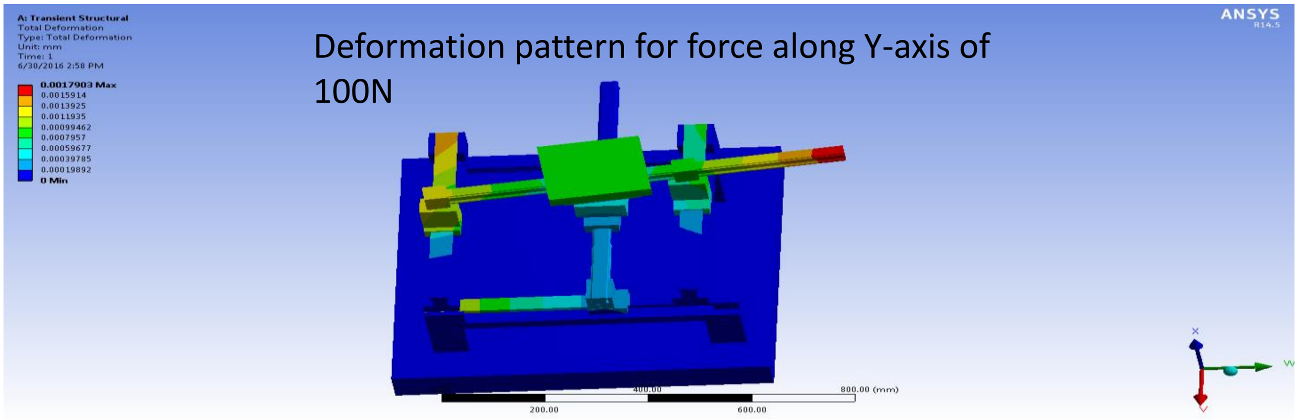


Figure 8.3

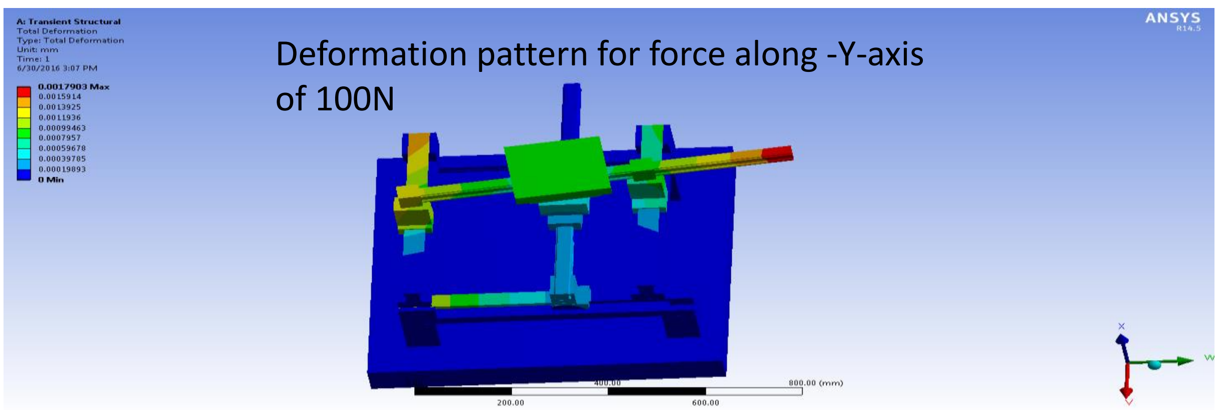


Figure 8.4

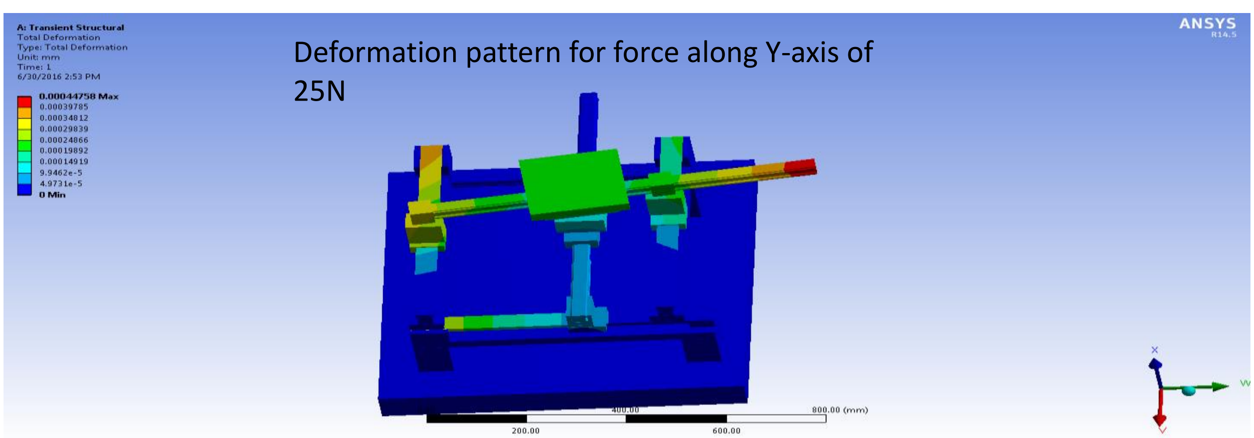


Figure 8.5

Figure8.6, Figure8.7 amd 8.8 represent the deformation analysis for 100N , -100N and 25N along Z-axis.

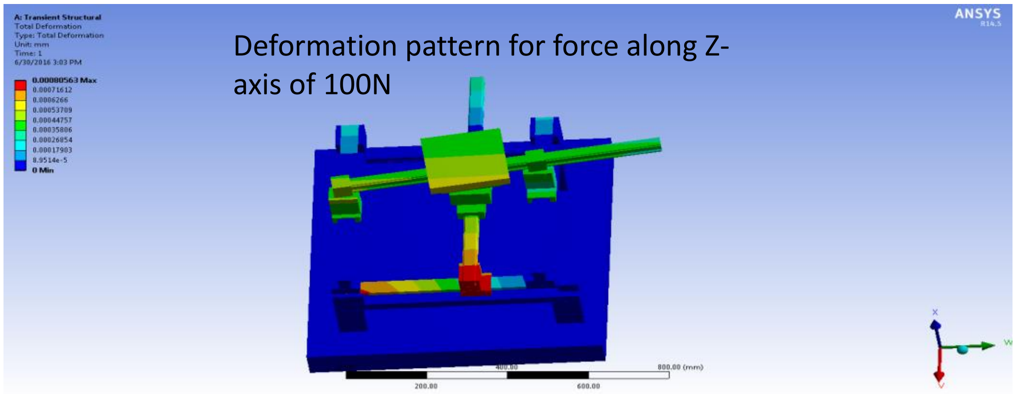


Figure 8.6

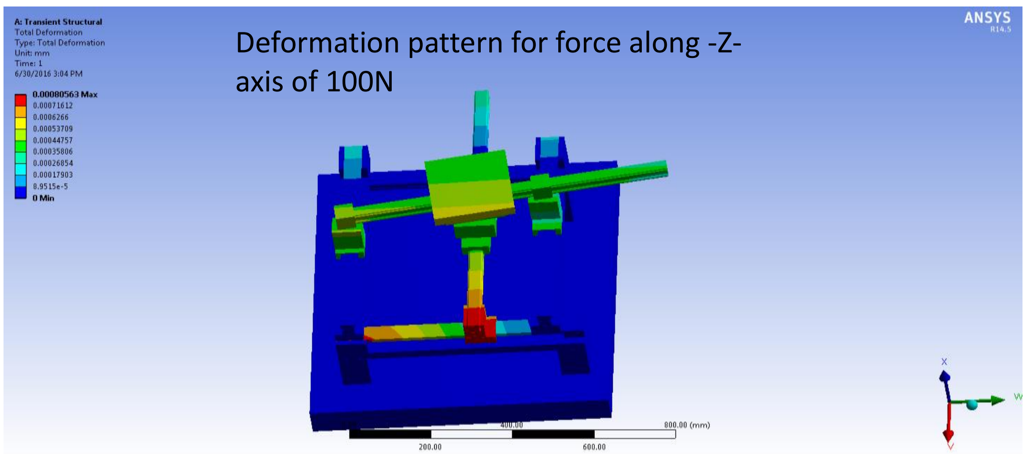


Figure 8.7

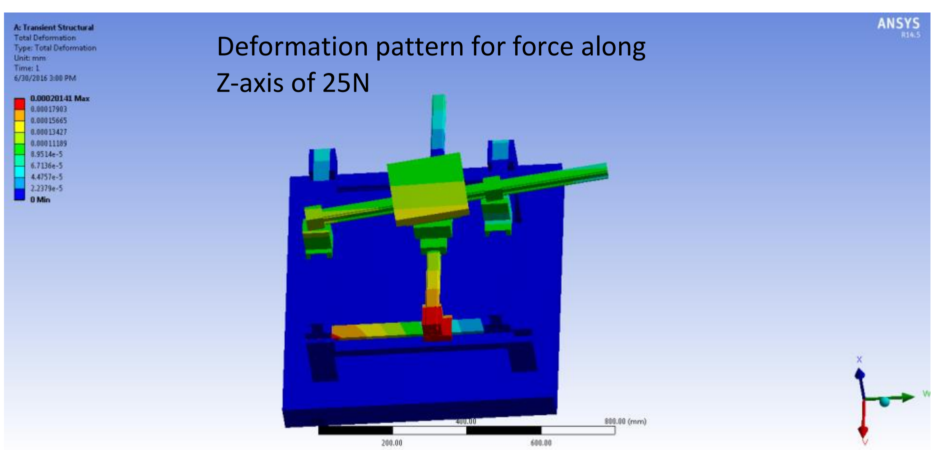


Figure 8.8

Appendix 2

Figure8.9, Figure8.10and Figure 8.11 represent the deformation analysis for -5N , 5N and 15N along X-axis and moment about z-axis is 0N-mm.

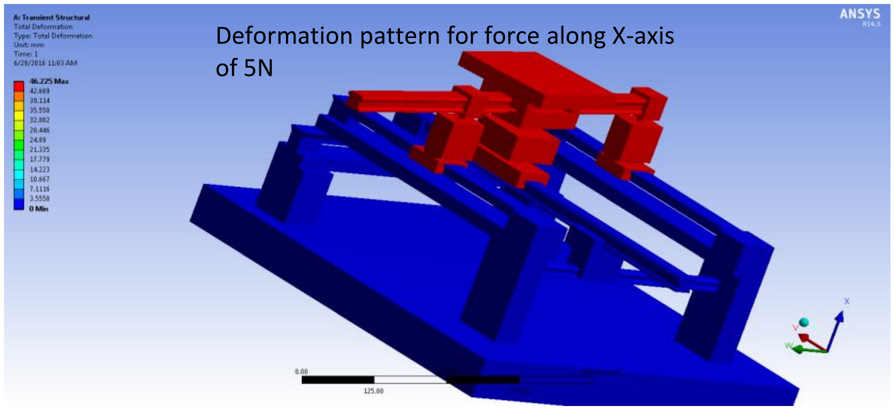


Figure 8.9

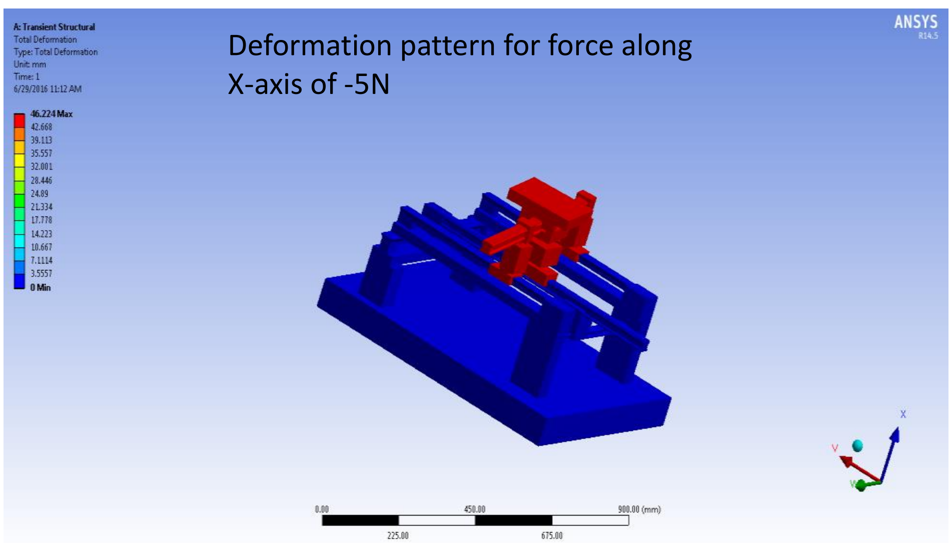


Figure 8.10

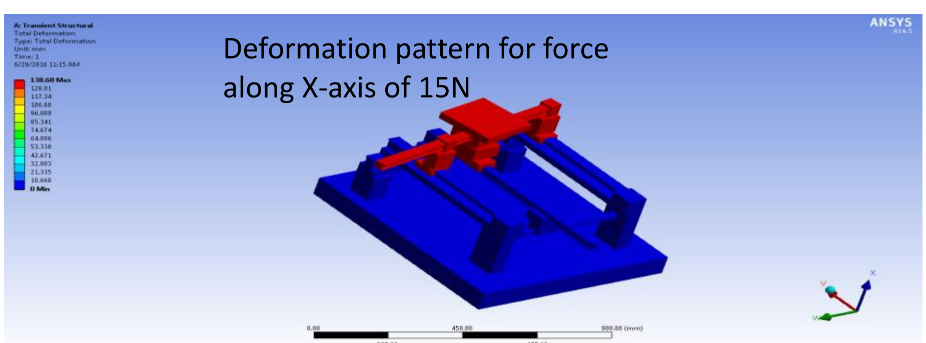


Figure 8.11

Figure8.12, Figure8.13and Figure 8.14 represents the deformation analysis for -5N-mm, 15N-mm and 20N-mm moments about Z-axis.

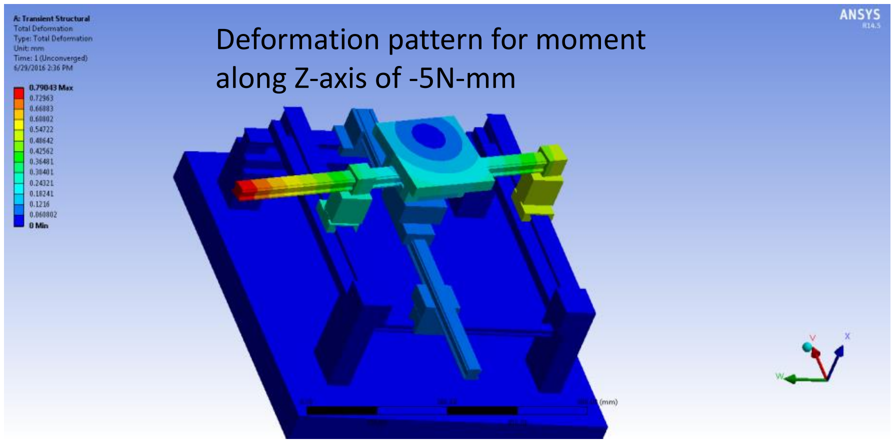


Figure 8.12

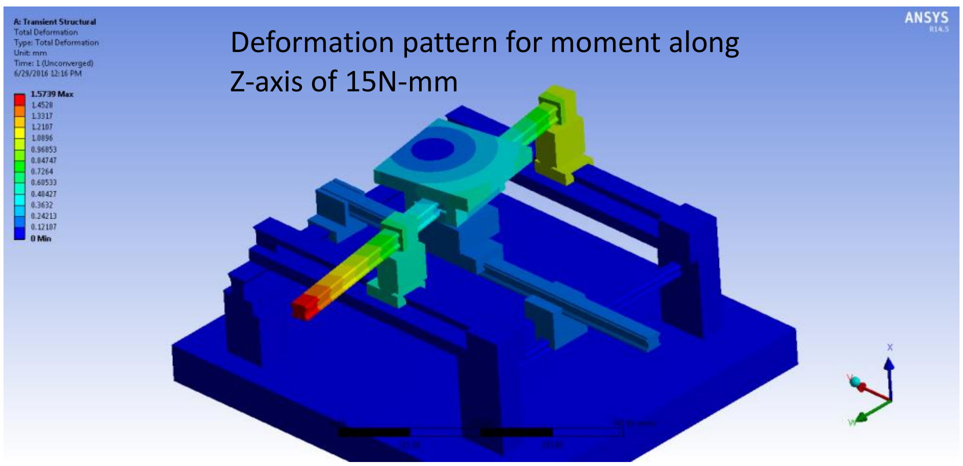


Figure 8.13

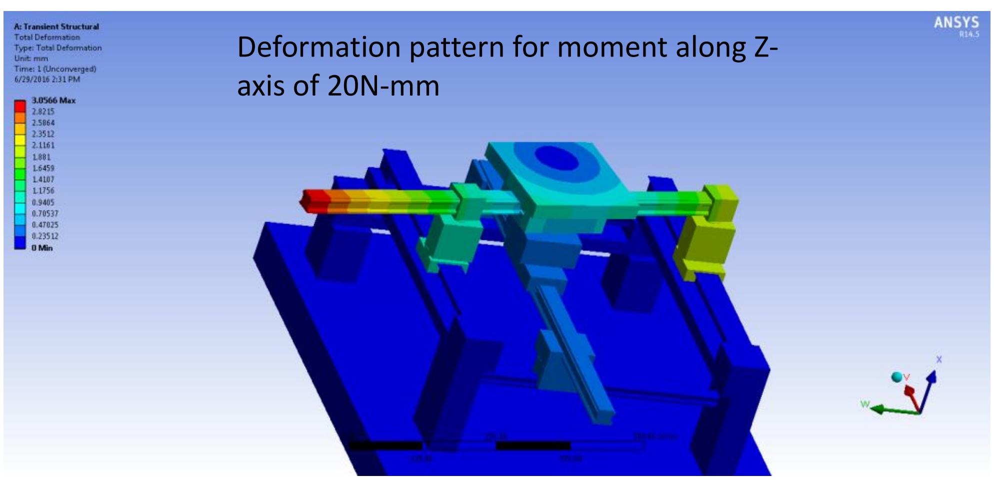
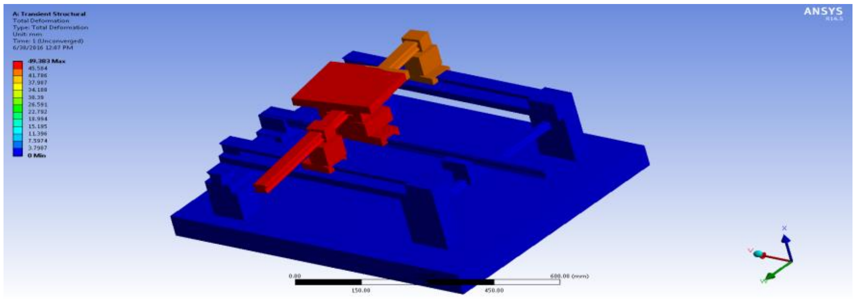


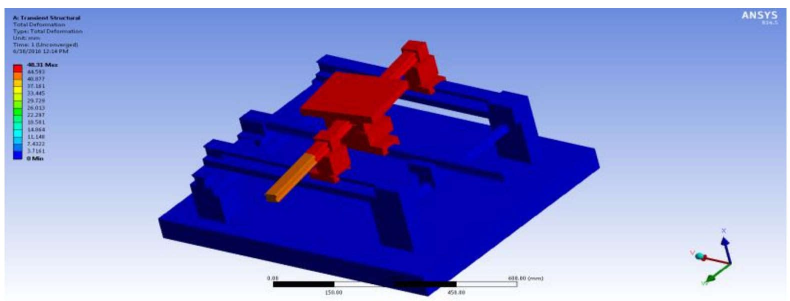
Figure 8.14

Figure8.15, Figure8.16 and Figure 8.17 represent the deformation analysis for 5N, -5N and 10N along X-axis, in this case moment about z-axis is -20N-mm.



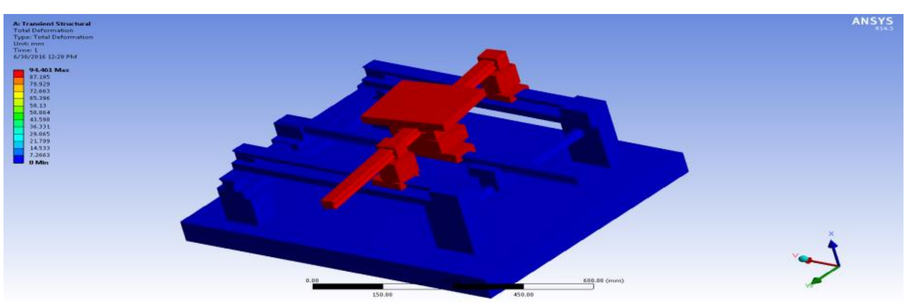
Deformation pattern for moment along
Z-axis of -20N-mm
And force of 5N along X-axis

Figure 8.15



Deformation pattern for moment along Z-
axis of -20N-mm
And force of -5N along X-axis

Figure 8.16



Deformation pattern for moment along
Z-axis of -20N-mm
And force of 10N along X-axis

Figure 8.17

Figure8.18, Figure8.19 and Figure 8.20 represent the deformation analysis for -5N, 10N and -10N along X-axis, in this case moment about Z-axis is 5N-mm.

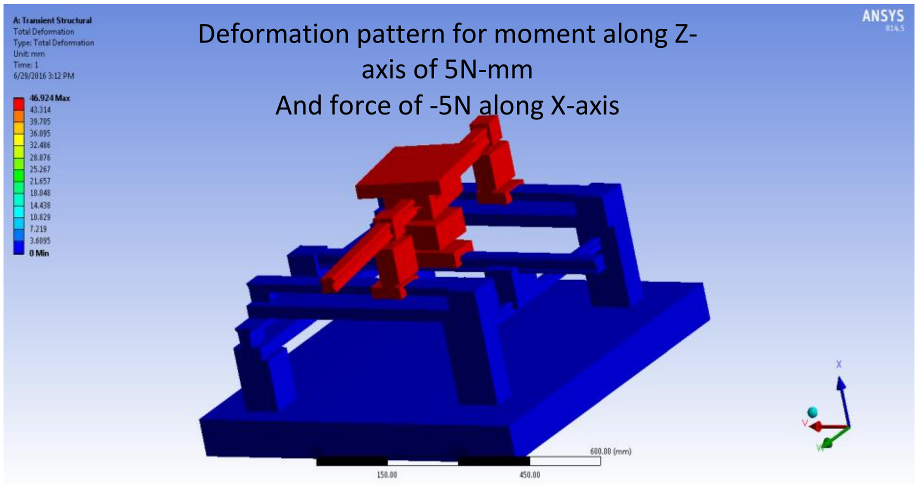


Figure8.18

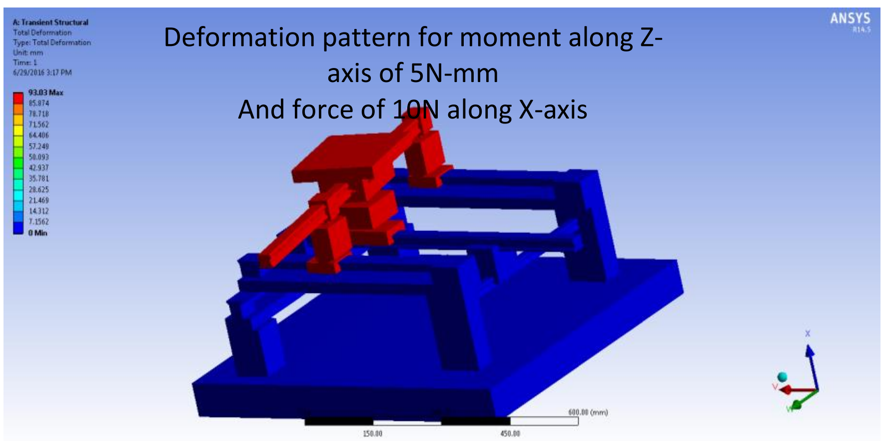


Figure 8.19

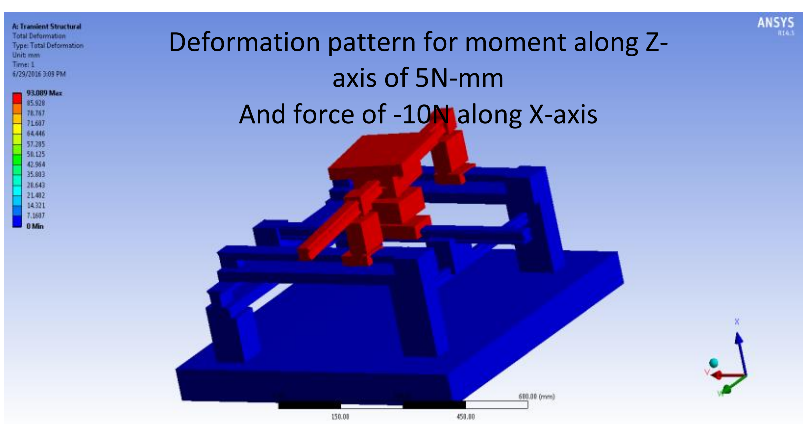
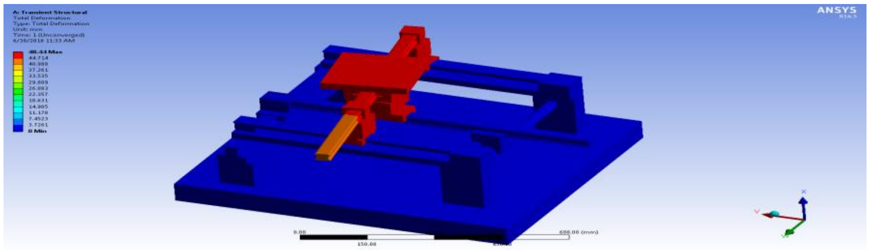


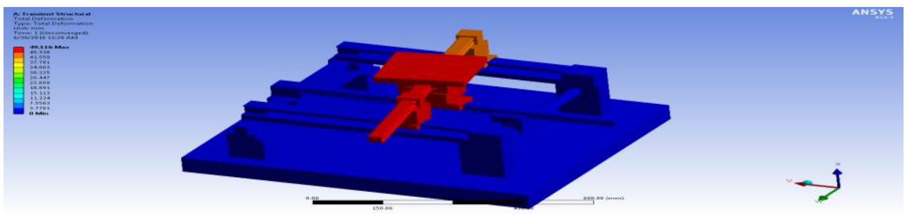
Figure8.20

Figure8.21 and Figure 8.22 Figure 8.23 represents the deformation analysis for 5N, -5N and -10N along X-axis, in this case moment about Z-axis is 20N-mm.



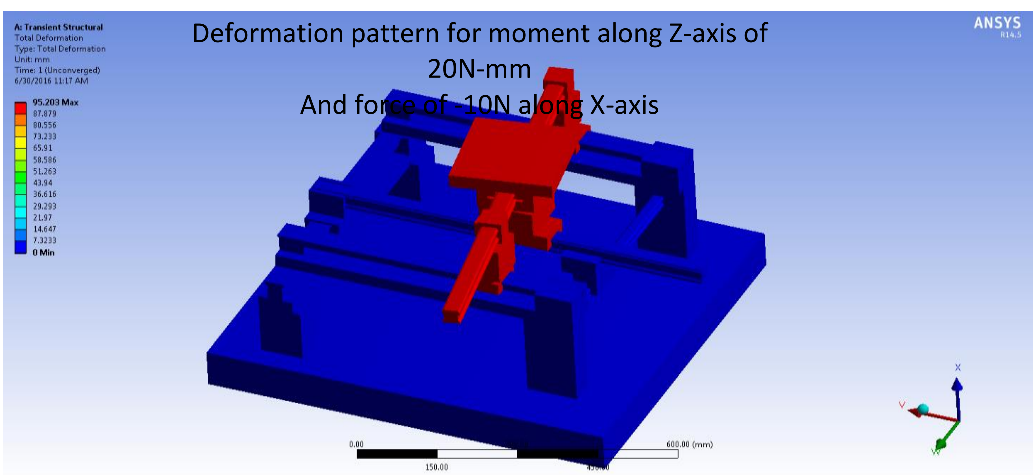
Deformation pattern for moment along Z-axis of 20N-mm
And force of 5N along X-axis

Figure 8.21



Deformation pattern for moment along Z-axis of 20N-mm
And force of -5N along X-axis

Figure 8.22



Deformation pattern for moment along Z-axis of 20N-mm
And force of -10N along X-axis

Figure 8.23