DESIGN & DEVELOPMENT OF MINIATURE HEXAPOD

Submitted in partial fulfillment of the requirements

of the degree of

Bachelor of Engineering

in

Mechanical

by

Rohit Voleti	111A6064
Bijoy Ramakrishnan	112A6002
Gokul Mohandas	112A6007
Rojenkoshy John	112A6009

Under the Guidance of:

Dr. Pradip Patil

SIES Graduate School of Technology
RISE WITH EDUCATION

Department of Mechanical Engineering

SIES Graduate School of Technology

2015-2016

CERTIFICATE

This is to certify that the project entitled ‘**Design & Development of Miniature Hexapod’** is a bonafied work of the following students, submitted to the University of Mumbai in partial fulfillment of the requirement for the award of the degree of **Bachelor of Engineering** in **Mechanical.**

Rohit Voleti	**111A6064**
Bijoy Ramakrishnan	**112A6002**
Gokul Mohandas	**112A6007**
Rojenkoshy John	**112A6009**

Dr. Pradip Patil	Dr. Pradip Patil	Dr. Alka Mahajan
Internal Guide	Head of Department	Principal

PROJECT REPORT APPROVAL

This project report entitled ***Design & Development of Miniature Hexapod*** by following students is approved for the degree of ***Bachelor of Engineering*** in ***Mechanical.***

Rohit Voleti	***111A6064***
Bijoy Ramakrishnan	***112A6002***
Gokul Mohandas	***112A6007***
Rojenkoshy John	***112A6009***

Name of External Examiner: --------------------------------

Signature: --------------------------------

Name of Internal Examiner: -------------------------------

Signature: --------------------------------

Date:

Place:

DECLARATION

I declare that this written submission represents my ideas in my own words and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

Rohit Voleti	111A6064	______________
Bijoy Ramakrishnan	112A6002	______________
Gokul Mohandas	112A6009	______________
Rojenkoshy John	112A6009	______________
		Signature

Date:

दूरभाष :
TELEPHONE : 25590081

E-mail: ravikg@barc.gov.in

सत्यमेव जयते

भारत सरकार
GOVERNMENT OF INDIA
भाभा परमाणु अनुसंधान केन्द्र
BHABHA ATOMIC RESEARCH CENTRE
Centre for Design and Manufacture

ट्रॉम्बे,
मुंबई–४०० ०८५.
TROMBAY,
MUMBAI -400 085

राष्ट्र की सेवा में परमाणु
BARC
ATOMS IN THE SERVICE OF THE NATION
भाभा परमाणु अनुसंधान केंद्र
BHABHA ATOMIC RESEARCH CENTRE

CERTIFICATE

This is to certify that the Project titled

DESIGN AND DEVELOPMENT OF MINIATURE HEXAPOD

Submitted by

1. ROHIT VOLETI
2. BIJOY RAMAKRISHNAN
3. GOKUL MOHANDAS
4. ROJENKOSHY JOHN

Embodies the bona-fide work done for project at **"CENTRE FOR DESIGN AND MANUFACTURE", BHABHA ATOMIC RESEARCH CENTER, MUMBAI** by them under our guidance and supervision.

This project work is carried out for the partial fulfillment of requirements for the degree of Bachelor of Engineering (B.E.) in Mechanical from University of Mumbai, for the academic year 2015-2016.

Signature of the External Guide: Ravikgupta 07/04/16

Name: Ravi Kumar Gupta

Designation: Scientific Officer / D

Date: 07/04/2016

रवि के. गुप्ता / Ravi K. Gu
अधिकारी/Scientific Office D
सरकार/Government of In
/भा.प.अ. केंद्र, CDM/BA
Mumbai-400 085

Seal of company

ACKNOWLEDGEMENT

We would like to express our ineffable gratitude to BARC and the entire CDM Department for permitting us to work on our project. We would also like to express our gratitude to V.K. Mishra & Ravi Gupta for their constant guidance and encouragement. We wish to express our deep sense of gratitude and thank to our Internal Guide, Dr. Pradip Patil for his direction, help and useful suggestions, which helped in completing our project work in time. We would also like to thank Dr. Alka Mahajan, our Principal for extending her support to carry out this project.

Also we would like to thank the entire faculty of Mechanical department for their valuable ideas and timely assistance in this project, last but not the least, we would like to thank our teaching and non-teaching staff members of our college for their support, in facilitating timely completion of this project.

Project Team

Rohit Voleti

Bijoy Ramakrishnan

Gokul Mohandas

Rojenkoshy John

ABSTRACT

The last few years have witnessed an important development in the use of robots in the industrial world, mainly due to their flexibility. However, the mechanical architecture of the most common robots does not seem adapted to certain tasks. Other types of architecture have therefore recently been studied, and are being more and more regularly used within the industrial world. This is so for the parallel robots. The hexapod is a parallel robot with six degrees of freedom.

A robot manipulator is an electronically controlled mechanism, consisting of multiple segments, that performs tasks by interacting with its environment. A manipulator is called a planar manipulator if all the moving links move in planes parallel to one another. A manipulator is called a parallel manipulator if it is made up of closed loop kinematic chain. The hexapod is a parallel manipulator with six degrees of freedom.

The literature survey shows that the drawbacks of a serial manipulator are the low transportable load and poor accuracy; inertia, centrifugal and Coriolis forces which make the control of the robot complex during high velocity motions; and one cannot design a micro serial robot simply by scaling down a larger version. Thus, serial robots are inappropriate for tasks requiring either the manipulation of heavy loads, or a good positioning accuracy, or to work at different scales. Hence, it calls for the use of parallel manipulators.

Parallel manipulators have been used in applications like airplane simulators, adjustable articulated trusses, mining machines, pointing devices, walking machines, machining centres, etc. The Hexapod is a six legged parallel robot with six degrees of freedom. After studying the literature on various Parallel kinematic machine (PKM) configurations, the configuration chosen for this system is 6-S$\underline{\text{P}}$S (S: Spherical; P: Prismatic), i.e. a 6-DoF positional and orientation device. This consists of a mobile platform that is connected to a stationary base through six parallel linear independent actuators with the help of end joints. Mobile platform is capable of moving in three linear directions and three angular directions and obtain its 6-DoF with respect to base from the combined computed movement of six independent actuators. Therefore, any pose (position and orientation) can be achieved by mobile platform in 3D space within range. The pay load is shared by its six linear independent actuators. The design, modelling, analysis and simulation of a miniature hexapod has been done in this project.

Contents

List of Figures

List of Tables

List of Abbreviations

DoF	Degrees of Freedom
f_i	The number of dof of the i^{th} joint
k	The number of joints
n	The number of links
PS	Prismatic, Spherical
PUR	Prismatic, Universal, Revolute
PUU	Prismatic, Universal, Universal
R$\underline{P}$R	Prismatic, Revolute, Revolute
R$\underline{P}$S	Revolute, Prismatic, Spherical
RRS	Revolute, Revolute, Spherical
RUU	Revolute, Universal, Universal
S$\underline{P}$S	Spherical, Prismatic, Spherical
U$\underline{P}$S	Universal, Prismatic, Spherical
U$\underline{P}$U	Universal, Prismatic, Universal
Λ	Motion Constant (3 for planar mechanisms and 6 for spatial mechanisms.)

Chapter 1

Introduction

1.1 Introduction

A robot manipulator is an electronically controlled mechanism, consisting of multiple segments, that performs tasks by interacting with its environment. They are also commonly referred to as robotic arms. Robot manipulators are extensively used in the industrial manufacturing sector and also have many other specialized applications. The study of robot manipulators involves dealing with the positions and orientations of the several segments that make up the manipulators. The manipulators are classified into 3 distinct groups as Serial Manipulators, Parallel Manipulators & Hybrid Manipulators. Hexapod comes under Parallel Manipulators. The drawbacks of Serial Manipulators such as Low transportable load & poor accuracy, large flexure torques on links, resulting in need for more stiffness & thereby becoming heavier and inability to design a micro serial robot simply by scaling down a larger version, are tackled in development of a Parallel Robot. A Miniature Hexapod is a scaled down model of the full scale Hexapod Parallel Manipulator. It can be incorporated in situations where a compact hexapod application is needed. The miniature hexapod being small in size, is also cost effective. The miniature hexapod can be used in various medical, military and engineering applications.

1.2 Problem Definition

Hexapod is a type of Parallel robot manipulator that incorporates six prismatic actuators. These are hinged on top & bottom plate. Devices placed on the top plate can be moved in the six degrees of freedom which makes it possible to move like a freely-suspended body. The full scale model of a Hexapod has size ranging from 1m to 10m. Hexapods of such large size are not desired for small load applications like positioning of lens during eye surgery or during study of an isotope. Apart from the large size these are very expensive devices. For small load applications a miniature hexapod is therefore required. To design a miniature hexapod which is less expensive and can be comfortably used in such scenarios is the aim of this project along with the simulating & testing of Miniature Hexapod for observing the effects of scaling it down from a Full-Scale model.

1.3 Research Objective

This research work is focused on the design and development of miniature 6-DOF parallel manipulator. The selection and designing of the joints and actuators for the miniature hexapod forms the core part of design. The development will be directed towards obtaining a lower stiffness to weight ratio and achieving lower friction in order to achieve high accuracy, precision and repeatability. Our primary aims include the design of various components of Miniature Hexapod for the given load and generating a CAD model. Testing these components for various modes of failure. Performing static and dynamic analysis using software. Evaluating results based on calculations & comparing calculated results with output obtained through simulation.

1.4 Scope of Work

Firstly, we are going to design the various components like actuator, housing, ball screw, motor, hinge etc. using the design principles studied before. Then kinematic analysis along with the kinematic equations will be done. We are further going to generate a CAD model using Creo 3.0 on the basis of dimensions calculated during the design stage. Next we are going to test the generated CAD Model in ANSYS for various failure criteria and subject to the design load. Later we are going to simulate the motion and working of the miniature hexapod using MATLAB.

1.5 Organization of Report

The project thesis is divided into 10 separate chapters.

The first chapter starts with the Introduction which includes the introductory passage, problem definition and scope of work. The second chapter consists of review of literature. The subsequent third chapter deals with the Design Methodology adopted. The fourth chapter deals with the Design Calculations for various Hexapod components. The following fifth chapter shows the various CAD model figures generated using previous design values. The sixth chapter encompasses the Design Analysis done on the CAD Models for various modes of failure for the design load and the maximum load range. The seventh chapter consists of the MATLAB algorithm & its solution. The following eighth chapter shows the results, followed by conclusions in the ninth chapter. Final chapter is the Appendices section.

Chapter 2

Review of Literature

2.1 Introduction to Manipulators [1]

The last few years have witnessed an important development in the use of robots in the industrial world, mainly due to their flexibility. However, the mechanical architecture of the most common robots does not seem adapted to certain tasks. Other types of architecture have therefore recently been studied, and are being more and more regularly used within the industrial world. This is so for the parallel robots. The hexapod is a parallel robot with six degrees of freedom. where a compact hexapod application is needed. The miniature hexapod being small in size, is also cost effective. The miniature hexapod can be used in various medical, military and engineering applications.

2.2 History of Hexapod

- 1800: Augustin Louis Cauchy, a pioneer in mathematical analysis, studied the stiffness of an "articulated octahedron," which is the ancestor of the hexapod. In 1949, V.E. Gough moved forward and built a parallel mechanism to test tires under combined loads.[1]

- 1900: One of the main theoretical problems in this field, called the spherical motion problem, to which we will return later, was the central point of a competition called Le Prix Vaillant that took place in France in the 1900's and was organized by the Acad´emie des Sciences. The prize was won on equal terms by Borel and Bricard

- 1928: James E. Gwinnett developed a motion platform (commonly as "motion base") for the entertainment industry. [2]

- 1947: Dr. Eric Gough applied the parallel kinematic platform to a tire testing machine developed working under Dunlop. This machine, or "Universal Rig" as it was called, was able to mechanically test tires under combined loads. [3]

- 1955: Gough built a prototype of this machine. For this structure, the moving element is a hexagonal platform whose vertices are all connected to a link by a ball-and-socket joint. The other end of the link is attached to the base by a universal joint. A linear actuator allows the modification of the total length of the link; this mechanism is therefore a closed-loop kinematic structure, actuated by 6 linear actuators. [3]

- 1962: Klauss Cappel developed vibration equipment for Franklin Institute. [4]

- 1965: D. Stewart began using a variant of the hexapod for his flight simulators. The robot he made was renamed after him, the "Stewart Platform. [5]

- 1971: The US Patent and Trademark Office granted a patent to Klaus Cappel for his invention and its use as a motion simulator. He got a request by the corporate office of the Sikorsky Aircraft Division of United Technologies for the design and construction of a 6-DOF helicopter flight simulator. [4]

- 1991: Charles C. Nguyen, Sami Antrazi and Zhen-Lei Zhou presented the kinematic analysis and implementation of a 6 DOF robotic wrist which is mounted to a general open kinematic chain manipulator to serve as a testbed for studying precision robotic assembly in space. [6]

- 1987: J.-P. Merlet and D. Daney address the design problems and show that classical design methodologies are not appropriate for such closed-loop mechanism and examine what alternatives are possible. [7]

- 2000: J P Merlet presented an algorithm to determine all the possible geometries of Gough-type 6 d.o.f parallel manipulators whose workspace has to include a desired workspace. This algorithm takes into account the leg length limits, the mechanical limits on the passive joints and interference between links. [8]

- 2000: Vivek Kumar Mehta & Bhaskar Dasgupta made an attempt to present a generalized approach of kinematic design for a 6-legged parallel manipulator, by considering only, the minimally required design parameters. The same approach has been used to design a 7-legged redundant parallel manipulator. [9]

- 2003: J P Merlet summarized the recent advances and various applications for a kind of manipulator was illustrated. Tracking the increasing developments over the last few years from a theoretical view point as well as for practical applications was his aim. [10]

- 2003: J P Merlet presented preliminary results of the design of a mini in-parallel 3 d.o.f. positioning system called MIPS. (Mini In-Parallel Positioning System). Its overall width will be about 1cm for a length of about 3cm and uses magnetic linear actuators [10]

- 2005: N. S. Tlale & P. Zhang presented the mechanical design, analysis and controller design of the parallel manipulator that was developed in MATLAB, Simulink and SimMechanics for understanding the kinematics and the dynamics of parallel manipulators and their controllers.

- 2006: Sungwook Yang, Robert A. MacLachlan, and Cameron N. Riviere presented the design and actuation of a six-degree-of-freedom (6-DOF) manipulator for a handheld instrument, known as "Micron," which performs active tremor compensation during microsurgery. The design incorporates a Gough-Stewart platform based on piezoelectric linear motors, with a specified minimum workspace of a cylinder 4 mm long and 4 mm in diameter at the end-effector. [11]

- 2007: Wei-Shan Chen, Hua Chen, Jun-Kao Liu solved problems about the manipulator configuration and link length, which makes the manipulator work safely in the safety length area of links. The extreme configuration is presented based on the idea of analysing the movement state of parallel manipulator in link space.

- 2008: Moshe Shoham, Member, Michael Burman, Eli Zehavi, Leo Joskowicz,, Eduard Batkilin, and Yigal Kunicher presented a new approach to robot-assisted spine and trauma surgery in which a miniature hexapod is directly mounted on the patient's bony structure near the surgical site. The construction, working, specifications are discussed in detail

- 2008: Khaled Assad Arrouk, Belhassen Chedli Bouzgarrou, Sergiu-dan Stan, Grigore Gogu presented a new method for determination and optimization of the workspace of parallel manipulators. The proposed method is based on a geometrical approach, and offers the possibility to generate automatically the workspace in a CAD environment.

- 2012: Brett Hartt, Brian Gilchrist & Vince Truman detailed the design and manufacture of a single large actuator for eventual integration into a telescope positioning system. New actuators which had evolved a set of specifications was defined. [12]

- 2012: Emrah Deniz Kunt, Ahmet Teoman Naskali, Asif Sabanovic presented design and control issues for the development of miniaturized manipulators which were aimed to be used in high precision assembly and manipulation tasks. The design procedures were given in details in order to provide solutions for miniaturization and experimental results were given to show the achieved performances.

- 2014: Zoran Pandilov and Vladimir Dukovski surveyed the position analysis, Jacobian and singularity analysis, stiffness analysis, dynamics and applications of serial and parallel robots. Also presented a detailed comparison of the characteristics of serial and parallel robots and their advantages and disadvantages.

- 2014: Singh J.V, Mishra Vinay, Sinha A.K presented the importance of parallel manipulator and the basic methodology for design and development of a parallel manipulator.

2.3 Manipulators [1]

A robot manipulator is an electronically controlled mechanism, consisting of multiple segments, that performs tasks by interacting with its environment. They are also commonly referred to as robotic arms. Robot manipulators are extensively used in the industrial manufacturing sector and also have many other specialized applications (for example, the Canadarm [1] was used on space shuttles to manipulate payloads). The study of robot manipulators involves dealing with the positions and orientations of the several segments that make up the manipulators. This module introduces the basic concepts that are required to describe these positions and orientations of rigid bodies in space and perform coordinate transformations.

Manipulators are composed of an assembly of links and joints. Links are defined as the rigid sections that make up the mechanism and joints are defined as the connection between two links. The device attached to the manipulator which interacts with its environment to perform tasks is called the end-effector.

2.4 Classification of Manipulators [1]

Manipulators can be classified according to a variety of criteria. The following are two of these criteria:

2.4.1 By Motion Characteristics:

1. *Planar manipulator:* A manipulator is called a planar manipulator if all the moving links move in planes parallel to one another.

2. *Spherical manipulator:* A manipulator is called a spherical manipulator if all the links perform spherical motions about a common stationary point.

3. *Spatial manipulator:* A manipulator is called a spatial manipulator if at least one of the links of the mechanism possesses a general spatial motion.

2.4.2 By Kinematic Structure:

1. *Open-loop manipulator (or serial robot):* A manipulator is called an open-loop manipulator if its links form an open-loop chain.

2. *Parallel manipulator:* A manipulator is called a parallel manipulator if it is made up of a closed-loop chain.

3. *Hybrid manipulator:* A manipulator is called a hybrid manipulator if it consists of open loop and closed loop chains.

2.5 Degrees of Freedom [1]

The number of degrees of freedom of a mechanism are defined as the number of independent variables that are required to completely identify its configuration in space.

The number of degrees of freedom for a manipulator can be calculated as:

$$\boldsymbol{ndof} = \boldsymbol{\lambda}\,(\boldsymbol{n}-\mathbf{1}) - \boldsymbol{\Sigma}_{\boldsymbol{i}}^{\boldsymbol{k}}(\boldsymbol{\lambda}-\boldsymbol{fi})$$

where n is the number of links (this includes the ground link), k is the number of joints, f_i is the number of degrees of freedom of the i_{th} joint and λ is 3 for planar mechanisms and 6 for spatial mechanisms.

2.6 Introduction to Serial Manipulators [2]

Currently, most existing manipulators present a decidedly anthropomorphic character, usually strongly resembling a human arm. They are constituted of a succession of rigid bodies, each of them being linked to its predecessor and its successor by a one DOF joint, for example allowing the rotation of a rigid body around an axis, or the translatory motion of a rigid body. This architecture will be called a serial robot with analogy to electrical systems. An example of a serial mechanism is the spherical robot, where a succession of segments goes from the base to the “end effector”, each segment being linked to its successor by a revolute joint. If each of the ‘n’ joints is actuated, it will usually be possible to control ‘n’ DOF of the end effector.

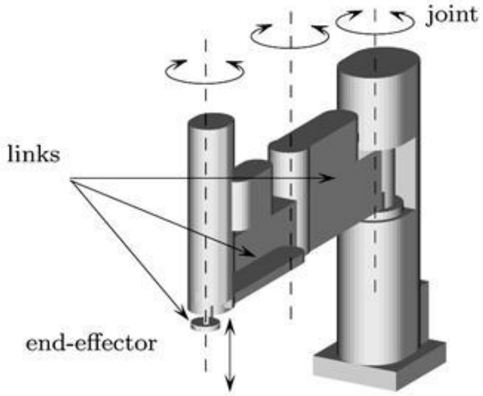


Figure 2.1 The "Scara Robot"

The serial robot Scara [2], as shown in Figure 1.1, represents a good architectural example. It allows the control of 4 DOF from the end-effector.

The main advantage of a serial manipulator is a large workspace with respect to the size of the robot and the floor space it occupies.

2.6.1 Drawbacks of serial manipulators [2]

The low transportable load and poor accuracy are both inherent in the mechanical architecture of existing manipulators, and in particular of the serial disposition of the links. Each of them has to support the weight of the segments following it in addition to the load. They are therefore all subject to large flexure torques, which means they must be stiffened, and thus become heavier. The successive positions of the links, together with the necessity of stiffening them, imply that the moving parts of the robot will have a significant mass. As a consequence, during high velocity motions, the manipulator experiences inertia, centrifugal and Coriolis forces which make the control of the robot complex. Serial robots operate under the action of two kinds of forces: inertia and friction. These forces have different scales: inertia forces essentially vary with the square of the lengths of the links; friction forces are relatively un-affected by such dimensions. This means that one cannot design a micro serial robot simply by scaling down a larger version; under such scaling, the inertia forces are reduced while the friction forces remain relatively unchanged.

Thus, serial robots are inappropriate for tasks requiring either the manipulation of heavy loads, or a good positioning accuracy, or to work at different scales.

2.6.2 Applications of serial robots [1][5]

Robots, basically serial robots, are used in applications that require repetitive tasks over long periods of time, operations in hazardous environments (like nuclear radiation, under water, space exploration, etc.), and precision work with high degree of reliability. They can also be used by handicapped persons to overcome some of their physical disabilities.

Some examples of use of industrial robots are following: machine loading and unloading, palletizing, die casting, forging, press work, arc welding and spot welding, heat treatment, spraying (paint, enamel, epoxy resin and other coatings), deburring, grinding, polishing, injection moulding, cutting (laser, plasma), inspection, assembly, packaging, material handling etc.

Figure 2.2 Arc welding robot

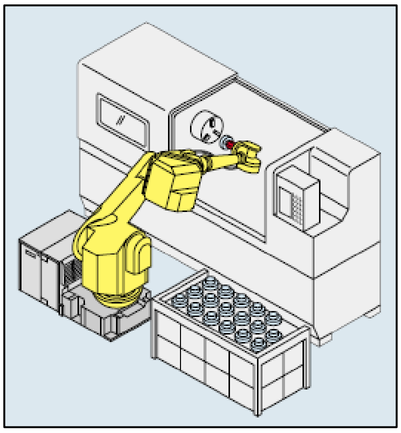


Figure 2.3 Robot application in machine loading and unloading

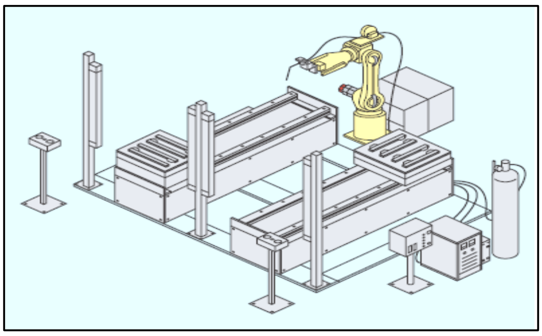


Figure 2.4 Application of robot in welding process

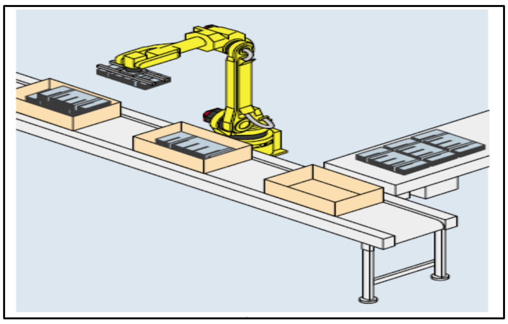


Figure 2.5 Packaging Robot

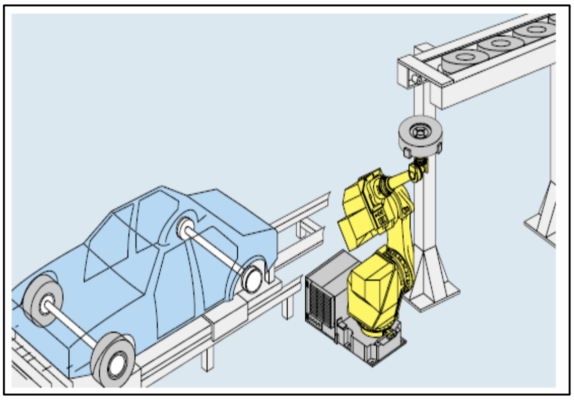


Figure 2.6 Robot application in assembly

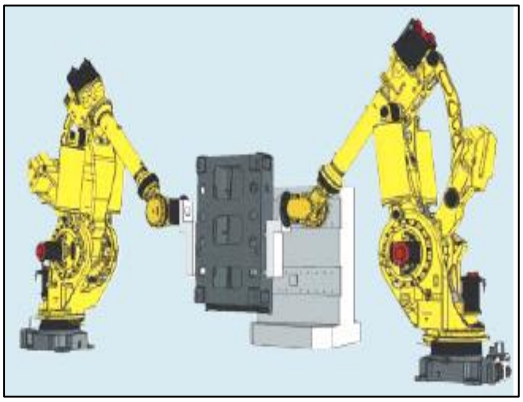


Figure 2.7 Robots in handling heavy objects

2.7 Introduction to Parallel Manipulators [3]

A parallel robot manipulator is composed of two or more closed-loop kinematic chains in which the end-effector (mobile platform) is connected to the fixed base platform by at least two independent kinematic chains. Between the base and end effector platforms are serial chains (called limbs or legs). Typically, the number of limbs is equal to the number of degrees of freedom such that every limb is controlled by one actuator and all actuators can be mounted at or near the fixed base. For this reason, parallel manipulators are sometimes called platform manipulators. Because the external load can be shared by the actuators, parallel manipulators tend to have a large load-carrying capacity.

Parallel manipulators have been used in applications like airplane simulators, adjustable articulated trusses, mining machines, pointing devices, walking machines, machining centres, etc.

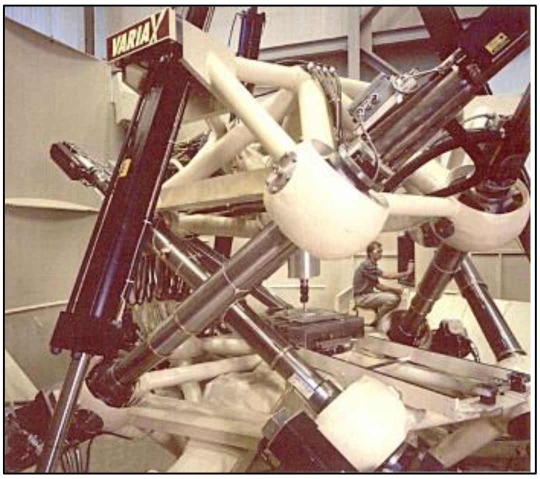


Figure 2.8 Example of parallel robot manipulator [9]

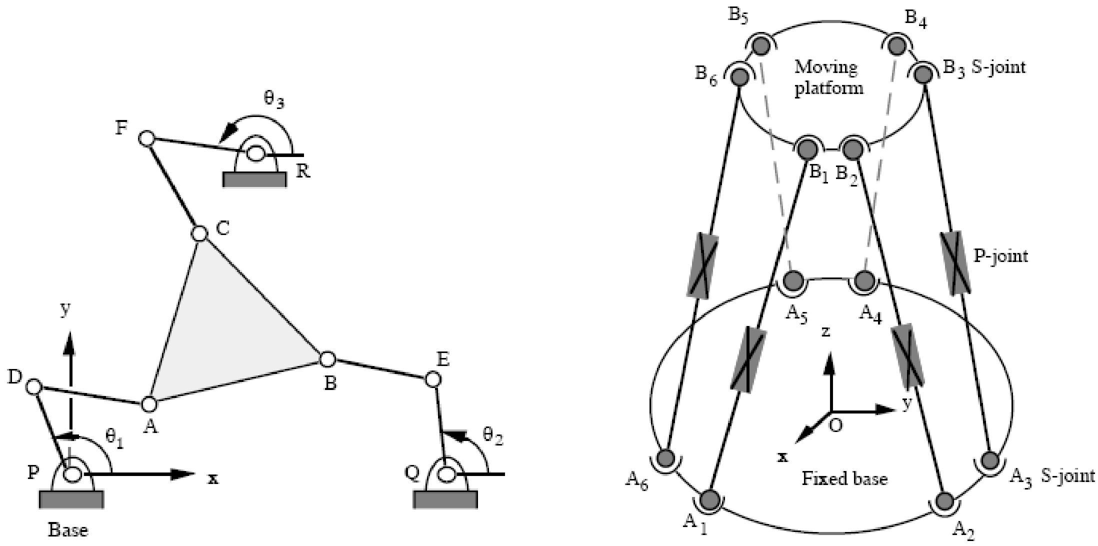
The development of parallel manipulators can be dated back to the early 1960's when Gough and Whitehall first devised a six-linear jack system for use as a universal tire testing machine. Later, Stewart developed a platform manipulator for use as an aircraft simulator. Hunt first made a systematic study of the structural kinematics of parallel manipulators. Since then, parallel manipulators have been studied by numerous researches. More than 100 different mechanical architectures of parallel robots have already been proposed.

Most of the 6-DOF parallel manipulators studied to date consist of six extensible limbs. These parallel manipulators possess the advantages of high stiffness, low inertia and large payload capacity. However, they suffer the problems of relatively small useful workspace, design difficulties and difficult control.

2.7.1 Classification of Parallel Robots [2][12]

In accordance with their motion characteristics, parallel robot manipulators can be classified as:

1. Planar
2. Spherical
3. Spatial manipulators



(a) **(b)**

Figure 2.9 a) Planar parallel robot manipulator
b) Spatial parallel robot manipulator

Position analysis of planar and spherical parallel robot manipulators is easier than position analysis of parallel robot manipulators, or if the spatial manipulator has less than 6 DOF, or if the parallel manipulator is symmetrical.

The parallel manipulator is symmetrical if it satisfies the following conditions [2]:

i. The number of limbs is equal to the numbers of degrees of freedom of the moving platform.
ii. The type and number of joints in all the limbs are arranged in an identical pattern.
iii. The number and location of actuated joints in all the limbs are the same.

When the conditions above are not satisfied, the manipulator is called asymmetrical. For position analysis (direct and indirect kinematics) for parallel manipulators, both vector and algebraic techniques are used.

2.7.2 Advantages of Parallel Manipulators [3] [15]

Following are some advantages as compared to Serial Manipulators:

1. Power actuators are directly connected to the base of the robot with the end effector. So, power actuators serve as structural elements conferring high load capacity even more than its own weight. This way, these platforms have a high proportional ratio of its payload and deadweight providing a high energetic efficiency. (Lazard, 1992).
2. Parallel structures are platforms capable to reach high velocities and develop big forces with a very important advantage: the low cost of manufacturing.
3. Parallel platforms are mechanically less complex than serial robots.

2.7.3 Disadvantages of Parallel Manipulators [3][15]

Parallel robots present some features that, depending on the application can be considered as disadvantages:

1. Kinematics of parallel robots is more complicated. In some occasions redundant sensors are necessary to control the system.
2. Working space is difficult to calculate due to the position and orientation of the end effector is extremely coupled. Several works have been reported about the position and orientation workspace of these platforms (Huan et al., 1999 &Almonacid et al. 2001).
3. Possible singularities are very complex to analyse. Singularities should be analysed specifically for every topology of parallel robot.
4. A general dynamic model for the parallel robot is difficult to obtain in opposite of linear robot. For these reason, parallel robots are controlled nowadays in a decoupling manner.

2.7.4 Applications of Parallel Robots [4][14]

The current applications of parallel robots are in domains such as fine positioning devices, simulators, motion generators (platforms), ultra-fast pick and place robots, machine-tools, medical applications, haptic devices, entertainment, force sensors, micro-robots, articulated trusses, etc.

Figure 2.10 Application of parallel robots

Figure 2.11 Parallel robots for fine positioning of UKIRT

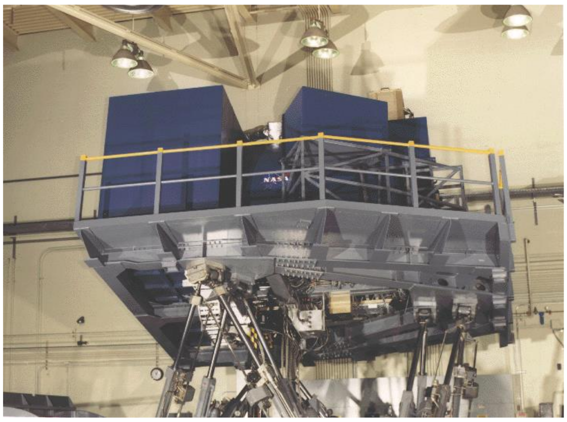


Figure 2.12: Application of parallel robots LARC-simulators

Figure 2.13: Parallel robots as motion simulator NASA platforms

Figure 2.14 Hexapod based machine tool

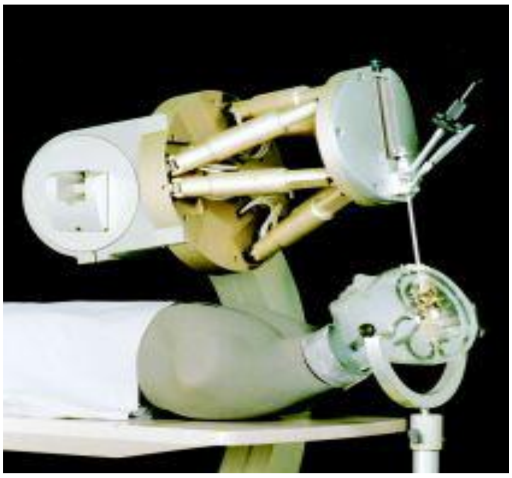


Figure 2.15 Hexapod for brain surgery.

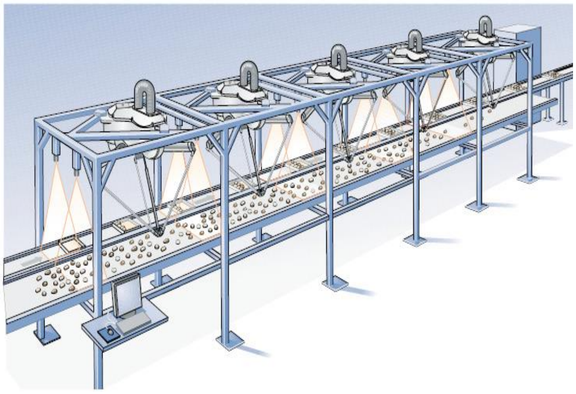


Figure 2.16 Ultra-fast pick and place robot

Figure 2.17 ABB-Flex Picker IRB 340

2.8 Comparison between Serial and Parallel Manipulators

Table.2.1 Comparison between Serial & Parallel Manipulators [10][16][19]

Feature	Serial Manipulator	Parallel Manipulator
Workspace	Large	Small & complex
Solving Forward kinematics	Easy	Very difficult
Solving inverse kinematics	Difficult	Easy
Position Error	Accumulates	Averages
Force Error	Averages	Accumulates

Maximum Force	Limited by maximum actuator force	Summation of all actuator forces
Stiffness	Low	High
Dynamic Characteristics	Poor, especially with increasing size	Very High
Areas of Application	A great number in different areas, especially in industry	Currently limited, especially in industry
Inertia	Large	Small
Payload / Weight Ratio	Low	High
Speed & Acceleration	Low	High
Accuracy	Low	High
Uniformity of components	Low	High
Calibration	Relatively Simple	Complicated
Workspace / Robot size Ratio	High	Low
Load capacity	Low transportable load	High transportable load
Load on actuators	Each link has to support the weight of the segments following it in addition to the load	Each link has to support only the main load
Flexure Torques	Subject to large flexure torques	Subject to lower flexure torques
Weight	Heavier	Lighter
Control	Complex.	Easier
Miniaturization	Not possible	Possible

If we analyse the table 2.1 we will see that both the types of robots have advantages and disadvantages. For example, parallel robots offer potential advantages compared with serial, with higher overall stiffness, higher precision, low inertia, and higher operating speeds and accelerations. However, these advantages could be easy compromised by reduced workspace, difficult mechanical design, and more complex kinematics and control algorithms.

It is really very difficult to say which kind of robotics is better, serial or parallel. A robot selection procedure is very difficult and complex activity. It depends on many different factors like type of application (dangerous, repetitive and boring, precise, etc.), task requirements (dof [1], speed, accuracy, and repeatability), load requirements, workspace, economic justification, programming time, maintaining, etc.

Parallel robots are most successful in applications like motion simulators, ultra-precision positioning devices, medical applications, ultra-fast pick and place robots and micro-robots. But serial robots dominate almost in all manufacturing applications. Probably this will change with continuously solving of the open problems in parallel robotics given in or using hybrid structures. Hybrid structures are, in fact, compromise between advantages and disadvantages of both robot structures, serial and parallel. Most successful manufacturing applications of parallel robots are in fact hybrid structures.

2.9 Parallel Manipulators [12][17]

Parallel manipulators are widely popular recently even though conventional serial manipulators possess large workspace and dexterous maneuverability. The basic problems with serial one are their cantilever structure makes them susceptible to bending at high load and vibration at high speed leading to lack of precision and many other problems. The kinematic chains which connect the platform to base is known as limb. Since the base is connected by many limbs the accuracy of the system is high.

Hence, in applications demanding high load carrying capacity and precise positioning, the parallel manipulators are the better alternatives and the last two decades' points to the potential embedded in this structure that has not yet been fully exploited

Day by day, the applications of the parallel manipulator in various field is become apparent and with a rapid rate utilized in precise manufacturing, medical science and in space exploration equipment.

Motions robots perform during a robotic operation in space can be divided into gross motion and fine motion. Gross motion permits low positioning accuracy, e.g. in obstacle avoidance, while fine motion requires very high positioning accuracies, usually of thousands of an inch, e.g. in mating and de-mating space-rated connectors.

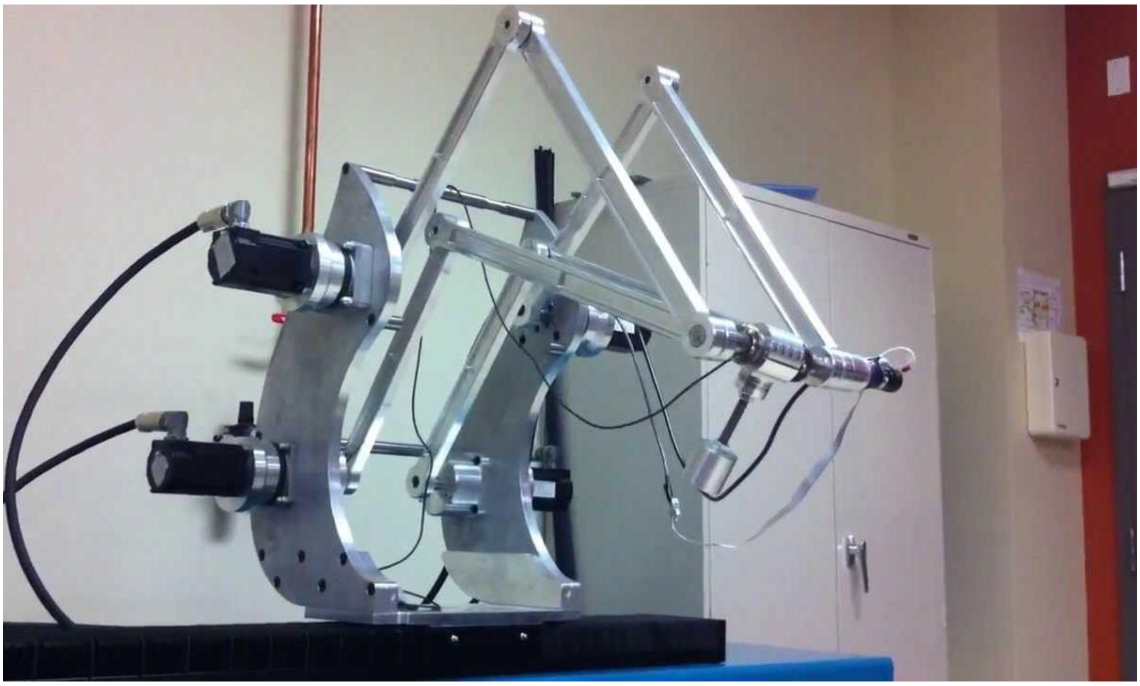


Figure 2.18 Med RUE wrist (for Medical Robot for vascular Ultrasound Examination) collaboration with the Hôpital Notre-Dame, a part of the Centre hospitalier de l'Universitéde Montréal [6]

The potential applications of parallel manipulators include mining machines, walking machines, both terrestrial and space applications including areas such as high speed manipulation, material handling, motion platforms, machine tools, medical fields, planetary exploration, satellite antennas, haptic devices, vehicle suspensions, variable-geometry trusses, cable-actuated cameras, and telescope positioning systems and pointing devices.

2.9.1 Parallel Manipulator Definition [12]

A generalized parallel robot is a closed loop kinematic chain mechanism whose moving platform is linked to the base by several independent kinematic chains. Links are connected to the platform by passive spherical or universal joints. The links therefore feel only compression or traction making them more accurate.

A kinematic chain is an assembly of links connected by joints. When every link in a kinematic chain is connected to other links by at least two distinct paths then it is called a closed loop chain. If every link is connected to its pair by only one path, kinematic chain is called an open loop chain. The combination of these chains is the mechanism, which, forms the basic mechanical structure of any robot.

In parallel manipulator closed-kinematic chain mechanism has been selected for the design of the end-effectors because even though it has relatively small workspace and low maneuverability, it possesses high positioning capability produced by its high structural rigidity and noncumulative actuator errors. Close kinematic chain mechanism also has higher strength-to-weight ratios as compared to open kinematic chain mechanism because the payload is proportionally distributed to the links. In addition, the inverse kinematic problem of the closed kinematic chain mechanism has simple closed-form solutions. Implementation of the CKC mechanism concept first appeared in the Stewart platform. [7]

The positioning accuracy of parallel manipulator is good and that for two reasons:

1. The (unmeasured) deformations of the links due to the flexure are reduced
2. The errors in the internal sensors of the robot (measurement of the lengths of the links) only slightly affect errors on the platform position.

For example, if all the sensors present the same error, the calculation of the pose of the platform based on the sensor measurements will showman error only for the vertical axis: the amplitude of the error will be about the same as the error in the sensors

2.9.2 Characteristics of Parallel Manipulator [17]

1. At least two chains support the end-effectors. Each of those chains contains at least one simple actuator.
2. There is an appropriate sensor to measure the value of the variables associated with the actuation (rotation angle or linear motion).

3. The number of actuators is the same as the number of degrees of freedom of the end-effector.
4. The mobility of the manipulator is zero when the actuators are locked

2.9.3 Usefulness of such system

1. A minimum of two chains allows us to distribute the load on the chains
2. The number of actuators is minimal.
3. The number of sensors necessary for the closed-loop control of the mechanism is minimal.
4. When the actuators are locked, the manipulator remains in its position; this is an important safety aspect for certain applications, such as medical robotics.

2.9.4 Idea of Parallel Robot [1][12][17]

Nature has always been the source of inspiration for the humankind and every new invention and conclusions made by humans have always been related to the nature. Nature has a trial error elimination methodology of reaching to the optimum path for any process, and we only utilize the resulting conclusions. Parallel bots are no different. It can be observed that:

- The bodies of load-carrying animals are more stably supported on multiple, in-parallel legs compared to the biped human. Examples present in our biosphere include bullocks, horses, elephants. They have a much load to self-weight capacity than humans. [8]
- Human beings also use both the arms in cooperation to handle heavy loads for precise work like writing, three fingers are actuated in parallel are used. Even the most professional photographers hold camera with two hands. Shooting from sniper rifle & Handling equipment during an operation(medical)

In general, it can be expected that robot manipulators having the end-effector connected to the ground via several chains having actuations in parallel will have greater rigidity and superior positioning capability. This makes the parallel manipulators attractive for certain applications and the last two decades have witnessed considerable research interest in this direction.

2.9.5 Architecture of Parallel Manipulator [17]

Essentially the parallel manipulator has a base plate and a top plate. The top plate can be moved relative to the base plate in all six degrees of freedom (x, y, z, roll, pitch and yaw). This is accomplished by connecting the top plate to the base plate with six legs. Six legs that can change their relative length in fact move the top plate to an arbitrary location and orientation within its workspace envelope. An important insight with the Hexapod is that each location of the top plate has only one deterministic leg configuration of the six legs. This is one key discovery to facilitate the method to configure the Hexapod.

Parallel manipulators can be visualized in a variety of link arrangement providing more or less the same degrees of freedom. It should be designed keeping in mind the application or payload. The links are generally lead screws which permit a very high degree of freedom motion of the link. It is usually made of steel. Preferably alloy steel with a normalizing for obtaining a standard result. Though thermal effects may not play a major role in final accuracy for temperature differences of 50~100^{o}C. It may raise questions above this range. But this does not imply a need to put elements to counter thermal expansion (like invar) since the application temperature always remains in this range.

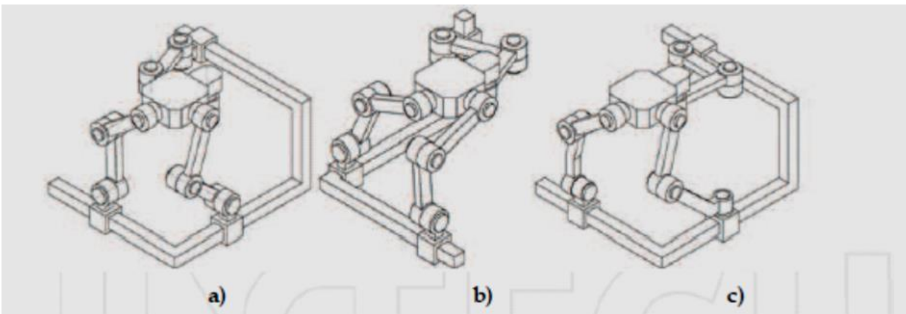


Figure 2.19 PRRR parallel mechanism [10]

Mathematical is the fundamental base for architecture. Here the singularities of the kinematic system are taken as the pivotal factor for designing the possible mechanism.

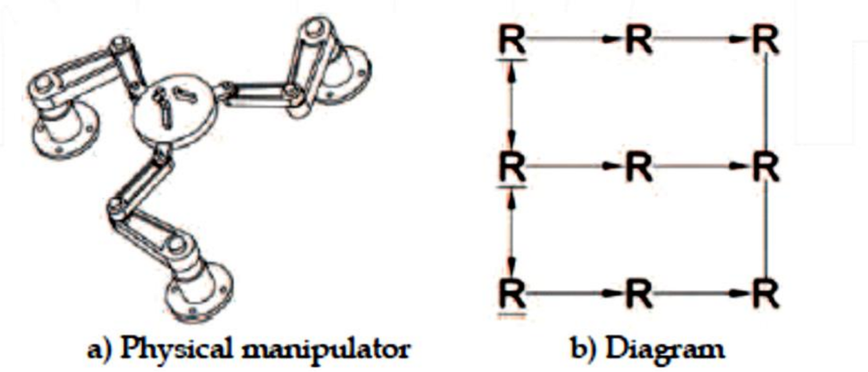


Figure 2.20 RRR parallel manipulator [10]

As pointed out by Stewart in his original paper, there are many possible designs for providing six DOF [10]. One of the obvious designs is a three axis gimbal superimposed on a three axis linear slide system. Stewart rejected this option, because he wanted to achieve the simplest and cohesive design with the highest capabilities in a wide range of applications. The original mechanism proposed by Stewart comprises out of a triangular plane, called the platform, of which each of the three comers is connected through a three-axis joint (spherical joint or ball-and socket joint) to one off the three legs. Each leg is connected to the ground by a two-axis joint (universal joint). Three additional actuators are connected to the three legs. Each additional actuator has one end connected via a rotary joint to the outer-cylinder end of each leg. The other end of each additional actuator is connected to the foundation or base via a universal joint

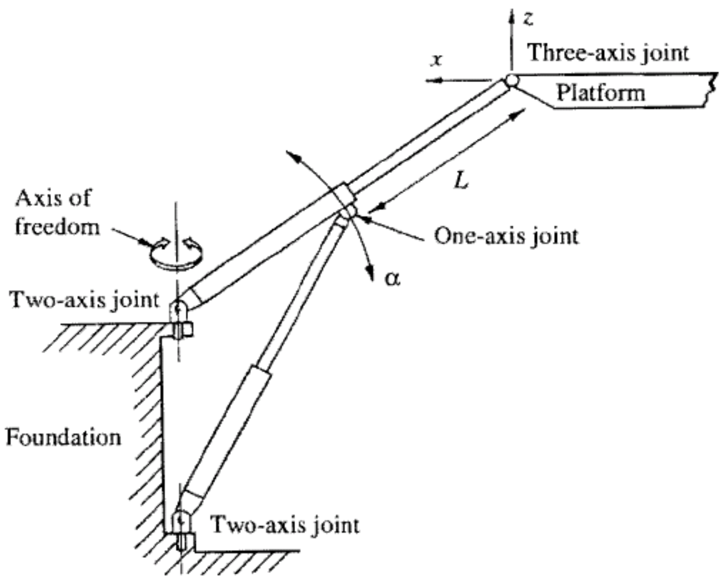


Figure 2.21 Stewart's original platform [10]

Also included in the communications on Stewart's article, are comments by Murdoch and Meier who mention the preferred arrangement that would result from the use of the "linear coordinate leg system". This is a similar arrangement to the one Gough used for his tire test machine, where the actuator foundation, and actuator-platform connecting points are co-planar. A general parallel manipulator has the actuator connection points in any position on the fixed and moving bodies, i.e. the actuator connection points are not restricted to be co-planar

The configuration of a spatial Stewart platform is not the only important design aspect. Equally important is the type of connections with which the actuators are connected to the moving platforms and base. Spatial parallel manipulators can also be described according to the kinematic chains that connect the fixed and moving bodies. For example: a 6-6 Stewart platform with the six linear actuator legs connected to the base and moving platforms via ball-and-socket (spherical) joints can also be labeled as a6-6 Stewart platform with six identical SPS (Spherical-Prismatic-Spherical) chains [10]

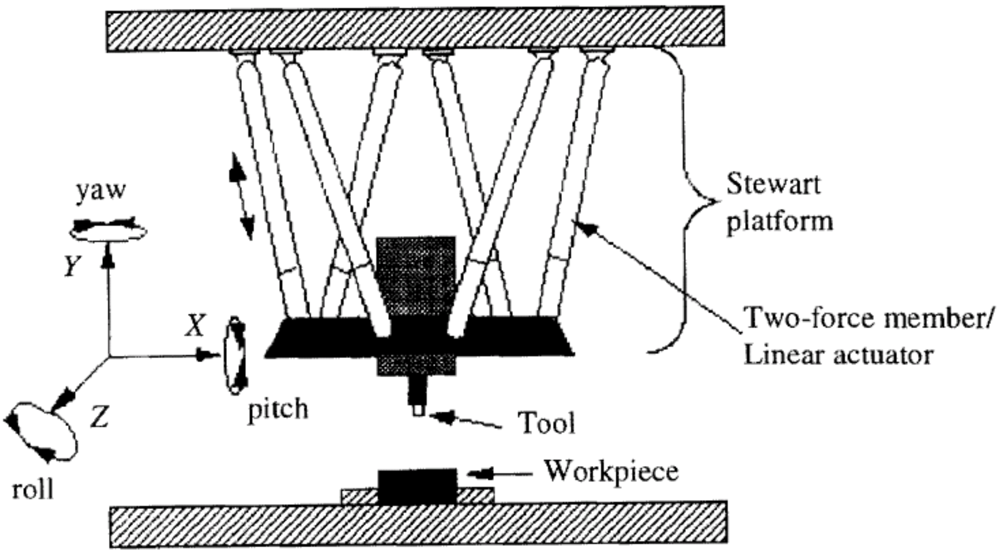


Figure 2.22 Hexapod as a six axis machining centre [19]

Stewart uses I-axis rotary, 2-axes universal and three axes spherical joints in his original platform. With a 6-3 or 3-6 configuration, the actuators are connected to the base with either aspherical or a universal joint, allowing rotation about respectively three or two axes. "Special" ball-and socket joints are to be used to connect the top ends of the actuators in pairs to the moving platform.

Fichter proposes that the ends of the legs be mounted on gimbals (Hooke joints), because if it is designed properly, a gimbal gives a much greater range of motion than a ball-and-socket joint. The platform gimbal is doubled to make the two adjacent legs coincident. The platform gimbal also has a third axis perpendicular to the platform plane, which makes it equivalent to a double ball joint. The base gimbal Fichter uses, has its first revolute axis inclined to the base plate to increase the useful range of motion of the joint

2.9.6 Architecture of Existing Manipulators [2]

The low transportable load and poor accuracy are both inherent in the mechanical architecture of existing manipulators, and in particular of the serial disposition of the links. Each of them has to support the weight of the segments following it in addition to the load: they are therefore all subject to large flexure torques, which means they must be stiffened, and thus become heavier. Positioning accuracy obviously depends on the flexural deformations that are not measured by the robot internal sensors. Moreover, the links magnify errors: a small measurement error in the internal sensors of the first one or two links will quickly lead to a large error in the position of the end-effector. For example, for a one-meter-long arm made up of just one revolute joint, a measurement error of 0.06 degrees leads to an error of 1 mm in the position of the end-effector. The presence of a drive with a reduction gear also induces a backlash which leads to inaccuracy. The violation of the assumed geometric constraints between the axes of the links also constitutes an important source of positioning errors. A slight perpendicularity error between the first two axes of a spherical manipulator will lead to errors in all vertical motions that, given the amplitude of the motions, must be taken into account. Note that the successive positions of the links, together with the necessity of stiffening them, imply that the moving parts of the robot will have a significant mass. As a consequence, during high velocity motions, the manipulator experiences inertia, centrifugal and Coriolis forces that makes the control of the robot complex. Serial robots operate under the action of two kinds of forces: inertia and friction. These forces have different scales: inertia forces essentially vary with the square of the lengths of the links; friction forces are relatively unaffected by such dimensions. This means that one cannot design a micro serial robot simply by scaling down a larger version; under such scaling, the inertia forces are reduced while the friction forces remain relatively unchanged.

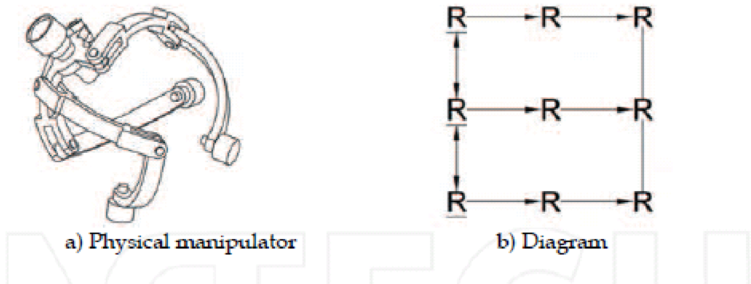


Fig 2.23 Kinematic composition of spherical 3RRR

Architecture of parallel manipulators also have some drawbacks, such as a limited workspace, more constraining singularity loci or a high coupling of kinematics and dynamics. Kinematic coupling [10] is one of the inherent characteristics of parallel manipulators in general. On the one hand, it is helpful in enhancing the rigidity and loading capability of the manipulator, which contributes to the parallel manipulators' applications in the field, such as for numerical control parallel machine tools and flight simulators, where a high loading capability is needed. On the other hand, the strong coupling has actually increased the difficult problems in the kinematic analysis and the control design. Although decoupled parallel manipulators are possibly inferior to general parallel manipulators in rigidity and loading capability, they are very simple in their kinematic solutions and motion controllability design. Therefore, the decoupled parallel robotic manipulators have a broad application prospect in medical mechanisms and micro-operation robots.

2.9.7 Components of Parallel Manipulators [12]

Serial or parallel kinematic chains are concatenated I the robot mechanism. The serial kinematic chain is formed by links connected sequentially by joints, links are connected in series as well as in parallel making one or more closed loops in a parallel mechanism. The mechanical architecture of parallel robots is based on parallel mechanisms in which a member called a moving platform is connected to a reference member by at least two limbs that can be simple or complex. The robot actuators are integrated in the limbs usually closed to the fixed member also called the base or fixed platform.

The terminology used here is mainly established in accordance with the terminology adopted by the International Federation for the Promotion of Mechanism and Machine Science (IFToMM). The main terms used here to describe the structure of parallel manipulator are kinematic pairs (joints) and kinematic links.

2.9.8 Definition of Link

IFToMM terminology defines a link as a mechanism element carrying kinematic pairing elements and a joint is a physical realization of kinematic pair. The pairing element represents the assembly of surfaces, lines or points of a solid body through which it may contact with another solid body. The kinematic pair is the mechanical model of the connection of two pairing elements having relative motion of a certain type and degree of freedom.

2.9.9 Kinematic Chain

A kinematic chain is an assembly of links and joints, and a mechanism is a kinematic chain in which one of its links is taken as a frame.

Frame is a mechanism element deemed to be fixed. The frame/ reference element can be fixed or may merely be deemed to be fixed with respect to other mobile elements. Two or more links connected together in the same link such that they have no relative motion between them can be considered as a single link.

2.9.10 Types of Links

1. *Monary link* - A mechanism element connected in the kinematic chain by only one joint (a link which carries only one kinematic pairing element).
2. *Binary link* - A mechanism element connected in the kinematic chain by two joints (a link connected to two other links).
3. *Polinary link* – A mechanism element connected in the kinematic chain by more than two joints

2.9.11 Open and Closed Kinematic Chain [12]

As per IFToMM terminology *a closed kinematic chain* is a kinematic chain in which each link is connected with at least two other links, and an *open kinematic chain* is a kinematic chain in which there is at least one link which is connected in the kinematic chain by just one point.

In a *simple open kinematic chain* only monary and binary links are connected. In a *complex kinematic chain* at least one polynary link exists.

We designate in each mechanism two extreme elements called reference element and final element. They are also called distal links.

In an open kinematic chain, these elements are situated at the extremities of the chain, in a single loop kinematic chain; the final element can be any element of the chain except the reference element.

In a parallel mechanism, the two distal links are the moving and the reference platform. The two platforms are connected by at least two simple or complex kinematic chains called limbs. Each limb contains at least one joint. A *simple limb* is composed of a simple open kinematic chain in which the final element is the mobile platform. A *complex limb* is composed of a complex kinematic chain in which the final element is also the mobile platform.

2.9.11 Kinematic Pair [12][20]

IFToMM termino0logy defines term *kinematic pair as* a mechanical model of the connection of links having relative motion of a certain type and degree of freedom. The word *joint* is used as synonym for the kinematic pair and also to define the physical realization of a kinematic pair.

Usually the types of lower pairs used in a parallel manipulator are as follows –

a) *Revolute joint* (R): Also known as a hinged joint, it keeps the axes of two rigid bodies together. Two rigid bodies constrained by a revolute pair have an independent rotary motion around their common axis. It has a DOF=1

b) *Prismatic joint* (P): It keeps the two axes if the two rigid bodies aligned and allows no relative motion. The two bodies constrained by this kind joint will be able to have an independent translational motion along the axis. It has a DOF= 1

c) *Spherical joint* (S): A spherical pair keeps two spherical centers together. Two bodies connected by this constraint will be able to rotate relatively around all 3 axes but there will be no relative translation along any of these axes. It has a DOF= 3

d) *Cylindrical joint (C)*: This joint keeps two axes of the two rigid bodies aligned. The two bodies that are part of this kind of system will have an independent translational motion along the axis and a relative rotary motion around the axis. It has a DOF= 2

e) *Helical joint* (H): The *screw pair* keeps two axes of two rigid bodies aligned and allows a relative screw motion. Two rigid bodies constrained by a screw pair a motion which is a composition of a translational motion along the axis and a corresponding rotary motion around the axis. It has a DOF= 1

f) *Universal joint* (U): It is used in cases where there is an axial misalignment present and there is a need to transmit power or torque from one shaft to another.

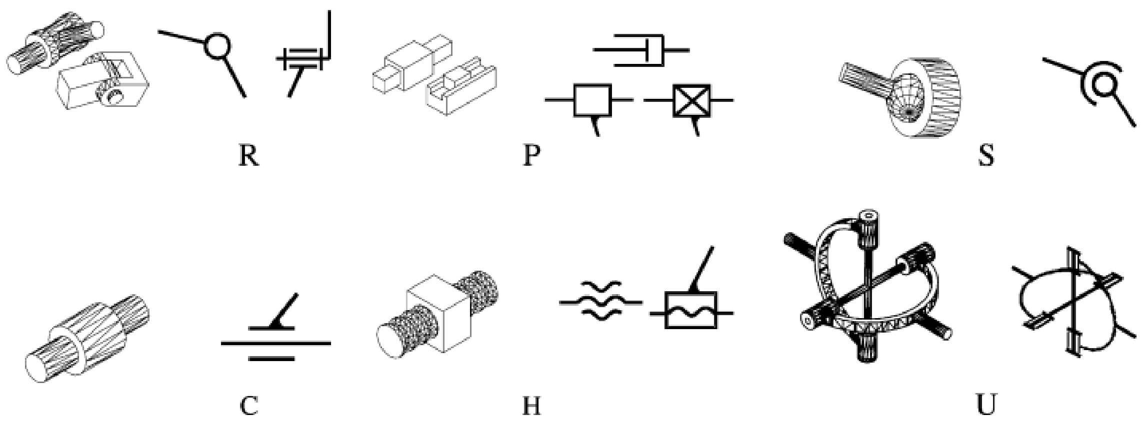


Figure 2.24 Traditional types of pairs [21][22]

The limbs of parallel manipulator can be constructed by having a combination of two to three joints which can be selected from the traditional joints mentioned in the previous page. But the accurate selection of the type and number of joints that make up a limb depends on what DOF is required for the end effector and the second criteria for the selection would be the ease of solving the kinematic equations. For example, although

both the limbs RPS and UPU have 5 DOF, it is hard to determine the kinematic characteristics of their end-effectors because of the coupled motions.

2.9.12 Principle for Type Design of Parallel Manipulator Mechanism [10][23]

Although one has had the theory for calculation of degrees of freedom for planar and spatial mechanisms, the theory cannot be used for analyzing and synthesizing the structural types of parallel robotic mechanisms, which have less than 6 DOF. The reason for this is that the available theory just relates the pairs and links, but the limbs, so that it is hard to calculate the degrees of freedom of some of parallel robotic mechanisms correctly. For example, according to the available theory for calculation of degrees of freedom, the degrees of freedom for the 3-UPU parallel mechanism could be 3, but actually, the mechanism can have 3 or 4 or 5 DOF, which depends on the position of the end-effector. For design of parallel robotic mechanisms with specific kinematic characteristics, it is very important to discuss the limbs with specific kinematic characteristics. For convenience, we let $ be the special Plucker coordinates for describing the displacement of the output link of a limb for a parallel mechanism, which is$\$_j = (v_{xj} v_{yj} v_{zj}, w_{xj} w_{yj} w_{zj})$, Where,$v_j(v_{xj} v_{yj} v_{zj})$expresses the translation of the output link of the limb j, and $w_j(w_{xj} w_{yj} w_{zj})$denotes the rotation of the output link of the limb j with respect to three Euler's angles, a, b and c. The special Plucker coordinates$v_{xj}, v_{yj}, v_{zj}, w_{xj}, w_{yj}, w_{zj}$can be taken as 1 or 0. When taking 1, it means that the limb j has that degree of freedom; when taking 0, it means that the limb j has no that degree of freedom.

In a parallel mechanism, if the parallel mechanism has specific degrees of freedom ($), the limbs 1; 2; ... and n by which the upper platform (moving end-effector) is connected with lower platform (fixed frame) have to satisfy the following condition:

Equation (2): $\$ = \$_1 \cap \$_2 \ldots\ldots \cap \$_n$

Eq. (2) expresses that the special Plucker coordinates of the final motion generated by the € upper platform of a parallel mechanism are equal to the intersection of the special Plucker coordinates of all limbs in the mechanism, which is the principle for type design of parallel

robotic mechanisms with specific degrees of freedom. Eq. (2) is very useful for design of parallel robotic mechanisms with the specific degrees of freedom.

The following table shows the classification of simple limbs for parallel mechanisms, in which the first letter expresses the joint connected with fixed frame (lower platform), and the last letter represents the joint connected with the moving platform (upper platform).

For instance, the limb UPS means that the limb is connected with fixed frame by the joint U and linked with moving platform by the joint S.

Table 2.2 Classification of simple limbs

DOF	Pairs	Types of limbs
6	P, S, S	SPS, PSS
	U, P, S	UPS, PUS
	R, S, S	RSS, SRS
	U, R, S	URS, RUS
5	R, R, S	RRS, RSR
	R, P, S	RPS, RSP, PRS, PSR
	P, U, U	PUU, UPU
4	P, U, R	PUR, PRU, UPR, RPU
3	R, R, R	RRR
	R, P, R	RPR, PRR
	H, R, P	HRP, PRH, RPH
2	R, R	
	P, R	PR, RP

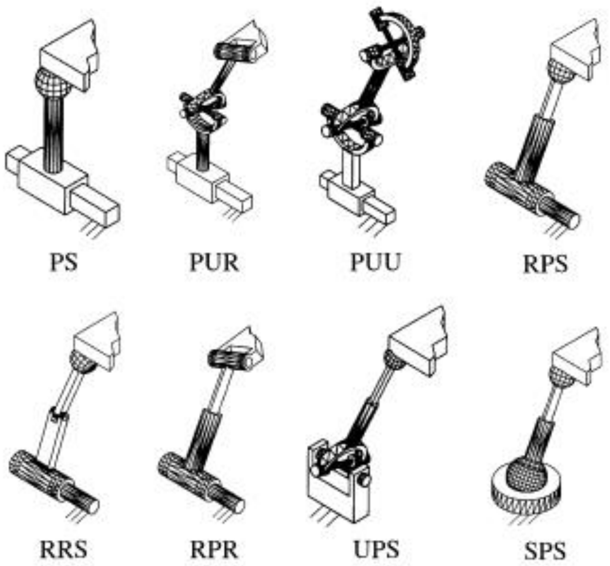


Figure 2.25 the limbs with traditional structure [24]

2.10 Types of Actuators [26]

a) Electro Mechanical Actuator:

Typically, an electric motor is mechanically connected to rotate a lead screw. A lead screw has a continuous helical thread machined on its circumference running along the length (similar to the thread on a bolt). Threaded onto the lead screw is a lead nut or ball nut with corresponding helical threads. The nut is prevented from rotating with the lead screw (typically the nut interlocks with a non-rotating part of the actuator body).

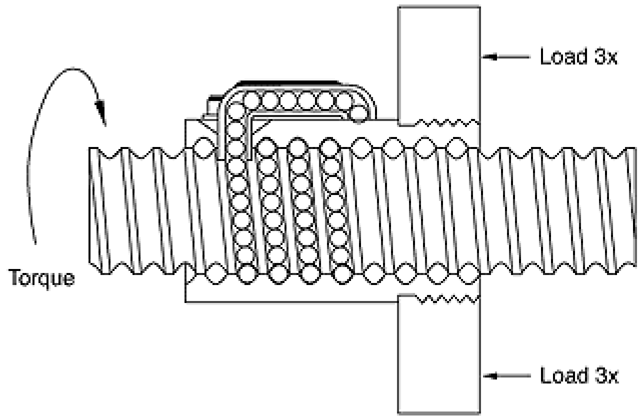


Figure 2.26 Ball Screw

Therefore, when the lead screw is rotated, the nut will be driven along the threads. The direction of motion of the nut depends on the direction of rotation of the lead screw. By connecting linkages to the nut, the motion can be converted to usable linear displacement. Most current actuators are built for high speed, high force, or a compromise between the two. When considering an actuator for a particular application, the most important specifications are typically travel, speed, force, accuracy, and lifetime.

b) Hydraulic Actuator:

Hydraulic cylinders get their power from pressurized hydraulic fluid, which is typically oil. The hydraulic cylinder consists of a cylinder barrel, in which a piston connected to a piston rod moves back and forth.

The barrel is closed on one end by the cylinder bottom (also called the cap) and the other end by the cylinder head (also called the gland) where the piston rod comes out of the cylinder. The piston has sliding rings and seals. The piston divides the inside of the cylinder into two chambers, the bottom chamber (cap end) and the piston rod side chamber.

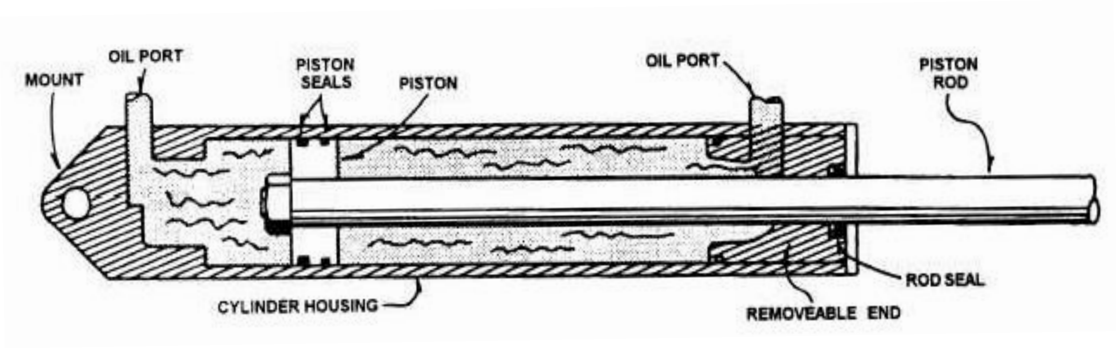


Figure 2.27 Hydraulic Actuator

A hydraulic cylinder is the actuator or "motor" side of this system. The "generator" side of the hydraulic system is the hydraulic pump which brings in a fixed or regulated flow of oil to the hydraulic cylinder, to move the piston. The piston pushes the oil in the other chamber back to the reservoir. If we assume that the oil enters from cap end, during extension stroke, and the oil pressure in the rod end / head end is approximately zero, the force F on the piston rod equals the pressure P in the cylinder times the piston area A.

b) *Pneumatic Actuator:*

Pneumatic actuators, or pneumatic cylinders, are similar to hydraulic actuators except they use compressed gas to generate force instead of a liquid. They work similarly to a piston in which air is pumped inside a chamber and pushed out of the other side of the chamber. Air actuators are not necessarily used for heavy duty machinery and instances where large amounts of weight are present. One of the reasons pneumatic linear actuators are preferred to other types is the fact that the power source is simply an air compressor. Because air is the input source, pneumatic actuators are able to be used in many places of mechanical activity. The downside is, most air compressors are large, bulky, and loud. They are hard to transport to other areas once installed. Pneumatic linear actuators are likely to leak and this makes them less efficient than mechanical linear actuators.

c) Piezoelectric Actuator:

This type of actuator uses the principle of piezoelectric effect for their actuation process. The piezoelectric effect is a property of certain materials in which application of a voltage to the material causes it to expand. Very high voltages correspond to only tiny expansions. As a result, piezoelectric actuators can achieve extremely fine positioning resolution, but also have a very short range of motion. In addition, piezoelectric materials exhibit hysteresis which makes it difficult to control their expansion in a repeatable manner.

The below table give us an idea about how the final DOF of a system is achieved

Table 2.3 Classification of Parallel Robot Mechanisms [28]

DOF	Each number is the DOF of each limb	Examples	Characteristics of structures	Kinematic performance of upper platform	
				Rotations	Translations
2	2, 2	2-$^{P}\underline{U}$	Planar	0	2
	3, 2	1-RRR & 1-$^{P}\underline{U}$		0	2
		1-RPR & 1-$^{P}\underline{U}$		0	2
	3, 2	3-RRR & 1-RR	Planar		
		1-RPR & 1-RP			
	6, 2	1-UPS & 1-$^{P}\underline{U}$	Planar	0	2
3	3, 3, 3	3-RRR	Spherical	3	0
		3-RRR	Planar	1	2
		3-RPR		1	2
		3-PRR		1	2
		3-P$\underline{U^*}$	Spatial	0	3
		3-$\underline{U^*}$P		0	3
	4, 4, 4	3-P$\underline{U^*}$R	Spatial	0	3
		3-P$\underline{\hat{}U}$R		0	3
		3-C$\underline{U\hat{}}$		0	3
		3-$\underline{\hat{}U}$C		0	3
		3-RPC		0	3
		3-RRC		0	3
	5, 5, 5	3-P$\underline{U^*}$U	Spatial	0	3
4	5, 5, 4, 4	2-PUU & 2-P$\underline{U^*}$R	Two axes of pairs	1	3
		2-PUU & 2-P$\underline{\hat{}U}$R	R are parallel	1	3
	6, 6, 4, 4	2-PUS & 2-P$\underline{U^*}$R	each other	1	3
		2-PUS & 2-P$\underline{\hat{}U}$R		1	3
	6, 6, 6, 4	3-PUS & 1-$^{P}\underline{U}$U		2	2
		3-PUS & 1-P$\underline{U^*}$R		1	3
		3-PUS & 1-P$\underline{\hat{}U}$R		1	3
5	6, 6, 6, 6, 5	4-PUS & 1-P$\underline{U^*}$U		2	3
		4-PUS & 1-P$\underline{\hat{}U}$U		2	3
		4-SPS & 1-P$\underline{U^*}$U		2	3

2.11 Open Problems in Field of Parallel Manipulator

In dynamics and control:

- Study of the dynamic behavior of the manipulator through extensive simulation and analytical/numerical tools for ODE systems.
- Exploration of possibilities of specialized control strategies which will take advantage of the parallel structure of the manipulator and will offer improved performance.
- Derivation of theoretical results regarding controllability and observability issues.
- Exploration of redundancy resolution schemes for statically redundant Stewart platform

In workspace and singularity:

- A detailed easy-to-use description of the workspace.
- Complete characterization of the singularity manifold.
- Study of the workspace partitioning by the singularity manifold.
- Workspace synthesis for the Stewart platform.
- Establishment of existence criteria for singularity-free paths with given end-poses.

In design:

- Optimal kinematic synthesis of the Stewart platform for well-conditioned workspace.
- Development of statically redundant Stewart platform and study of its characteristics.
- Comparison of non-redundant and redundant Stewart platforms regarding performance and assessment of the advantages and costs of redundancy.
- Developing and designing new types of kinematic joints for getting desired kinematic characteristics.
- Designing smaller joints having high accuracy and repeatability.

2.12 Conclusion from Literature Survey:

As the field of robotics [10] originated with serial manipulators and for a long time they were the only type of manipulators in existence, the techniques for kinematic and dynamic analysis of robot manipulators were developed specially for that class of manipulators. Those techniques are often not appropriate for the analysis of the Stewart platform in particular and of parallel manipulators in general in the sense that, applied to parallel manipulators, they tend to approach the problems in a roundabout way and increase computational complexity. Hence, for the kinematic and dynamic analysis of parallel manipulators, new perspectives and methods may have to be employed keeping in view their distinctive features as compared to their serial counterparts. In addition, the new problems that arise in the parallel manipulators have to be understood and solved to pave the way for their effective application in situations where they are expected to offer better performance

Secondly, supporting of the payload and precise positioning have to be recognized as the primary role of a parallel manipulator and design should be based on the criteria of stiffness and rigidity. In general, it has to be understood that the different nature of parallel manipulators, compared to their conventional serial counterparts, calls for unconventional strategies and novel concepts for analysis and design.

Chapter 3

Design Methodology

3.1 Design Constraints:

The CAD model of the hexapod was made keeping all the mechanical constraints in position.

Table 3.1: Constraints applied to Hexapod Model

Part-Part	Motion required	Type of constraint used
Base plate	nil	DEFAULT
Base plate- Hinge	-	RIGID
Knuckle-Yoke	1 DOF-rotation	PIN
Yoke-Block	-	RIGID
Block-Yoke	-	RIGID
Yoke-knuckle	1 DOF- rotation	PIN
Knuckle-Actuator base plate	-	RIGID
Actuator base plate-motor	-	RIGID
Actuator base plate-housing	-	RIGID
Motor-Spline shaft	1DOF-rotation	PIN
Spline Shaft-Nut	1 DOF-linear	SLIDER
Nut-Nut shell	-	RIGID
Nut shell –Knuckle	-	RIGID
Knuckle-Yoke	1 DOF-rotation	PIN

Yoke-Block	-	RIGID
Block-Yoke	-	RIGID
Yoke-Knuckle	1 DOF- rotation	PIN
Knuckle-Top plate	6 DOF	GENERAL

The above table shows constraints applied to the main Hexapod Assembly. Assembly of hexapod requires the constraints to be perfect. Any discrepancy in assembly can restrict the motion of the assembly and fail to create the required motion of model.

3.2 Modelling Tree:

Design of model was completed in a three stage tree. The primary modelling was done by distributing the model into the important sub-assemblies. The primary sub-assemblies were hinge, linear actuator, plate selections. The complex components such as linear actuator were further broken in to screw-nut assembly, motor-housing-spline shell assembly. The breaking of model allows fast and efficient modelling. This also enables problem oriented remodelling of the specific part. The remodelled parent part automatically adjusts to its position in the assembly unless the references have not been changed. The model consists of multiple sub-assemblies hence reduces the complexity of finding errors and correcting it.

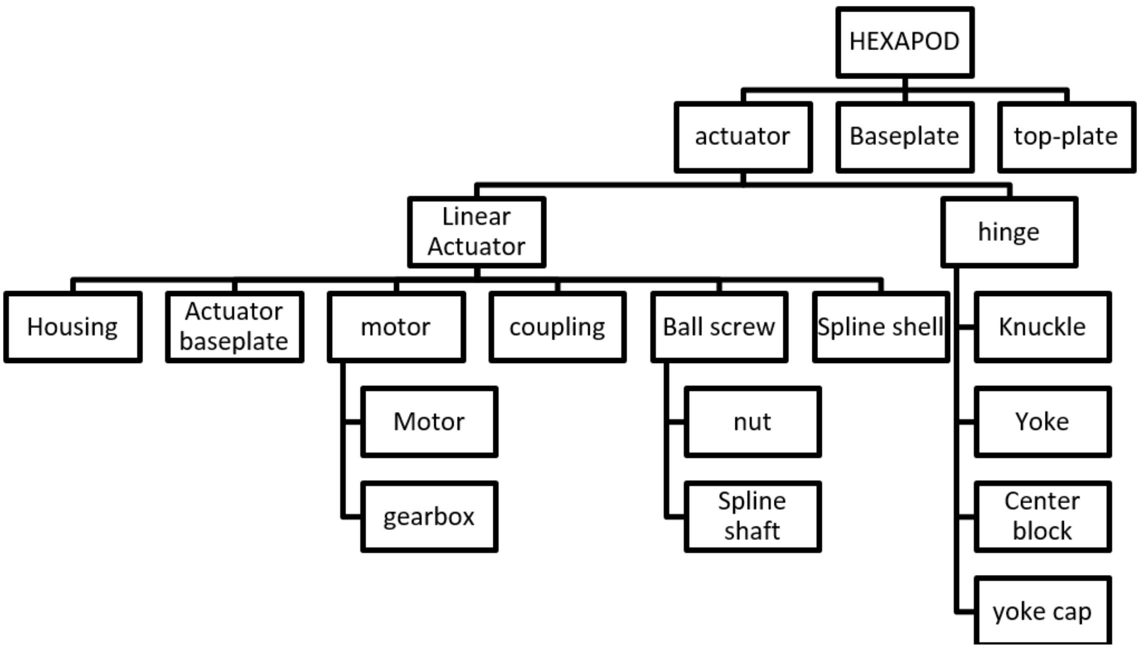


Figure 3.1 Modelling Tree

Assembly of parts was done in the above shown order. The above sequence allows the designer to concentrate on individual parts and assemble it as per the actual manufacturing order. This prevents the problems in manufacturing. Also the model has more chance of getting approved by the manufacturing department without being sent back for remodelling, citing manufacturing difficulties.

3.3 Mechanism Building and animation:

Testing the model and singularity analysis is a vital part of completion of design. The model has also been animated to complete the motion as required. The constraints on the parts were applied as per the table.

Two types of animation were done

1. *To check the mechanism freedom, interference with parts and actuation limits*:
   This part was done for initial passing of model for applying further complex 3d equation. In this part only 1or 2 actuators were linearly actuated with other links dependent on then. The model could produce translation and rotation of unknown magnitude in this stage. The animation allowed us to decide the limits our model can be actuated by trial-error method.
2. *To fix position of point on top plate and corresponding actuator length required*:

This part pertained to the actual application of the hexapod of precision positioning. The length of actuators was solved using MATLAB and the coordinate transferred to excel sheet. The positions were further fed into the animation software. This animation shows the actual dynamics of the model in application.

Chapter 4

Design Calculations

4.1 Design of Hinge Joint:

Material Selection:

Selecting Corrosion resistant alloy steel and Nickel based coating 6 & 6A as the material for hinge ……. (From Mahadevan Design Data Book)

$$[\sigma_u] = 480 N/mm^2$$

$$[\sigma_y] = 210\ N/mm^2$$

Taking FOS = 4.5

Therefore,

$$[\sigma_T] = \frac{[\sigma_u]}{4.5} = 46.67\ N/mm^2$$

$$\tau = 0.5[\sigma_T] = 23.335\ N/mm^2$$

4.1.1 Design of Yoke:

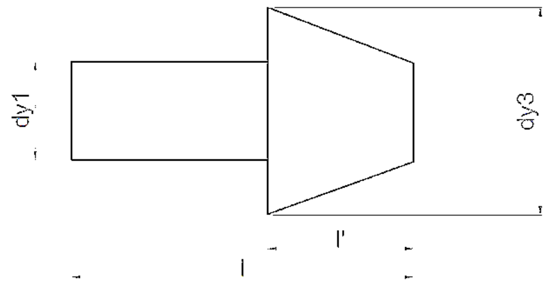


Figure 4.1 Yoke

Crushing of hinge at hole for yoke,

Taking,

$$[\sigma_{cr}] = 2.6[\sigma_T] = 74.67\mathrm{N}/mm^2$$

$$[\sigma_{cr}] = \frac{P}{d_y \times l'} = \frac{10 \times 9.81}{d_y \times l'}$$

$$\therefore\ d_y \times l' = 1.31mm^2$$

Considering shear of yoke,

$$\tau = \frac{P}{\pi/_4 \times {d_y}^2}$$

$$\therefore\ d_{y_1} = 2.313\ mm$$

Taking,

$$d_{y_1} = 4\ mm$$

$\therefore$ Length of yoke in hinge,

$$d_y \times l' = 1.31\ mm^2$$

$$\therefore l' = 0.3275\ mm$$

Taking, $l' = 5mm$

Therefore, Induced crushing strength,

$$\sigma_{cr_{ind}} = \frac{P}{d_y \times l} = 4.905 < [\sigma_{cr}]$$

Taking, Total length of yoke,

$$l = 10\ mm$$

Giving a taper of 20:100 mm for the yoke,

Since, $l = 10\ mm$

$\therefore\ d_{y_3} = 6\ mm$ ……. (as $d_{y_1} = 4\ mm$)

4.1.2 Design of Clamp:

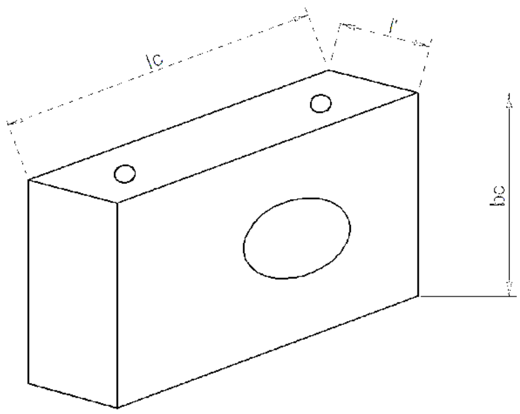


Figure 4.2 Clamp

Taking length of clamp as,

$$l_c = d_y + 2d_n + c$$

Taking, $d_n = 3.2\ mm$

$$clearance\ (c) = 10\ mm$$

$$\therefore\ l_c = 4 + (2 \times 3.2) + 10 = 20.4\ mm$$

$$\therefore\ l_c = 20.4\ mm$$

Taking, $l_c = 22mm$

∴ For clamp,

$$l_c = 22mm$$

$$l' = 5\ mm$$

Taking, $b_c = \ d_y + c$

$$b_c = 4 + 3 = 7\ mm$$

Checking for induced shear stress in hole of clamp after it is cut into half.

$$\therefore\ \tau = \frac{P}{2 \times l' \times {}^{b_c}/_{2}} = \frac{10 \times 9.81}{2 \times 5 \times {}^{7}/_{2}}$$

$$\therefore \tau = 2.8\frac{N}{mm^2}\ < [\tau] = 23.335\frac{N}{mm^2}$$

Taper diameter of hole inside clamp:

As taper of yoke is 20:100 i.e. 1:5 mm and d_y = 4 mm and l’ = 5 mm

$$\therefore\ d_{y_2} = 5mm$$

4.1.3 Design of hinge body:

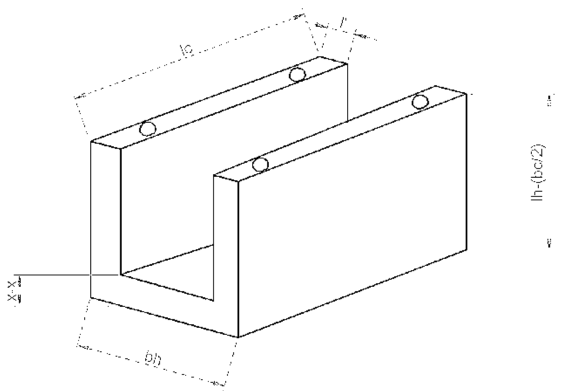


Figure 4.3 Hinge Body

Considering shear failure at section X-X

$$\therefore \tau = \frac{P}{l_c \times (X - X)}$$

$$\therefore (X - X) = \frac{P}{\tau \times l_c}$$

$$\therefore (X - X) = 0.19\ mm$$

Taking, $(X - X) = 2mm$

Therefore, the induced shear stress is,

$$\tau_{ind} = \frac{P}{(X - X) \times\ l_c}$$

$$\tau_{ind} = \frac{10 \times 9.81}{2 \times 22}$$

$$\tau_{ind} = 2.23 \frac{N}{mm^2} < [\tau] = 23.335\ N/mm^2$$

Breadth of hinge:

$$b_h = (diameter\ of\ connector\ of\ actuator) + (length\ of\ yoke\ in\ block) + (length\ of\ yoke\ between\ hinge\ \&\ block) + (width\ of\ clamp)$$

$$b_h = 29 + (2 \times 5) + (2 \times 5)$$

$$b_h = 49\ mm$$

Selection of nuts & bolts:

Selecting bolts of diameter = 3.2 mm

Checking for bearing stress,

$$[\sigma_{br}] = 0.5\ [\sigma_t] = 23.335 \frac{N}{mm^2}$$

Consider bearing failure of 3.2 mm diameter bolt inside the hinge

$$\therefore [\sigma_{br}] = \frac{P}{d_n \times l_n}$$

Where, l_n is the length of bolt.

$$\therefore l_n = \frac{10 \times 9.81}{3.2 \times 23.335}$$

$$\therefore l_n = 1.314\ mm$$

Taking, $l_n = 14\ mm$

Taking, $$l_h = l_n + c$$

Taking clearance as 5mm

$$l_h = \ l_n + 5$$

$$l_h = 19mm$$

Checking for bearing stress induced in nuts with $l_n = 14mm$

$$\sigma_{br_{ind}} = \frac{P}{d_n \times l_n}$$

$$\sigma_{br_{ind}} = \frac{10 \times 9.81}{3.2 \times 14}$$

$$\therefore \sigma_{br_{ind}} = 2.189 \frac{N}{mm^2} < [\sigma_{br}] = 23.335 \frac{N}{mm^2}$$

Further,

Diameter of hole in block (d_b) = 6mm

4.2 Design of Actuator:

Components of actuator-

1. Ball screw and nut
2. Motor selection
3. Housing
4. Coupling
5. Screw casing shaft

4.2.1 Ball Screw Selection:

Calculating the Maximum Axial Load

Guide surface resistance (f) = 20 N (without load)

Axial load (m) = 10 kg

Maximum speed (Vmax) = 0.3 m/s

Acceleration (a) = 2mm/sec

Accordingly, the required values are obtained as follows.

- During upward acceleration:

$$F_{a_1} = (m \times g) + f + (m \times a) = 118.12\ N$$

- During upward uniform motion:

$$F_{a_2} = (m \times g) + f = 98.12\ N$$

- During upward deceleration

$$F_{a_3} = (m \times g) + f - (m \times a) = 118.08\ N$$

- During downward acceleration:

$$F_{a_4} = (m \times g) - f - (m \times a) = 78.08\ N$$

- During downward uniform motion:

$$F_{a_5} = (m \times g) - f = 78.12\ N$$

- During downward deceleration

$$F_{a_6} = (m \times g) - f + (m \times a) = 78.12\ N$$

Thus, the maximum axial load applied on the Ball Screw is as follows:

$$F_{a_{max}} = F_{a_1} = 118.12\ N$$

Buckling Load of the Screw Shaft

Factor according to the mounting method (η_2) = 20 …… (from THK Catalogue, A-712)

Since the mounting method for the section between the nut and the bearing, where buckling is to be considered, is "fixed-fixed".

Distance between two mounting surface (l_a) = 150 mm (estimate)

Screw-shaft thread minor diameter (d_1) =11.8 mm

Permissible Compressive and Tensile Load of the Screw Shaft

P_2 = 116 d_{12} = 116 × 11.82 = 16151.84 N

Thus, the buckling load and the permissible compressive and tensile load of the screw shaft are at least equal to the maximum axial load. Therefore, a Ball Screw that meets these requirements can be used without a problem.

Maximum Rotational Speed:

Shaft Diameter = 14 mm

Lead = 4 mm

Maximum Speed = 2 mm/s

$$\therefore N_{max} = \frac{V_{max} \times 60}{Lead} = 30\ min^{-1}$$

Permissible Rotational Speed:

It is determined by the dangerous speed of the Screw Shaft

Factor according to the mounting method, (η_2) = 15.1 …… (from THK catalogue, A-714)

Since the mounting method for the section between the nut and the bearing, where dangerous speed is to be considered, is "fixed-supported".

Distance between two mounting surfaces (l_b) = 150 mm (estimate)

Screw shaft diameter = 14mm;

Lead = 4 mm:

Screw-shaft thread minor diameter (d_1) = 11.8 mm

$$\therefore \text{N} = 7919.1 \text{ rpm}$$

Thus, the dangerous speed and the DN value of the screw shaft are met.

Selecting a Nut Model Number

The Rolled Ball Screw with a screw shaft diameter of 14 mm and a lead of 4 mm is the following large-lead Rolled Ball Screw model.

DIK 1404-04 whose C_a = 3 kN & C_{0_a}= 5.1 kN

Studying the Permissible Axial Load

Assuming that an impact load is applied during an acceleration and a deceleration, set the static safety factor (FOS) at 3 …… (Table 21 on A-721 of the THK Catalogue).

$$F_{max} = {}^{5100}/_{3} = 1700\ N$$

The obtained permissible axial load is greater than the maximum axial load of 100 N, and therefore, there will be no problem with this model.

Average Axial Load (F_{avg}) = 100 N

Dynamic load rating (C_a) = 3000 N

Load factor (f_w) = 1.5 …… (Table 22 on A-722 of the THK Catalogue)

Average load (F_m) = 100 N

Nominal life (L) $= 8 \times 10^9$ revolutions

Calculating the Service Life Time on the Basis of the Nominal Life

Nominal life (L) = 2.34×10^9 rev

Average revolutions per minute (N_m) = 305 min^{-1}

∴ Service Life Time (Ln) = 43, 718 hrs

Calculating the Service Life in Travel Distance on the Basis of the Nominal Life

Nominal life (L) = 8×10^9 rev

Lead (P_h) = 4 mm

∴ L_s = L × $P_h \times 10^{-6}$ = 32000 km

With all the conditions stated above, model DIK 1404-04 satisfies the desired service life time of 20,000 hours.

Safety Factor selection:

Given that the static load rating is 5.1 kN

Static Safety Factor is initially selected $f_s = 3$ from Table 21, A721 of the THK Catalogue,

Therefore, Maximum force per actuator is,

$$F_{amax} = \frac{Static\ Load\ Rating}{Static\ Safety\ Factor}$$

$$F_{amax} = \frac{5.1}{3} = 1.7\ kN$$

$$\therefore\ F_{amax} = 1700\ N$$

For the intended design load of 100 N per actuator,

$$Safety\ Factor = \frac{1700}{100} = 17$$

Limiting Lower Safety Factor = 5

Maximum load that can be taken as,

$$Load_{max} = \frac{1700}{5} = 340\ N$$

4.2.2 Motor Selection:

Motor selection was done based on the following requirements

v = 2 mm/s

a = 2 mm/s^2

Driving force required at ball screw,

$$T = \frac{F\ \times P}{2 \times \pi \times \eta}$$

$$T = \ \frac{10 \times 4}{2 \times \pi \times 0.95}$$

$$T\ = 6.701\ kg - mm$$

For FOS = 2,

$$T'\ = 13.4\ kg - mm$$

$$T'\ = 2kg - cm$$

Rotation of ball screw per second,

$$N = \frac{Distance\ per\ second}{Distance\ per\ rotation\ of\ scew}$$

$$N\ = \ \frac{2}{4} = 0.5\ rps$$

Angular velocity of ball screw = $2 \times \pi \times N\ = 3.14 \frac{rad}{s}$

Further,

$$Power\ required\ \ = \ Torque\ \times\ Angular\ Velocity$$

$$= 0.004 \times 314$$

$$= 1.256\ W$$

Therefore, power required by motor is assumed to be 2W.

From the catalogue of “Maxon Motors”, we select standard motor as “DCX14L”

4.2.3 Design of Housing:

Purpose: Primary purpose is to protect the system from dust particles and enclose the moving parts. This will make it aesthetically more appealing and safe. The housing should not interfere with the working of system. It also provides a slot which can limit the translator motion of the ball screw nut.

Material: Housing is made of aluminium sheet of 2 mm thickness to reduce thickness and cost.

4.2.4 Coupling Design & Selection:

In order to convert input shaft to motor shaft and output shaft to end of ball screw

Taking into consideration the axial misalignment and space constraints, we select Muff Coupling.

Material Selection:

Using C30 material for casing, keys and bolts.

We know that,

Torque being transmitted (T) = 0.2 Nm

Input Shaft Diameter = 3 mm

Output Shaft Diameter = 14 mm

Using empirical relations,

Outer diameter of sleeve = 2d + 10 ≈ 40 mm

Length of coupling (L) = 3.5d ≈ 50 mm

At one end of the coupling, a hole of 14 mm diameter and depth 20 mm is made.

At the other end of the coupling, a hole of 3 mm diameter and depth 15 mm is made.

At the side of the ball screw:

Key Selection:

From PSG Design Data Book Page 5.21

For the diameter of shaft = 14 mm

Taper Key is selected of dimensions:

b = 5 mm

h = 5 mm

depth of keyway in shaft (t_1) = 3 mm

depth of keyway in hub/sleeve (t_2) = 1.7 mm

Checking for failure:

For C30 material,

$$[\sigma_y] = 300\ \mathrm{N/mm^2}$$

Taking FOS = 6

Therefore,

$$[\sigma_T] = \frac{[\sigma_y]}{6} = 50\ N/mm^2$$

$$\tau = 0.5[\sigma_T] = 25\ N/mm^2$$

Assuming length of key = 20 mm

Checking for failure under shear stress

$$Torque\ = b \times l \times\ \tau_{ind} \times \frac{d}{2}$$

$$0.2 \times 10^3\ = 5 \times 20 \times\ \tau_{ind} \times \frac{14}{2}$$

$$\tau_{ind} = \frac{200}{5 \times 20 \times 7} = 0.285 \frac{N}{mm^2}$$

$$\therefore \tau_{ind} \ll [\tau] = 25\ N/mm^2$$

Checking for crushing stress in sleeve portion

$$Torque\ = t_2 \times l \times\ \sigma_{ind} \times \frac{d}{2}$$

$$200\ = 1.7 \times 20 \times\ \sigma_{ind} \times \frac{14}{2}$$

$$\sigma_{ind} = \frac{200}{1.7 \times 20 \times 7} = 0.84 \frac{N}{mm^2}$$

$$\therefore \sigma_{ind} \ll [\sigma_c] = 50\ N/mm^2$$

Hence safe in torque transfer.

Checking for safety of sleeve,

$$T = \tau_{ind} \times \frac{\pi}{16} \times \frac{D^4 - d^4}{D}$$

$$200 = \tau_{ind} \times \frac{\pi}{16} \times \frac{30^4 - 14^4}{30}$$

$$\tau_{ind} = 0.034\ N/mm^2$$

Hence, design of sleeve is safe under torsional stress.

It is to be noted here,

No key is used to fix the motor shaft and the coupling, as the motor shaft would become weak if a keyway is made in it. Instead a grub screw of dimensions M3 and flat bottom is used in order to make the connection between the coupling and motor shaft

4.3 Design of Base Plate

About: Base Pate acts as a structural base for the Hexapod assembly. Its primary purpose is to support all the structures which will include bolting the hinge, which will be supporting the entire assembly of hexapod.

The base plate should have the following properties:

1. Good machinability – For tap drilling to fix the hinge
2. Good damping properties – Reduce vibrations
3. High Density – To lower the centre of mass of the assembly
4. High Strength
5. Low cost & Easy availability

Selection of Material:

Based on the above requirements we select sheet metal of gauge 6.

Design:

We propose a circular/triangular base plate with a circular bore to reduce weight. The above shape(s) was selected to reduce machinability and simple construction. The size of gauge 6 was selected by using constant optimization trial and error method for checking for failure of various sizes for the given load range.

Chapter 5

CAD Models

5.1 Main Assembly:

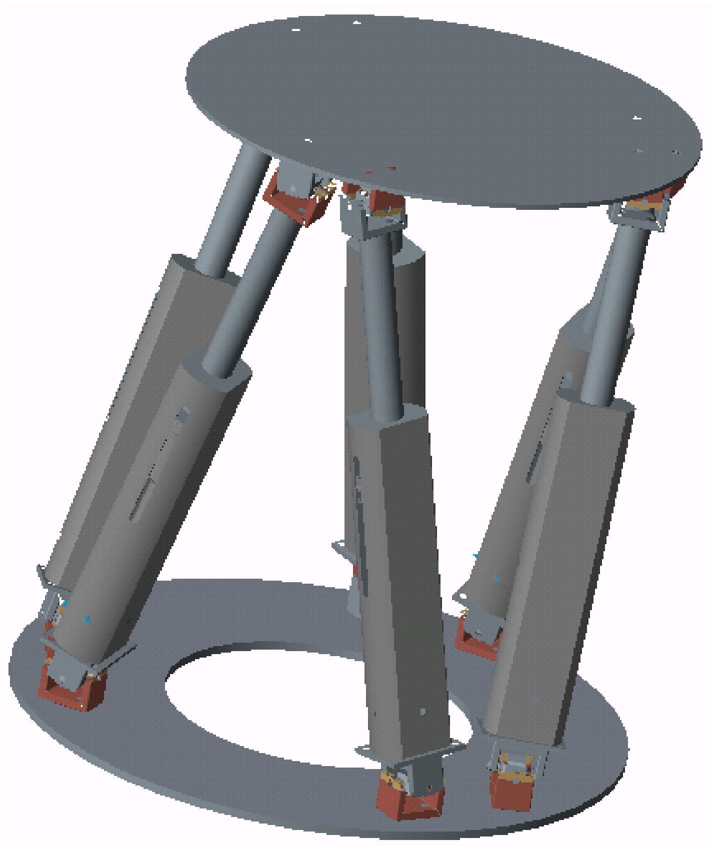


Figure 5.1 Hexapod Main Assembly (Solid)

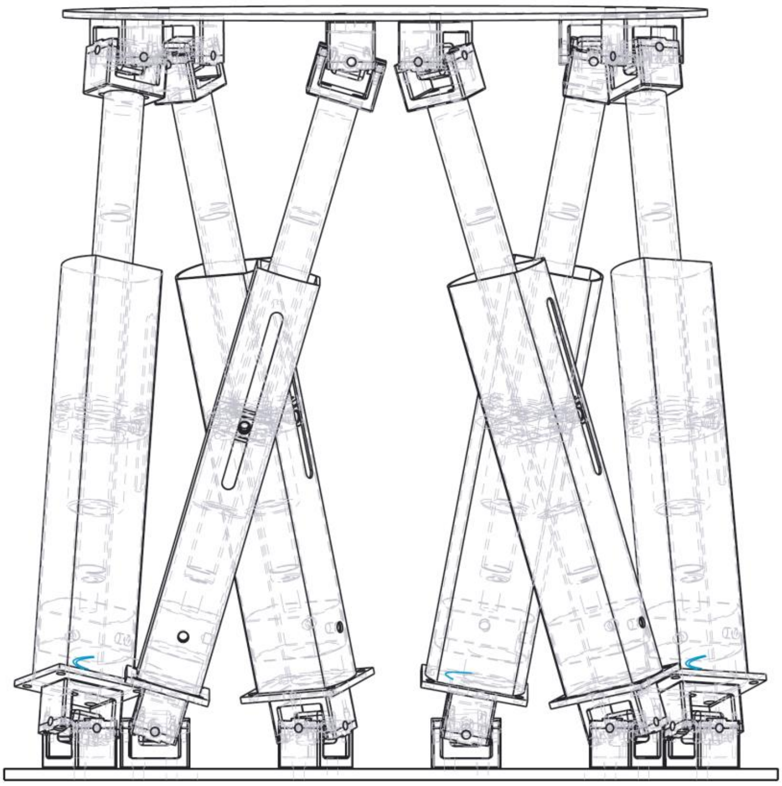


Figure 5.2 Hexapod Main Assembly (Hidden)

5.2 Actuator:

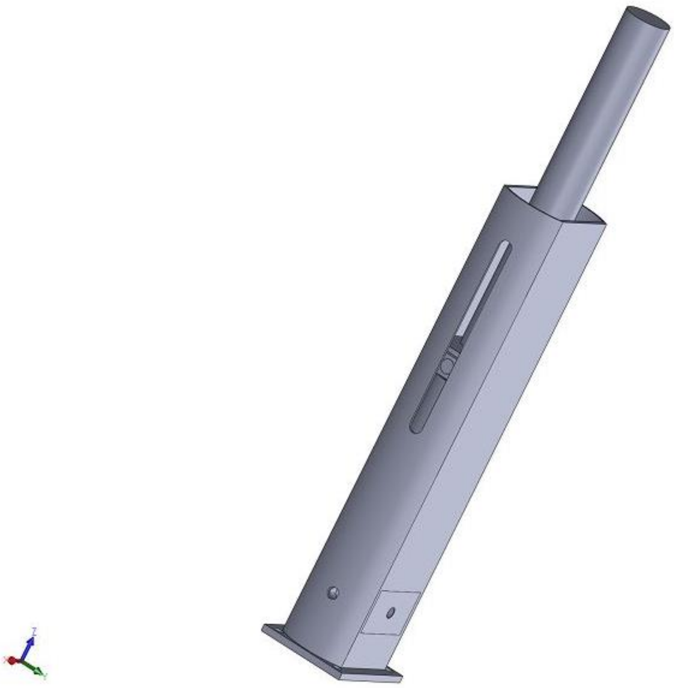


Figure 5.3 Actuator Assembly (Solid)

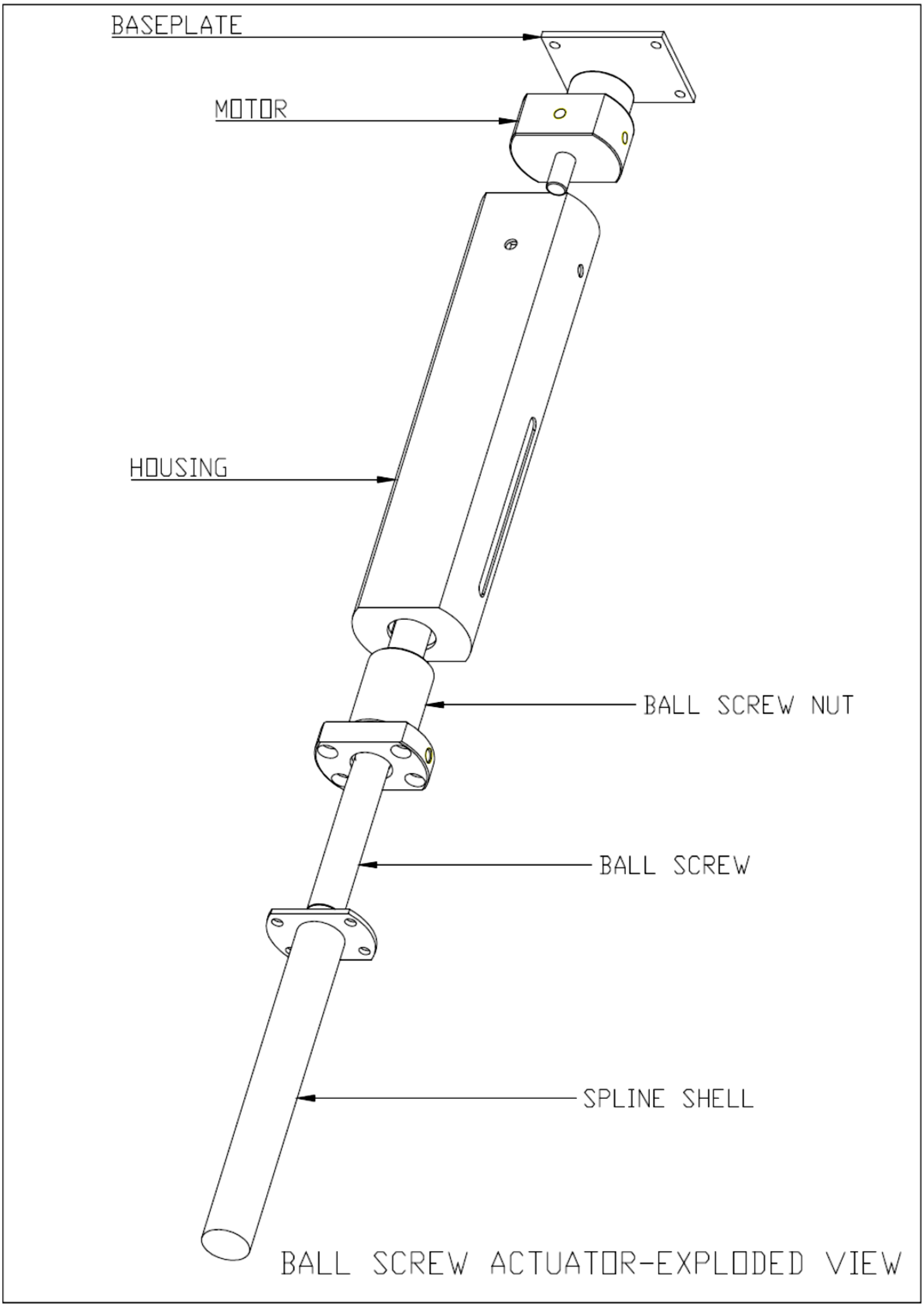


Figure 5.4 Actuator Exploded View

5.3 Hinge:

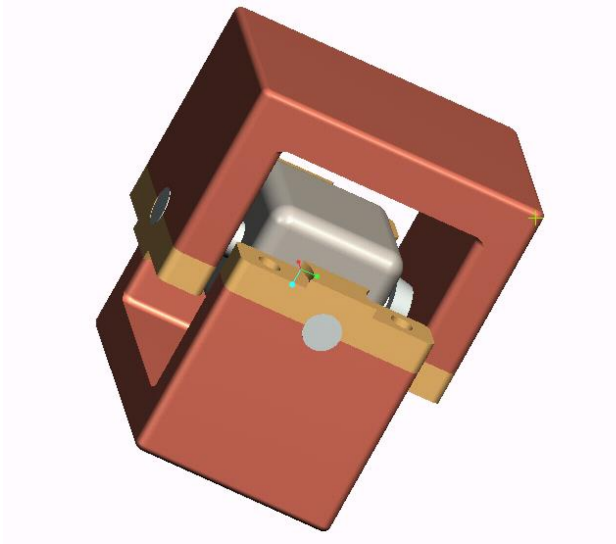


Figure 5.5 Hinge Assembly (Solid)

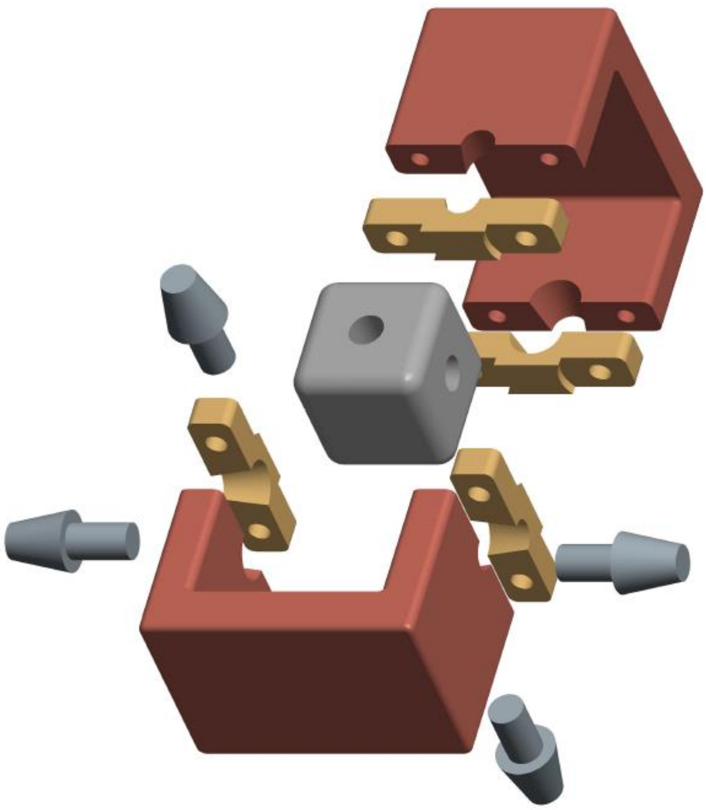


Figure 5.6 Hinge Exploded

5.4 Ball Screw:

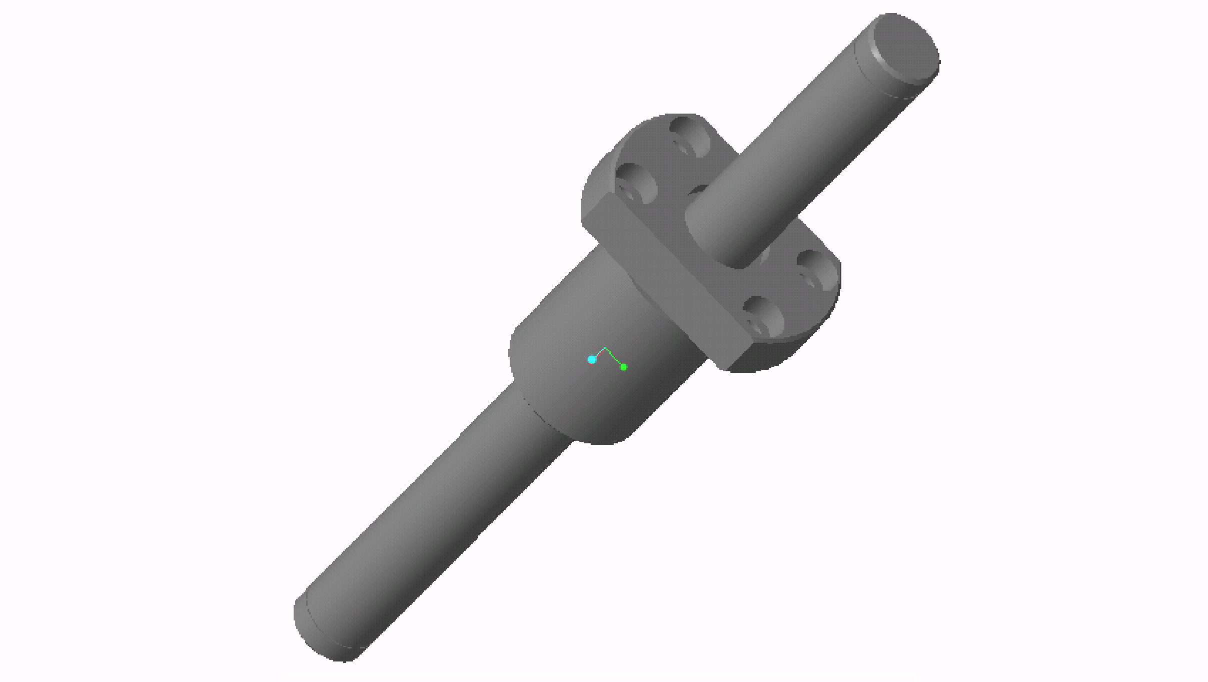


Figure 5.7 Ball Screw (Solid)

5.5 Base Plate:

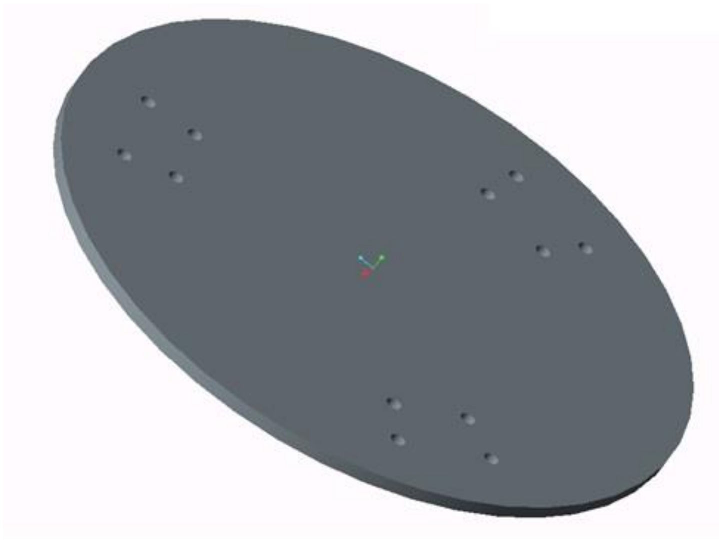


Figure 5.8 Base Plate (Solid)

5.6 Top Plate

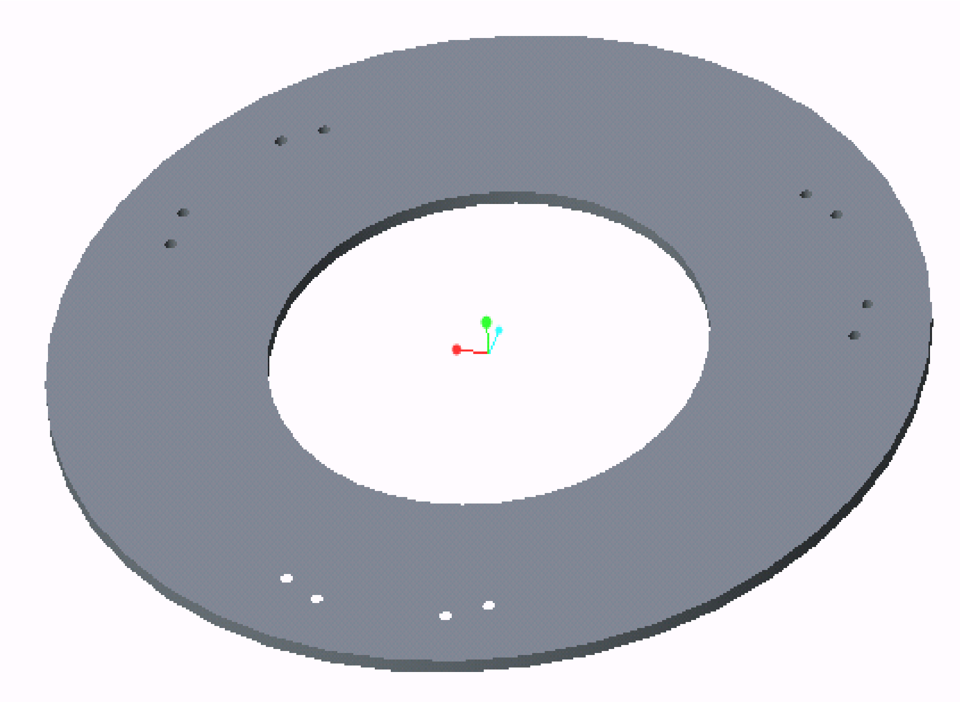


Figure 5.9 Top Plate (Solid)

Chapter 6

Design Analysis

6.1 Actuator Analysis:

6.1.1 Deformation at 100 N:

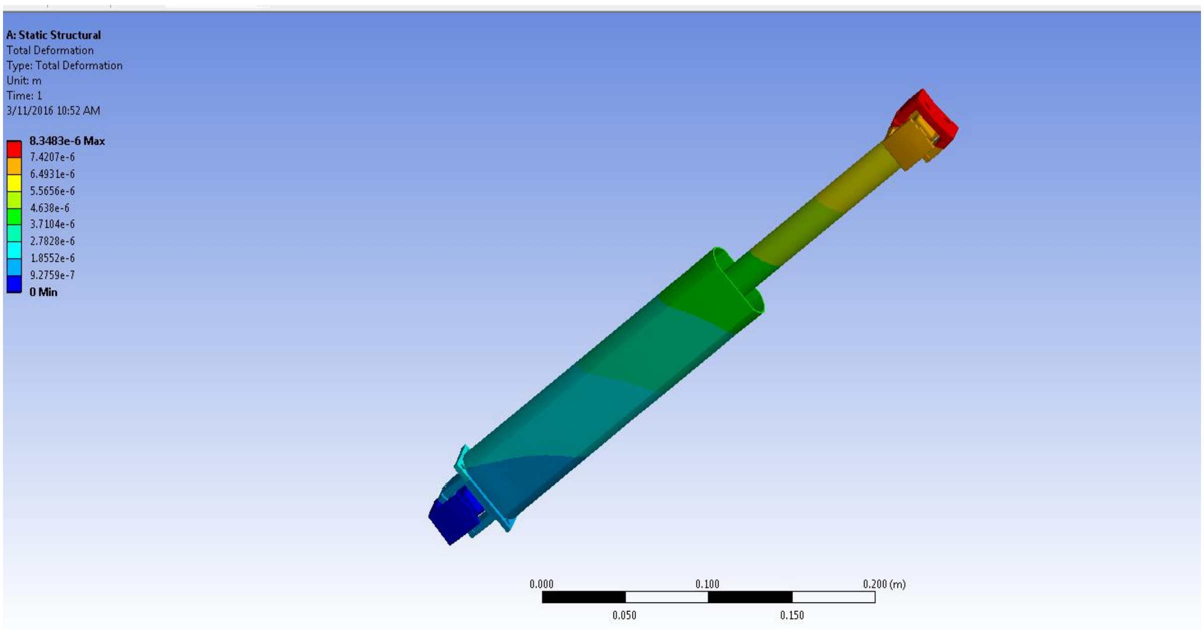


Figure 6.1 Actuator Deformation at 100 N

6.1.2 Equivalent Stress at 100N

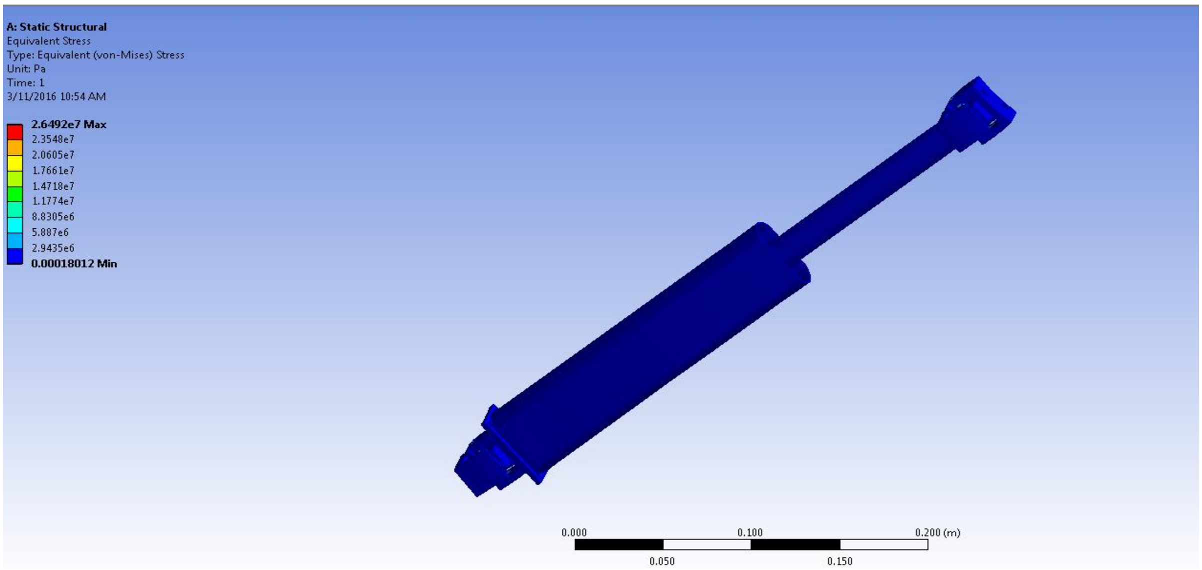


Figure 6.2 Equivalent Stress at 100 N

6.1.3 Deformation at 300 N:

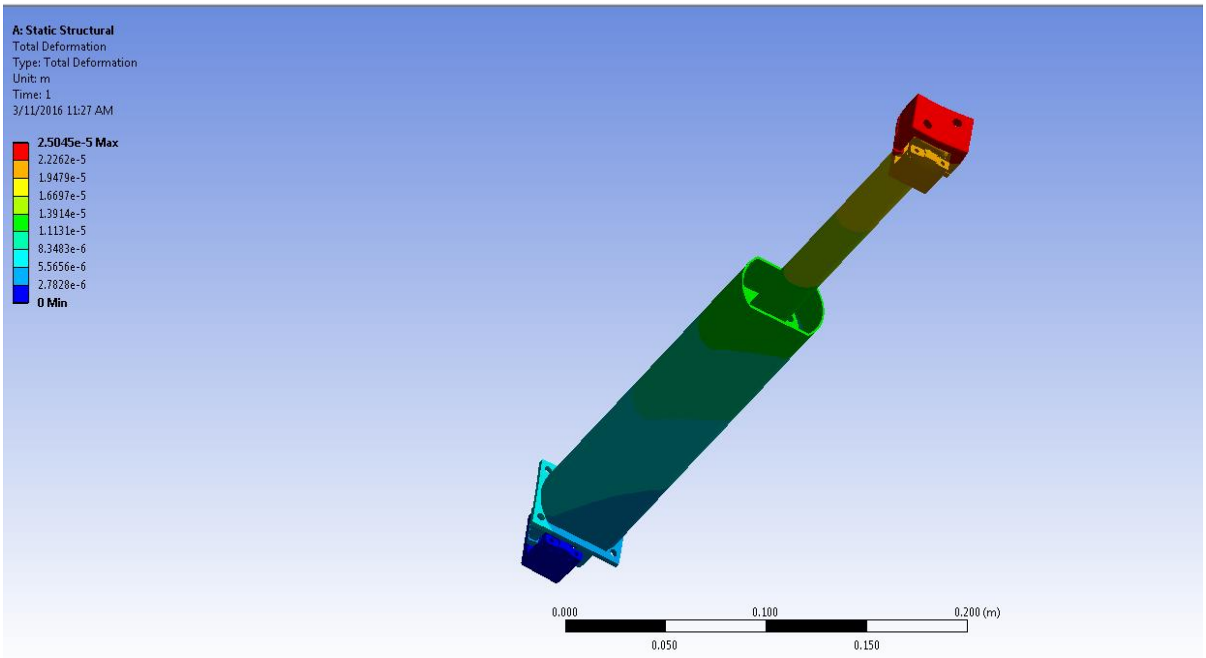


Figure 6.3 Actuator Deformation at 300 N

6.1.4 Equivalent Stress at 300 N:

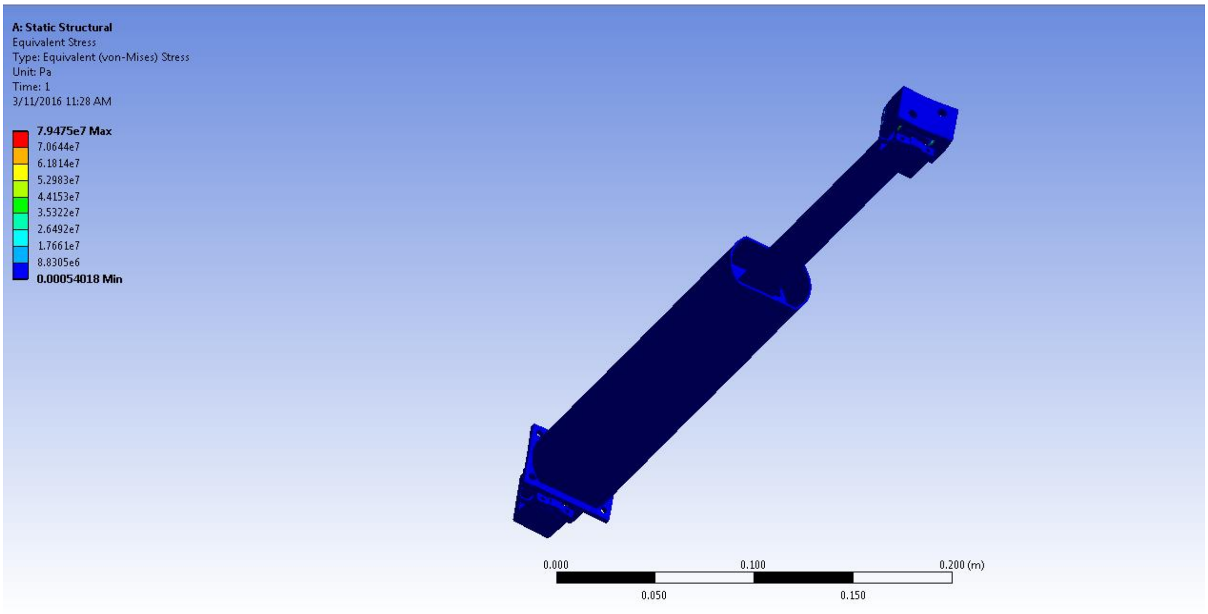


Figure 6.4 Equivalent Stress at 300 N

6.1.5 Deformation at 400 N:

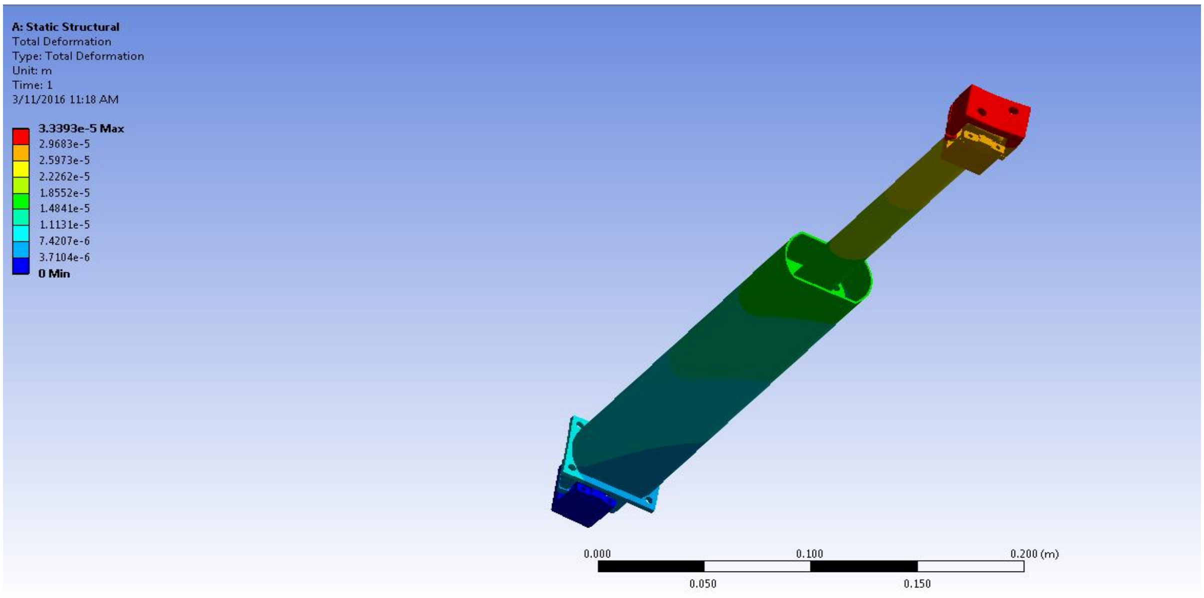


Figure 6.5 Actuator Deformation at 400 N

6.1.6 Equivalent Stress at 400 N:

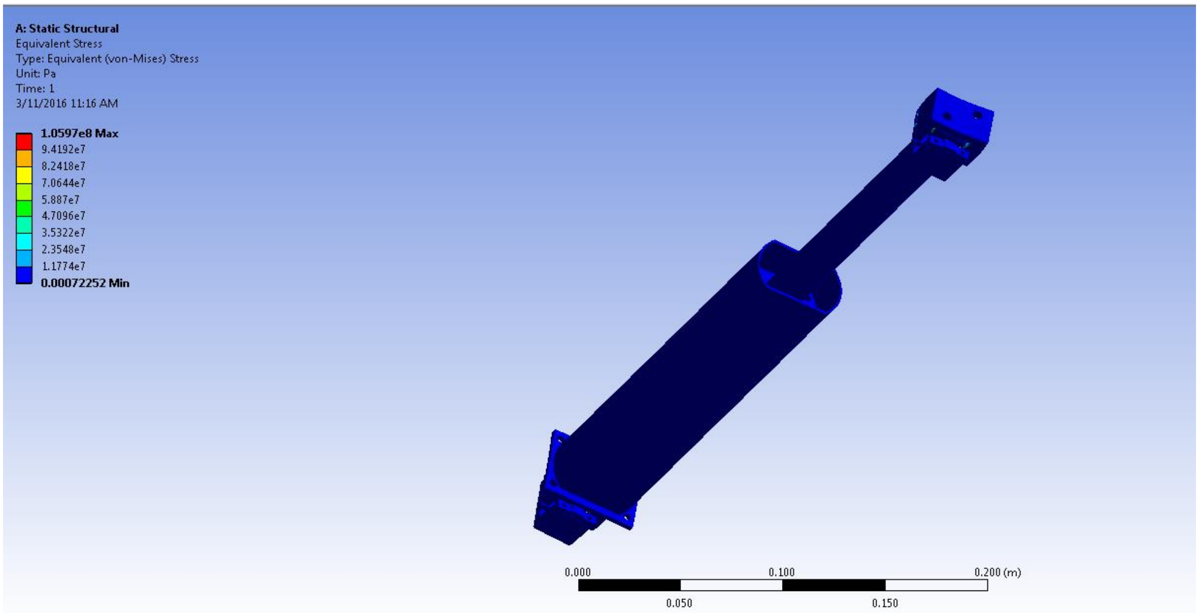


Figure 6.6 Equivalent Stress at 400 N

6.2 Base Plate Analysis:

6.2.1 Deformation at 125 kgf:

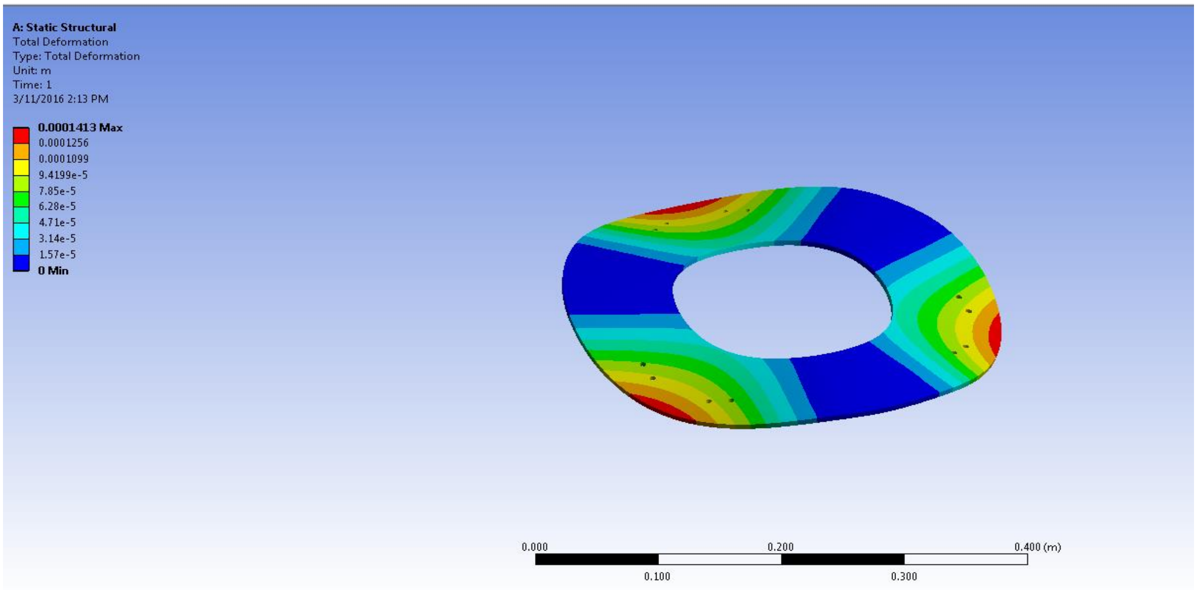


Figure 6.7 Base Plate Deformation at 125 kgf

6.2.2 Equivalent Stress at 125 kgf:

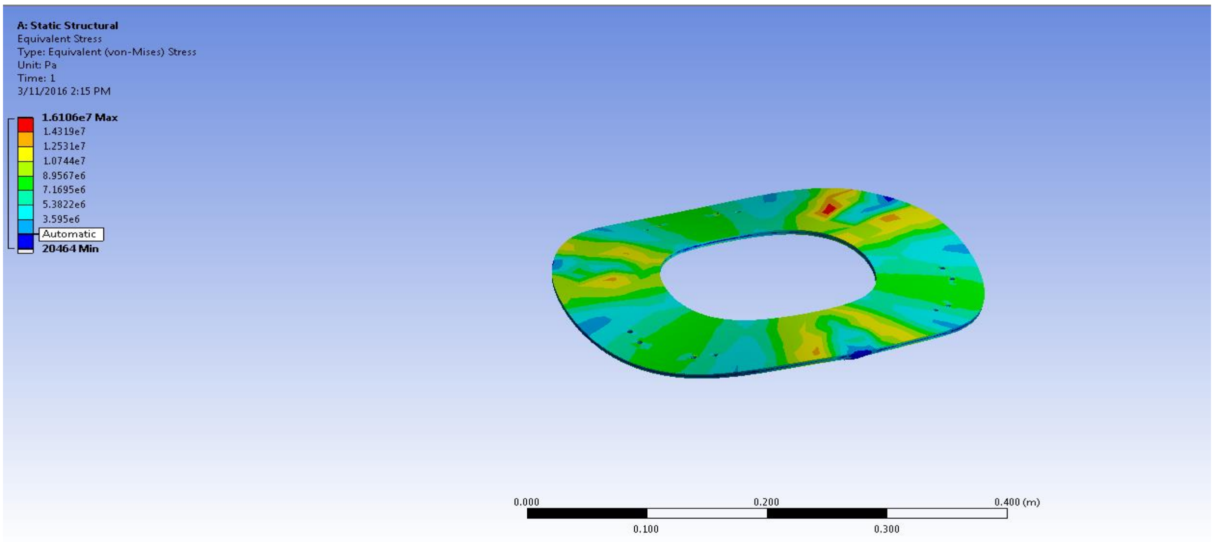


Figure 6.8 Equivalent Stress at 125 kgf

6.3 Hinge Analysis:

6.3.1 Equivalent Stress at 100 N:

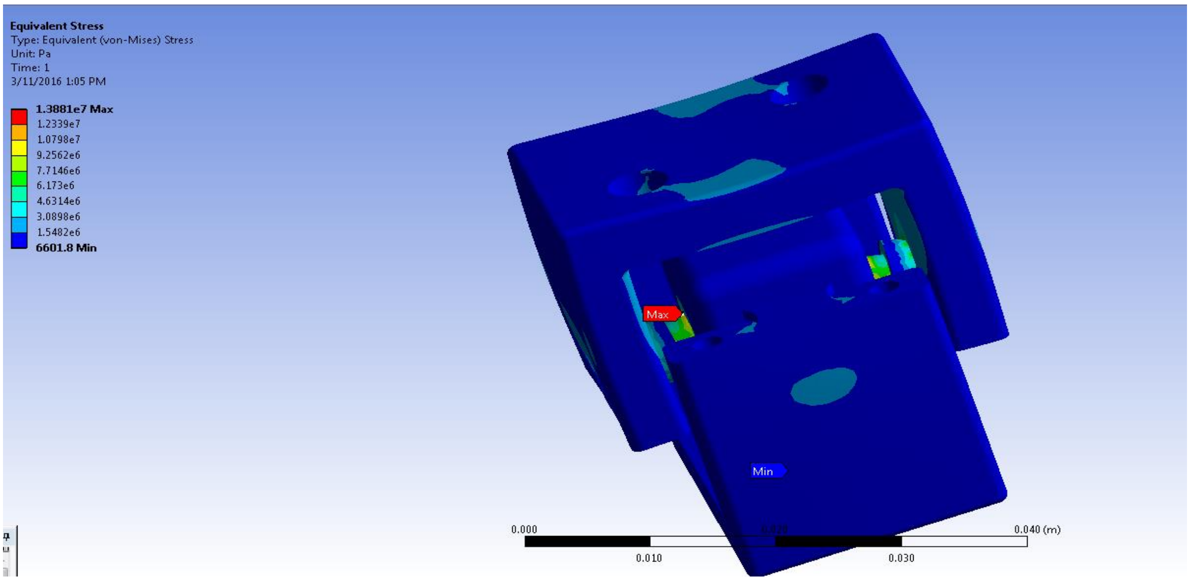


Figure 6.9 Equivalent Stress at 100 N

6.3.2 Deformation at 100 N:

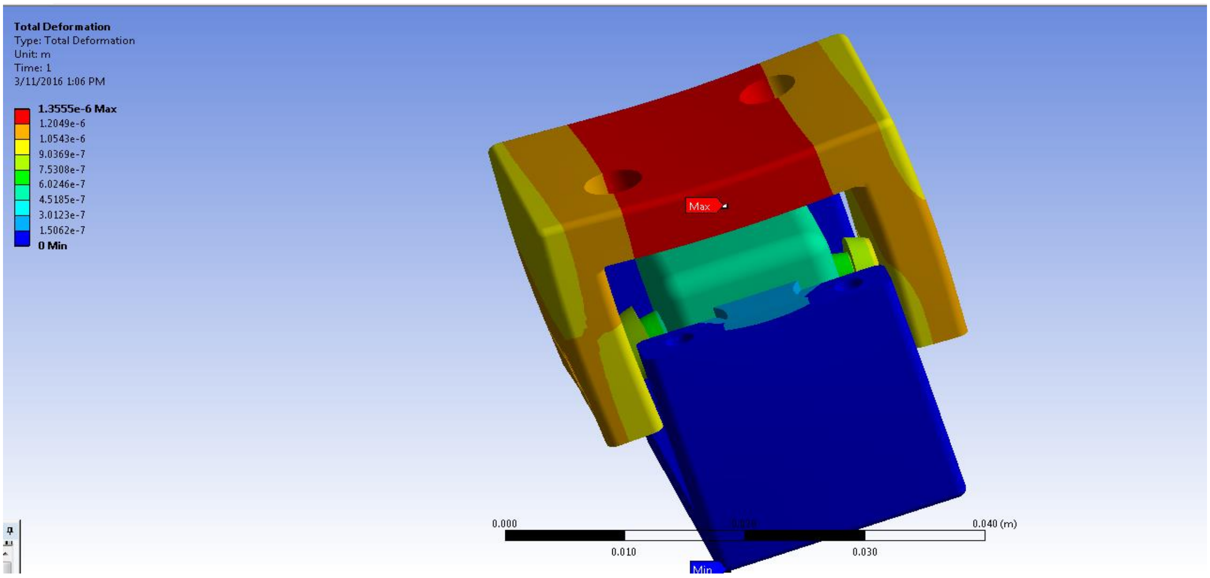


Figure 6.10 Hinge Deformation at 100 N

6.4 Main Assembly Analysis:

6.4.1 Safety Factor at 600 N:

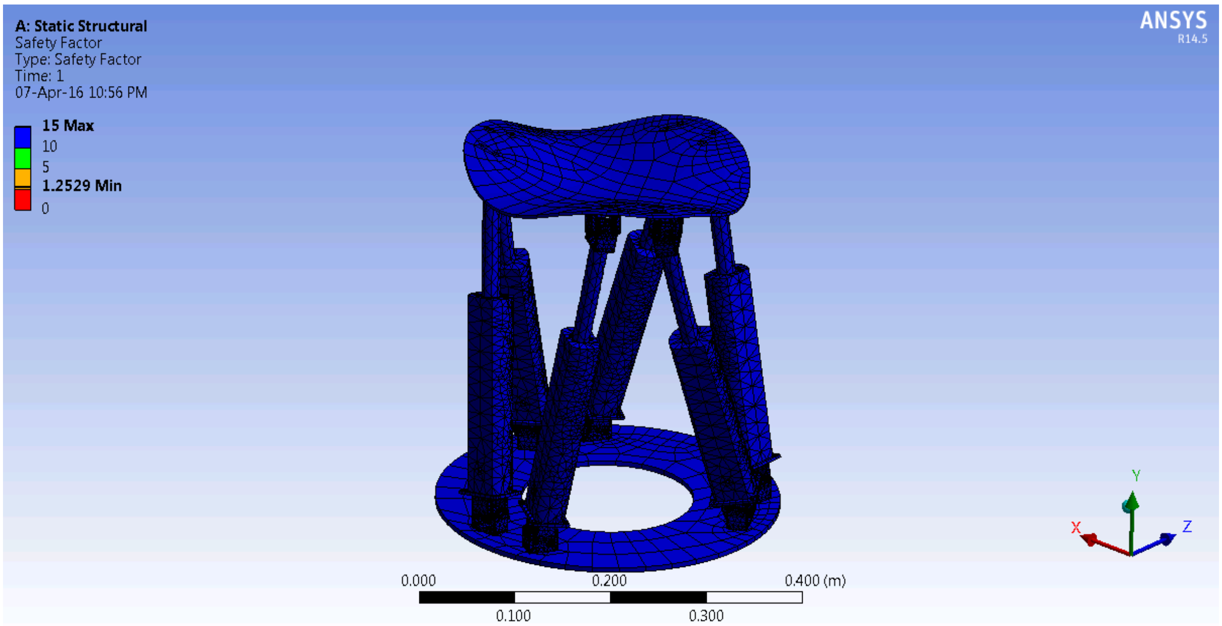


Figure 6.11 Safety Factor at 600 N

6.4.2 Directional Deformation at 600 N:

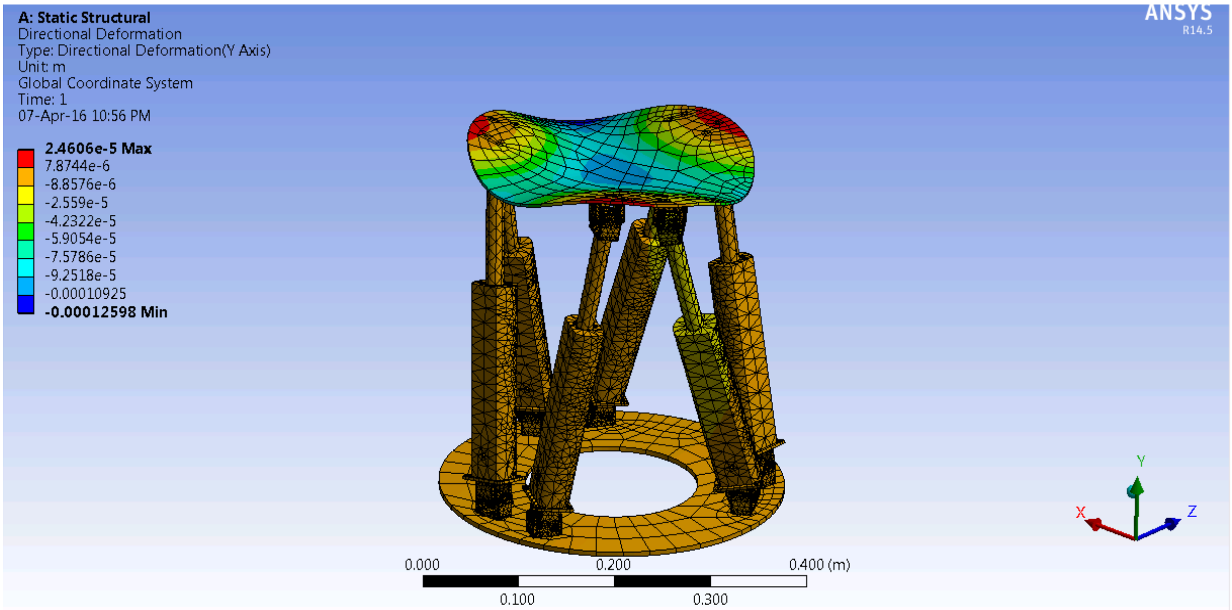


Figure 6.12 Directional Deformation at 600 N

6.4.3 Strain Energy at 600 N:

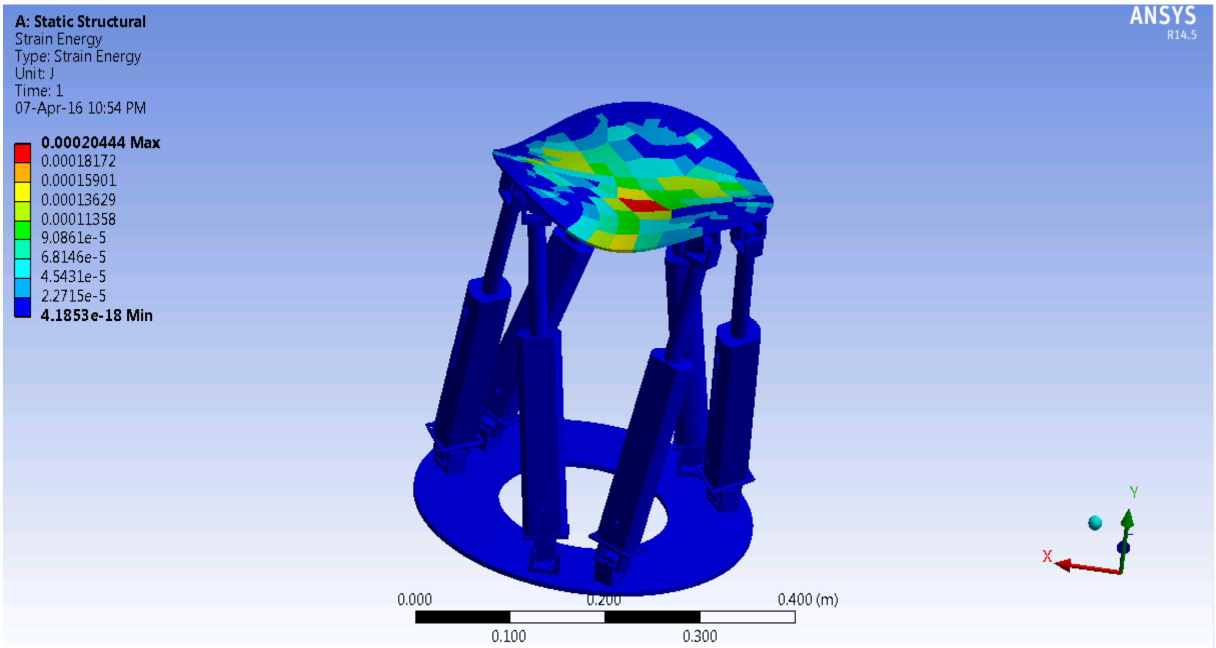


Figure 6.13 Strain Energy at 600 N

6.4.4 Shear Stress at 600 N:

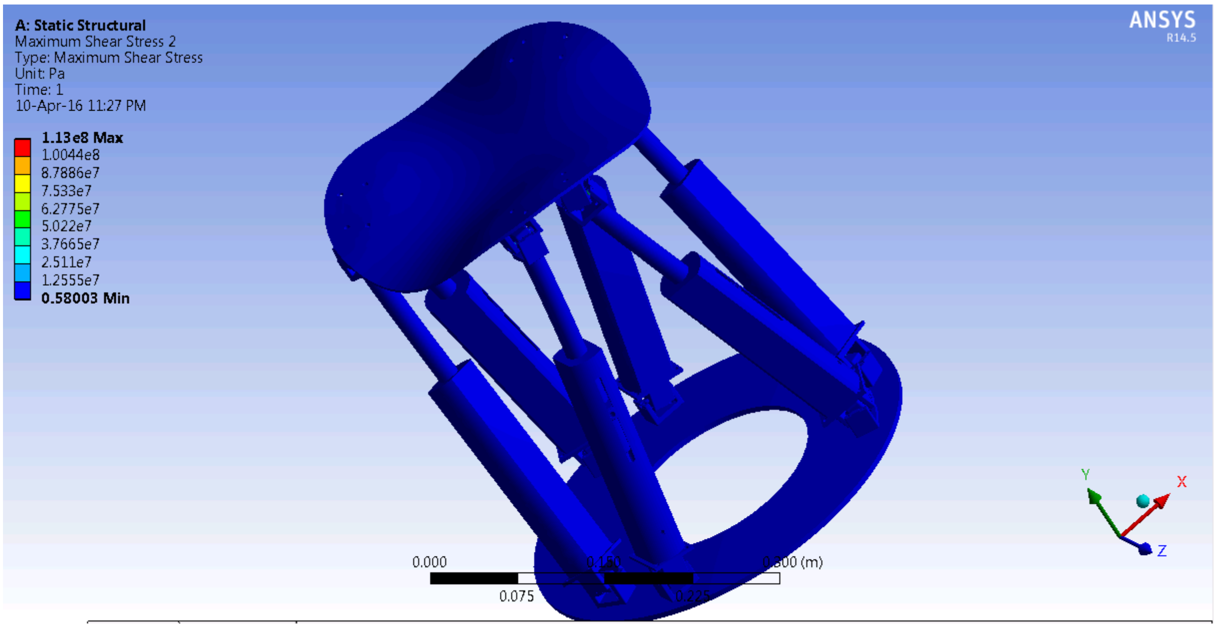


Figure 6.14 Shear Stress at 600 N

Chapter 7

Simulation using MATLAB

7.1 Context:

A MATLAB program is written, as shown below, which finds out the lengths and angles of each actuator of the hexapod for the desired motion of the top plate. The input required to be given to the program is the final co-ordinates of the centre of the top plate. Using these co-ordinates and the co-ordinates of the centre of the plate when it is unactuated, the program finds the length of each actuator as well as the angle it makes with each of the co-ordinate axes. These co-ordinates can be fed to the controller of the hexapod to generate the appropriate signals for the corresponding motors of the actuators.

The top plate is considered as a plane defined by the six screw points corresponding to the six actuators and the centre point. When the centre point is to be moved to a new position, then the entire plate will move by the value equal to the change in values of the x, y, z co-ordinates the centre point. Now, the concept of transformations is used and the entire plate is translated by values equal to these changes. Using the new position of the screw points and the original fixed positions of the screw points on the base plate, the length of each of the actuators is calculated by considering the actuators as a vector passing through the screw points one each on top and bottom plates. Thus, the magnitude of the vector will be the length of the screw. Now, considering the actuators as a line passing through two points, one each on top and bottom plates, the direction ratios and hence the direction cosines of the lines are determined. Evaluating the cos inverse of the direction cosines, we get the angle made by the actuators with each of the co-ordinate axes. Thus, giving the input as the final co-ordinates of the centre point of the top plate, we get the length and angles of each of the actuators as the output. It is to be noted that, to simplify the program, the final orientation of the plane is not considered in evaluating the length and angles of the actuators.

7.2 Algorithm:

→ Top Plate is initially assumed to be horizontal.

→ Centre of base plate is considered as the origin of the 3-D space

→ Screw considered as a vector passing through two points - one on top plate and other on base plate

→ Using transformations, find new point on top plate

→ Screw defined as new vector passing through new point on top plate

→ Vector passing through (x_1, y_1, z_1) and (x_2, y_2, z_2) is $(x_2 - x_1)$i + $(y_2 - y_1)$j + $(z_2 - z_1)$k

→ Length of screw is the magnitude of this vector

→ Direction ratio of a line passing through points (x_1, y_1, z_1) and (x_2, y_2, z_2) are:

› a= $(x_2 - x_1)$

› b= $(y_2 - y_1)$

› c= $(z_2 - z_1)$

→ Direction cosines are defined as

› l = a /$\sqrt{a^2 + b^2 + c^2}$

› m = b / $\sqrt{a^2 + b^2 + c^2}$

› n = c / $\sqrt{a^2 + b^2 + c^2}$

→ Cos inverse of l, m, n gives angle of vector(screw) with x, y, z axes

Refer Appendix I for MATLAB Program code.

7.3 Solution:

```
>> hexapod_positions2

transform_to =

     4     8    33

length_of_screw1 =

   33.1512

length_of_screw2 =

   33.5559

length_of_screw3 =

   41.4005

length_of_screw4 =

   39.4081

length_of_screw5 =

   37.9737

length_of_screw6 =

   33.2716

x_angle_screw1 =

   88.2714

y_angle_screw1 =

   84.8079

z_angle_screw1 =
```

```
    5.4737

x_angle_screw2 =

   79.5726

y_angle_screw2 =

   88.2714

z_angle_screw2 =

    5.4737

x_angle_screw3 =

   63.0976

y_angle_screw3 =

   52.8936

z_angle_screw3 =

    5.4737

x_angle_screw4 =

   76.0356

y_angle_screw4 =

   52.8936

z_angle_screw4 =

    5.4737

x_angle_screw5 =

   76.0356

y_angle_screw5 =

   59.1493

z_angle_screw5 =
```

```
    5.4737

x_angle_screw6 =

   84.8079

y_angle_screw6 =

   95.1921

z_angle_screw6 =

   5.4737 >>
```

Chapter 8

Results

1. Actuator Deformation at 100 N, 300 N & 400 N was 8.348 microns, 25.04 microns & 33 microns respectively.
2. Actuator Equivalent (Von-Mises) stress at 100 N, 300 N & 400 N was 26.49 MPa, 79.47 MPa & 105 MPa respectively.
3. Base Plate Deformation at 125 kgf was 141.3 microns and the corresponding stress was 16.10 MPa.
4. Hinge Deformation at 100 N was 1.33 microns and the corresponding stress was 13.88 MPa. As the design stress is 46.67 MPa, Hinge is safe.
5. Total deformation was observed to be 24 microns on the above load.
6. Load of 300N gave a FOS of 5 whereas the load of 400N gave a FOS less than 5.
7. So maximum load on each actuator for a FOS of 5 is 300N or 1800N for the entire hexapod.

Chapter 9

Conclusion

This project was inspired by the benefits of the parallel manipulator devices which can be used in highly precise applications. The aim of the project was to design a miniature hexapod of size in the range of 30-40 cm for low load and space constraints applications. The literature survey revealed the scope of various prismatic arrangements and the different types of actuators that can be utilized for the hexapod. Accordingly, universal joint and ball screw actuators were selected since ball screw actuators provide very low friction and minimal backlash required for accurate positioning of the hexapod, although piezo electric actuators could also be used competitively for still smaller range of actuation. The miniature hexapod was designed for the given load of 100 N (per actuator). Motion constraints instead of static constraints were used during assembly of CAD model to make it more practical oriented. The designs were done analytically and tested for different failures using analysis software. The deformation was found out to be under 1 mm. Maximum load of 2040 N (340 N per actuator) can be sustained within the permissible deflection limits and keeping a safety factor of 5. Use of standard available components for the hexapod will ease the process of manufacturing and assembly of it. MATLAB program simplifies the process of actuation as it makes the system semi-autonomous although rotational orientations were approached as a dynamic random constraint in this work. Virtual simulation of the CAD model authenticates the positional orientation of the actuators without interference for various positions of the hexapod.

There is scope of more in-depth analysis by studying the workspace and checking for singularities. A much more complex MATLAB code can be generated for angular motion simulation as well as determination of singularity points & workspace range. By varying the architecture and automation of its components, the Miniature Hexapod can find diverse applications in fields of engineering, medicine and defence.

.

Chapter 10

Appendices

10.1 Appendix I:

MATLAB code for giving translational motion commands to the Hexapod:

```
%% SUMMARY

%Matrix A denotes coordinates of screw position when the top plate is horizontal i.e. unactuated

%Matrix “transform_to” denotes the point to which the centre of the top plate

%is to be moved

%Matrix “new_pts” denotes the co-ordinates of the screw points after it has

%been translated(transformed) to the new position mentioned in matrix “transform_to”

%Matrix D denotes the co-ordinates of the screw points on the bottom plate
```

```
%% PROGRAM BEGINS HERE.....

%%a, b, c, d, e, f are the co-ordinates of screws on top plate

%let top plate be at a vertical distance r=30cm from bottom plate

% A is matrix having co-ordinates of screw when top plate is
unactuated in

% the homogeneous co-ordinates

r=30;

A=[2,3,r,1;6,2,r,1;4,6,r,1;5,5,r,1;8,6,r,1;2,-4,r,1];


%% centre of top plate is at (0,0,r) when in unactuated position

% B is co-ordinate of centre of top plate

B=[0,0,r];


%if centre of top plate is to be moved to a position C=(4,8,33)

%C is denoted as transform_to

transform_to=[4,8,33]


% so all screw points should be translated by matrix transform_to

%tx,ty,tz are translation values

tx=transform_to(1)-B(1);

ty=transform_to(2)-B(2);

tz=transform_to(3)-B(3);


%so translation matrix in homogeneous cordinates is
```

```
%it is denoted by matrix translate
translate=[1,0,0,0;0,1,0,0;0,0,1,0;tx,ty,tz,1];

%%New Positions of all screw points after translation
%it is denoted by matrix new_pts
new_pts=A*translate;

%% let matrix D is co-ordinates of screw points on bottom plate
% so matrix D in homogeneous co-ordinates
D=[5,8,0,1;4,9,0,1;-7,-6,0,1;1,-7,0,1;4,-3,0,1;3,7,0,1];



%%VERY IMPORTANT CONSIDERATION
% It is considered that first screw point of top plate is
connected to
% first screw point on bottom plate and second screw point on
top plate is
% connected to the second screw point on bottom plate and so
on...i.e. A(1) is
% connected to D(1) and A(2) is connected to D(2) and so on

%% LENGTH OF SCREW
% each screw is considered as a vector passing through the
corresponding
% points on top and bottom plates
```

```
% so vectors of each screw is defined as{new_pts(1)-D(1)},
{new_pts(2)-D(2)} and so on

vector_screw1=new_pts(1,1:3)-D(1,1:3);

vector_screw2=new_pts(2,1:3)-D(2,1:3);

vector_screw3=new_pts(3,1:3)-D(3,1:3);

vector_screw4=new_pts(4,1:3)-D(4,1:3);

vector_screw5=new_pts(5,1:3)-D(5,1:3);

vector_screw6=new_pts(6,1:3)-D(6,1:3);


% Length of screw is the magnitude of the vector of the screw

% so length of screw 1 is sqrt(vector_screw1.^2)

% i.e. magnitude of vector ai+bj+ck is sqrt(a^2+b^2+c^2)

length_of_screw1=sqrt(sum(vector_screw1.^2))

length_of_screw2=sqrt(sum(vector_screw2.^2))

length_of_screw3=sqrt(sum(vector_screw3.^2))

length_of_screw4=sqrt(sum(vector_screw4.^2))

length_of_screw5=sqrt(sum(vector_screw5.^2))

length_of_screw6=sqrt(sum(vector_screw6.^2))

%% TO FIND ANGLE MADE BY EACH SCREW WITH EACH OF THE AXES


% direction ratio of a line passing through points (x1,y1,z1)
and

% (x2,y2,z2) are p=(x2-x1), q=(y2-y1), r=(z2-z1)

% so here it will be difference of matrices new_pts and D

%So direction ratios(drs) are
```

```
drs=new_pts(1:6,1:3)-D(1:6,1:3);


%%Direction cosines

%direction cosines are defined as

%l=+-p/(sqrt(p^2+q^2+r^2))  and  m=+-q/(sqrt(p^2+q^2+r^2))  and
n=+-r/(sqrt(p^2+q^2+r^2))


%direction cosines of screw 1

l1=drs(1,1)/sqrt(sum(drs(1,1:3).^2));

m1=drs(1,2)/sqrt(sum(drs(1,1:3).^2));

n1=drs(1,3)/sqrt(sum(drs(1,1:3).^2));


%direction cosines of screw 2

l2=drs(2,1)/sqrt(sum(drs(1,1:3).^2));

m2=drs(2,2)/sqrt(sum(drs(1,1:3).^2));

n2=drs(2,3)/sqrt(sum(drs(1,1:3).^2));


%direction cosines of screw 3

l3=drs(3,1)/sqrt(sum(drs(1,1:3).^2));

m3=drs(3,2)/sqrt(sum(drs(1,1:3).^2));

n3=drs(3,3)/sqrt(sum(drs(1,1:3).^2));


%direction cosines of screw 4

l4=drs(4,1)/sqrt(sum(drs(1,1:3).^2));
```

```
m4=drs(4,2)/sqrt(sum(drs(1,1:3).^2));

n4=drs(4,3)/sqrt(sum(drs(1,1:3).^2));


%direction cosines of screw 5

l5=drs(5,1)/sqrt(sum(drs(1,1:3).^2));

m5=drs(5,2)/sqrt(sum(drs(1,1:3).^2));

n5=drs(5,3)/sqrt(sum(drs(1,1:3).^2));


%direction cosines of screw 6

l6=drs(6,1)/sqrt(sum(drs(1,1:3).^2));

m6=drs(6,2)/sqrt(sum(drs(1,1:3).^2));

n6=drs(6,3)/sqrt(sum(drs(1,1:3).^2));


%%ANGLES MADE BY EACH SCREW WITH THE CO-ORDINATE AXES

%angles made by the screws with the coordinate axes are the cos

% inverse values of the direction cosines

% cos inverse of l gives angle with x axis, cos inverse of m
gives angle with y axis

% cos inverse of n gives angle with z axis


% Angles made by screw 1 in degrees

x_angle_screw1=acos(l1);

x_angle_screw1=x_angle_screw1*180/(pi)

y_angle_screw1=acos(m1);
```

```
y_angle_screw1=y_angle_screw1*180/(pi)
z_angle_screw1=acos(n1);
z_angle_screw1=z_angle_screw1*180/(pi)

% Angles made by screw 2 in degrees
x_angle_screw2=acos(l2);
x_angle_screw2=x_angle_screw2*180/(pi)
y_angle_screw2=acos(m2);
y_angle_screw2=y_angle_screw2*180/(pi)
z_angle_screw2=acos(n2);
z_angle_screw2=z_angle_screw2*180/(pi)

% Angles made by screw 3 in degrees
x_angle_screw3=acos(l3);
x_angle_screw3=x_angle_screw3*180/(pi)
y_angle_screw3=acos(m3);
y_angle_screw3=y_angle_screw3*180/(pi)
z_angle_screw3=acos(n3);
z_angle_screw3=z_angle_screw3*180/(pi)

% Angles made by screw 4 in degrees
x_angle_screw4=acos(l4);
x_angle_screw4=x_angle_screw4*180/(pi)
y_angle_screw4=acos(m4);
```

```
y_angle_screw4=y_angle_screw4*180/(pi)

z_angle_screw4=acos(n4);

z_angle_screw4=z_angle_screw4*180/(pi)


% Angles made by screw 5 in degrees

x_angle_screw5=acos(l5);

x_angle_screw5=x_angle_screw5*180/(pi)

y_angle_screw5=acos(m5);

y_angle_screw5=y_angle_screw5*180/(pi)

z_angle_screw5=acos(n5);

z_angle_screw5=z_angle_screw5*180/(pi)


% Angles made by screw 6 in degrees

x_angle_screw6=acos(l6);

x_angle_screw6=x_angle_screw6*180/(pi)

y_angle_screw6=acos(m6);

y_angle_screw6=y_angle_screw6*180/(pi)

z_angle_screw6=acos(n6);

z_angle_screw6=z_angle_screw6*180/(pi)
```

References

[1] **Merlet J.P**., *Parallel Robots,* 2nd edition, Springer Publications, 2006

[2] **Gwinnett, J.E.**, "*Amusement devices*," US Patent No. 1,789,680, January 20, 1931.

[3] **Gough, V.E. and Whitehall, S.G**., *Universal tyre test machine*, Proceedings of the FISITA Ninth International Technical Congress, pp. 117-137, May, 1962.

[4] **Cappel, K.L**., "*Motion simulator*," US Patent No. 3,295,224, January 3, 1967.

[5] **Stewart, D**., *A platform with six degrees of freedom*, Proceedings of the IMechE, Vol. 180, Pt. 1, No. 15, pp. 371-385, 1965-66.

[6] **Charles C. Nguyen, Sami Antrazi and Zhen-Lei Zhou**, *Analysis and Design of a Six-Degree-Of-Freedom Stewart Platform-Based Robotic Wrist*. Wiley Interscience Publications, 2004

[7] **P. Merletand D. Daney,** *Appropriate Design of Parallel Manipulators*. Robotica, Volume 19, Issue 03, May 2001

[8] **J.P Merlet,** *Designing a parallel robot for a specific workspace*. CSME Transactions 31, 4, 2007

[9] **Vivek Kumar Mehta& Bhaskar Dasgupta,** A *general approach for optimal kinematic design of 6-DOF parallel manipulators*, Transactions of NAMRI/SME 1994; 22: 283-289.

[10] **Lazard D, Merlet J. P.** *The (true) Stewart platform has 12 configurations*. Proceedings of the 1994 IEEE International Conference on Robotics and Automation. p. 2160. doi:10.1109/ROBOT.1994.350969. ISBN 0-8186-5330-2

[11] **Tompkins, Eric**. *The History of the Pneumatic Tyre*. Dunlop. pp. 86, 91. ISBN 0-903214-14-8.

[12] **Bonev, I.A**., *The True Origins of Parallel Robots*, Parallel MIC online review

[13] **Y. D. Patel, P. M. George,** *Parallel Manipulators Applications* - A Survey revised March 25, 2012; accepted April 2, 2012

[14] **Hamid. D. Taghirad**, *PARALLEL ROBOTS: Mechanics and control* (ISBN:978146655576)

[15] **Xiaoyu Wang and Luc Baron**, *Topology and Geometry of Serial and Parallel Manipulators*. (Parallel Manipulators, New Developments, Book edited by: Jee-Hwan Ryu, ISBN 978-3-902613-20-2, pp. 498, April 2008, I-Tech Education and Publishing, Vienna, Austria)

[16] **Feng Gao, Weimin Li, Xianchao Zhao, Zhenlin Jin, Hui Zha**, *New kinematic structures for 2-,3-,4-, and 5- DOF parallel manipulator design,* Mechanism a Machine Theory 37 (2002) 1395 – 1411

[17] **Grigore Gogu**, *Structural Synthesis of Parallel Robots,* Part 5, Springer, 2004

[18] **Fassi, G. Wiens**, *Multiaxis Machining: PKMs and Traditional Machining Centers*, Journal of manufacturing Processes Vol.21 No.1, 2000

[19] **F.Rehsteiner, R. Neugebauer, S. Spiewak, F. Wieland**, *Putting Parallel Kinematics Machine (PKM) to productive work*, Annals of the CIRP, 48/1: 345-350, 1999

[20] **F. Xi, W. Han, M. Verner**, A.Ross, *Development of a sliding leg tripod as an add-on device for manufacturing*, Robotica, Volume 19, Issue 03, May 200

[21] **J. Wang and O. Masory**, "*On the Accuracy of a Stewart Platform Part 1- The Effect of Manufacturing Tolerances*," Proceedings of the 1993 IEEE Int. Conference on Robotics and Automation, pp.114-120.

[22] **T. Ropponen, T. Arai**, "*Accuracy Analysis of a Modified Stewart Platform Manipulator*"

[23] **D. Stewart**, *Proc. Instn. Mech. Engrs*. (Part I) 180 (15) (1965/66) 371-386

[24] **P.Sui, L.Yao, J. Dai, H. Wang**, *Development and key issues of the Ankle Rehabilitation*, 13th World Congress in Mechanism and Machine Science

[25] **V.E. Gough, S.G. Whitehall**, in *Proc. 9th Int. Tech. Congr. F.I.S.I.T.A.* May 1962, Instnb Mech. Engrs 117, 1962

[26] **K.H. Hunt**, *Kinematic Geometry of Mechanisms*, Clarendon Press, Oxford, 1978

[27] **M. Baret**, in: Proc. AGARD Conf. 249, Piloted Aircraft Environment Simulation Techniques, 1978, pp. 22.1-22.8.

[28] **H. McCallion, P.D. Truong**, Proc. 5th World Congress. Theory Mach. Mech., 1979, pp. 611-616.