A Thesis Report on

A COMPARATIVE STUDY ON POSSIBLE ARCHITECTURAL DESIGNS OF LINK MODULES FOR MODULAR MANIPULATORS

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DECLARATION

I hereby declare that the seminar report entitled **"A COMPARATIVE STUDY ON POSSIBLE ARCHITECTURAL DESIGNS OF LINK MODULES FOR MODULAR MANIPULATORS"** is an authentic record of my study carried out as requirement for the award of degree of **Master of Engineering in CAD/CAM Engineering** during 4th semester (Jan 2015 - July 2015) at Thapar University, Patiala under the supervision of **Dr. Ashish Singla** (Assistant Professor, Mechanical Engineering Department).

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ABSTRACT

The conventional manipulator plays an important role in the industries while performing different operations. Since 20th century many researchers have designed several designs and made the task simpler by using conventional manipulator. But in many cases the demand of the industry changes rapidly due to modernization. Whenever this happens the industry needs to change either environment or the manipulator. As changing the environment of industry is costly and time consuming even changing conventional manipulator is not feasible every time, modular manipulators are designed to overcome this issue. The aim of this study is to make the manipulators more flexible by changing the design of the conventional manipulators. In this thesis, two different approaches are used for designing of the modular manipulator. In first approach, bevel gears are used to change the joint angle termed as bevel gear approach whereas in the second approach, helical gears are used to change the joint angle termed as helical gear approach. In both the approaches a subassembly of base and shaft is designed which helps in changing the link twist angle. The variation in link twist angle makes the modular manipulators more flexible than conventional manipulators. For both the approaches, four links are designed having different link lengths which help in changing the link length. Therefore the modular manipulator can be used for variety of applications. The design part of modular manipulator is carried out using SolidWorks. Using both the approaches, 2-link and 4-link modular manipulators are assembled. The static analyses of 2-link modular manipulators are done using ANSYS for different configurations. The dynamic study is also carried out for 2-link and 4-link modular manipulators using SimWise 4D for different configurations. Based on the results obtained the design of links are optimized and dynamic study is carried out again. The results showed significant improvement in the performance of the modified modular manipulators compared to the modular manipulators.

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Chapter 1

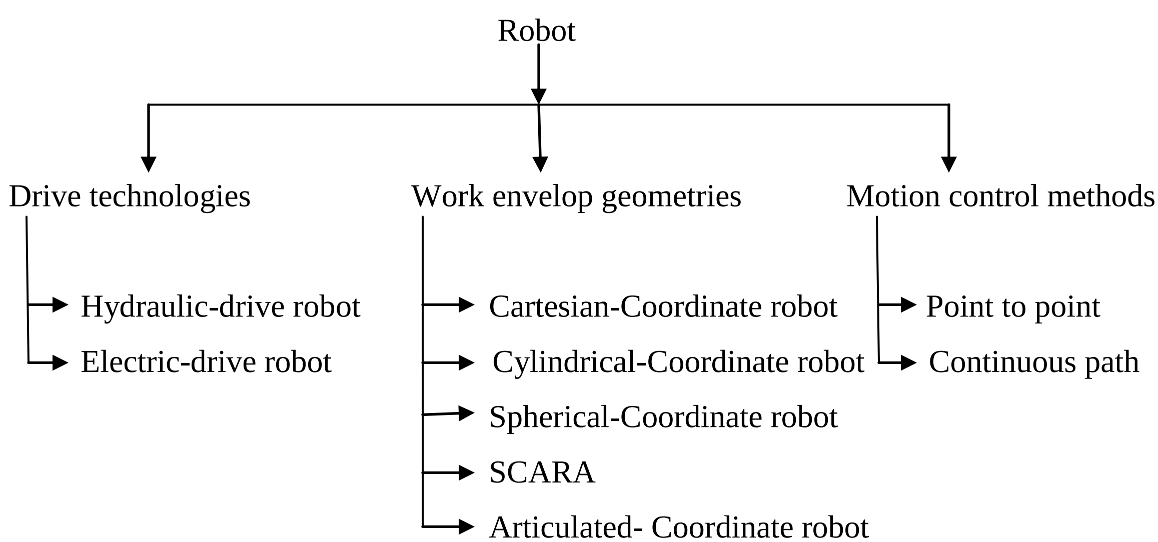
Introduction

1.1 Robot

Robot can be defined as an electromechanical device that makes use of mechanical structure and sensors controlled by a program in order to manipulate physical object. The robots that are used for industrial purpose are also known as robotic manipulator or a robotic arm. A robotic arm consists of a chain of rigid links that are joined together by means of flexible joints. The flexible joints play a vital role in deciding the degree of freedom for a robot. For performing any operation using robotic arm an end-effector is attached at the end generally termed as tool, gripper or hand.

1.2 Robot Classification

The robots are classified based on various parameters such as drive technologies, work envelop geometries and motion control methods. The classification is as follows:



The drive technologies that are generally used are electric and hydraulic. The joints are powered by these drives which in turn move the structure of the robot. In most of the cases, DC servo motor or DC stepper motor are used as electric drive. For the end-effector, a pneumatic drive can be used depending on requirement of application.

The work envelop of the robot can be defined as locus of all points that are reachable by the tool tip in three dimensional space. Robot can have two basic types of joints revolute and prismatic joint. Revolute joint provides rotation about an axis. Prismatic joint provides the linear motion for the robot along an axis. Based on these joints, there are different standard configurations shown in Figure 1.1.

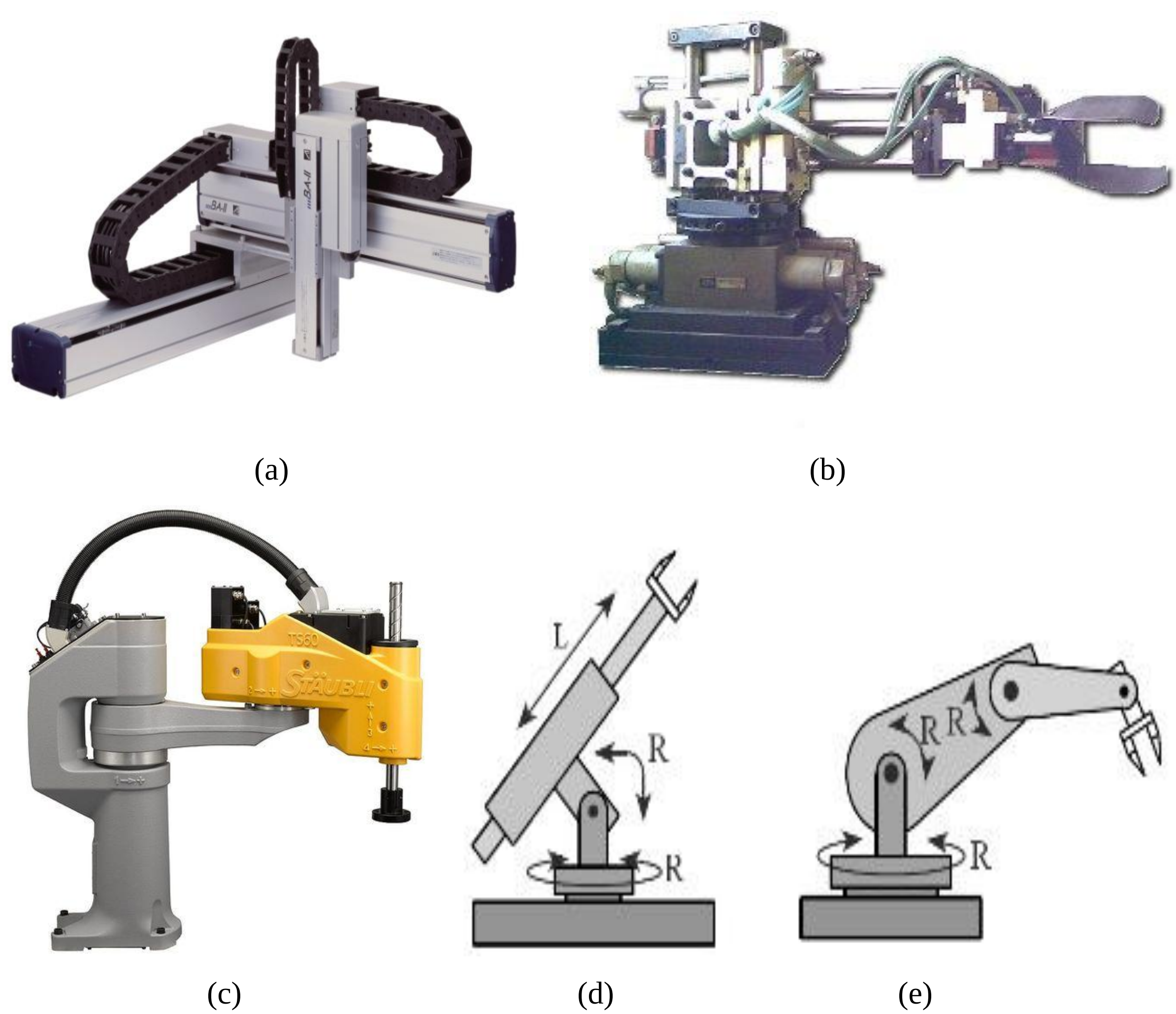


Figure 1.1: (a) Cartesian-Coordinate robot [G1] (b) Cylindrical-Coordinate robot [G2] (c) SCARA [G3] (d) Spherical-Coordinate robot [G4] (e) Articulated- Coordinate robot [G4]

The manipulators can be classified into two more types (i) Serial manipulator, (ii) parallel manipulator.

(I) **Serial manipulators** Serial manipulators are having series of links connected by motor-actuated joints that extend from a base to an end-effector as shown in Figure 1.2.

(II) **Parallel manipulators** Parallel manipulators use several computer-controlled serial chains to support a single platform, or end-effector as shown in Figure 1.3.

Figure 1.2: SCARA manipulator [G5]

Figure 1.3: Hexapod positioning system [G6]

As conventional manipulators are generally designed for a specific application in industry due to which there is always a requirement of new manipulator for new application or operation. This will add the manufacturing and setup cost to product. This problem can be overcome by using the modular manipulators.

1.3 Modular Manipulator

Modular manipulators are new type of manipulators that are designed to increase the utilization of manipulators by modularizing their architecture. The effectiveness and functionality of a modular manipulator is simple and easy to increase compared to conventional manipulators. These manipulators are generally composed of several different or identical module types which vary in size according to the application. The architectural structure of module provides redundancy in modular manipulators, as they can be designed with more than 6 degrees of freedom (DOFs). The program for controlling, inverse kinematics and dynamics for modular manipulators is more complex than traditional manipulators. Different cross section and shapes can be used for the modules of the modular manipulator. The degree of freedom increases as the number of the modules connected to each other increases. Modular manipulators can be manually or self-reconfigured to form a different robot that may perform different applications according to the working environment.

1.4 Motivation

Today the most precious thing is time and then the resources for an industry. Every organization or an industry wants to utilize the time and resources to full extent as possible. To fulfill this type of demand the modular manipulator plays a vital role. The modular manipulator can be assembled as per the required application and can be controlled using programs. This provides the motivation to design a modular manipulator that can meet the industry standard and can be used for various applications. The modular manipulator is more complex to study as there are many possibilities with the set of modules to assemble a modular manipulator. The inverse kinematics and dynamic study of modular manipulator are much more complex than conventional manipulator. All these reasons are enough to motivate me to study the modular manipulators and design it to meet the challenges and as the author’s interest is in domain of the robotics.

1.5 Application of Modular Manipulators

The thesis focus on the modular manipulators that can be used in the industry for material handling, pick and place operation, tightening of screws and etc. The applications of the thesis can vary according to the requirement in the industry. The manipulator can handle a load of maximum 5 kilograms. The modules and joints of manipulator is designed in such a way that based on the application the manipulator can be assembled. The modular manipulator presented can have variable degree of freedom as per the requirement. The design presented helps in saving cost for setup and purchasing of new conventional manipulator as the application changes. The modular manipulator also cuts the production time of an object in the industry. Thus the study can help the industry to save the resources.

1.6 Scope of the Thesis

In 21th century the demand of the world is changing rapidly. The changes in the demands force the organization or an industry to make changes in the product. As the product design and specification changes the industry need to change their manufacturing and automation unit. So this thesis mainly focuses on the design of modular manipulators to accommodate the changes in automation of an organization. As the modular manipulators are complex in terms of their structure, kinematic study and dynamic study but are more flexible to perform different tasks. Therefore the research should be carried out on modular manipulators.

1.7 Organization of the Thesis

The organization of thesis is given below:

In **Chapter 2,** the literature review of the modular manipulator is discussed. The main focus is given on the design of the modules and the modularity associated with it. This chapter also covers the evolution of modular manipulator. The discussion on how the performance changes when the open linked chain is replaced by a closed chain in a manipulator is given in this chapter.

In **Chapter 3,** the design of the joints and links is discussed. Two different designs are presented one is bevel gear approach and other is helical gear approach. The joints and links are assembled together to show 2-link modular manipulator and 4-link modular manipulator using both approaches. The working of modular manipulators is discussed.

In **Chapter 4,** the 2-link modular manipulators are presented in different configuration with both bevel gear approach and helical gear approach. These different configurations of the manipulators are analyzed when the load at link is varied. The static analyses of the manipulators are done in ANSYS. The stress and deformation of the modular manipulators are computed.

In **Chapter 5,** the 2-link and 4-link modular manipulators are shown with different configuration with both bevel gear approach and helical gear approach. The dynamic analyses of these manipulators are done using SimWise 4D. The results are obtained in the form of plots for stress and displacement and are given in this chapter. The design of links is then modified and again the analyses are done. At last results are compared.

In **Chapter 6,** conclusion of the thesis with the results is discussed and the future directions in which the work can be extended are given.

Chapter 2

Literature Review

2.1 Introduction

This Chapter discusses about the literature review of the modular manipulators. The main focus is given on the design part of the manipulator. Different designs of modular manipulators which are given by the researchers are presented in this chapter. Merits and demerits are also discussed in order to analyze the design and certain observations are made to develop a new design.

2.2 Denavit-Hartenberg (D-H) representation

Denavit-Hartenberg(D-H) representation was proposed by Denavit and Hartenberg [1] in 1955. This representation gives a systematic notation for assigning right handed orthonormal coordinate frames, one to each link in an open kinematic chain of links. After assigning coordinate frame we can map the tool tip frame to the base frame using the 4x4 homogeneous coordinate transformation matrix termed as arm matrix. Based on arm matrix we can calculate the kinematics and dynamics related to a manipulator.

2.3 Different Designs of Robots

In this section, different types of designs for the robot are discussed. The discussion helps in knowing how the design helps in simplifying a task. The different designs also show how the complexity of the robot increases with the design. The robots with more degree of freedom are also complex to handle as variation in single angle or length can damage the whole structure of the robot. The kinematic and the dynamics of the robot also becomes complex in this type of cases.

2.3.1 ACM

The active cord mechanism (ACM) having snake-like robotic mechanism, was development by Hirose [Hirose, 1993]. The ACM was used to try to mimic snake movement. It is a homogeneous modular robot. Locomotion and manipulation was implemented in for the ACM. Figure 2.1(a) shows ACM-R1. It operates in 3D but was not having the ability to self-reconfigure.

2.3.2 TETROBOT

A modular system, TETROBOT was implemented by Hamlin and Sanderson [Hamlin and Sanderson, 1996]. A homogeneous truss structured robot as shown in Figure 2.1(b) was designed using Novel spherical joints. The spherical joint design allows the structure to move spherically around a centre of rotation. However, some connecting parts are assembled manually. There were several possible configurations of system presented by authors as follows: Double Octahedral, Tetrahedral Manipulator as shown in Figure 2.1(b) and Six Legged Walker TETROBOT. The applications of these manipulators were construction sites and space/sea exploration.

2.3.3 CEBOT

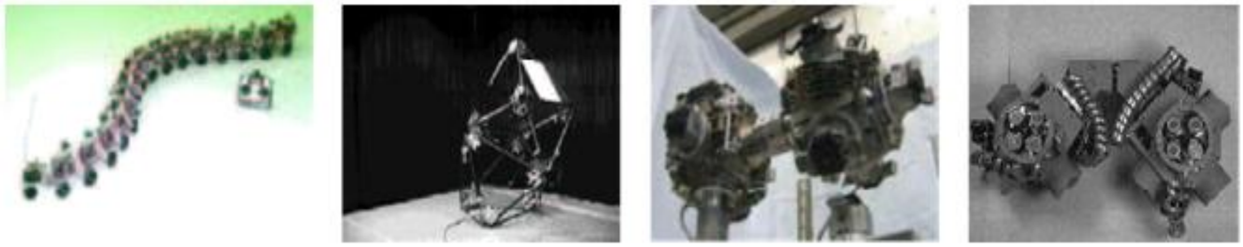
Fukuda and Kawauchi [Fukuda and Kawauchi, 1990] developed a cellular robotic system (CEBOT). CEBOT is a homogeneous modular robot composed of cell having limited sensing and computation. The study of examining an optimal arrangement of cells for a particular application was carried out. The robot was not self reconfigure. The Experiments were carried out for automated reconfiguration.

2.3.4 Fracta

3D [Murata *et al.*, 1998] and 2D [Tomita *et al.*, 1999] categories of homogeneous distributed system were considered by Murata *et al.* Fracta as shown in Figure 2.1(c) was designed in such a way that it has three symmetric axes with twelve degrees of freedom. The connecting arms are attached to each faces of the cube. By means of rotating the arms and an automatic connection mechanism self-reconfiguration was achieved. Every unit was controlled with microprocessor and communication system. The demerit of this design is that each module is very big and heavy. The connection mechanism uses six sensors and encoders, further increasing system complexity.

2.3.5 Molecule

A 3D homogeneous self-reconfigurable system is the Molecule as shown in Figure 2.1(d). Each molecule has a pair of two degree of freedom atoms which is connected by a link (termed as bond). 3D shapes are formed by suitably connecting a number of modules [Rus and McGray, 1998]. Each atom can perform twelve movements resulting in self-reconfiguration. Independent movement on a substrate of molecules including 90 degrees concave and convex transitions and straight-line traversal to adjacent surface can be per-formed.



(a) (b) (c) (d)

Figure 2.1: (a) ACM-R1 [2] (b) Tetrobot [3] (c) Fracta [5] (d) Molecule [7]

2.3.6 Metamorphic Robotic System

Chirikjian [Chirikjian, 1994; Pamecha and Chirikjian, 1996] demonstrated the metamorphic robotic system as shown in Figure 2.2(a). The shape of module is planar hexagonal having three Degree of freedom that combines with others having different geometry. The merit of each module is that it has abilities to connect, disconnect and rotate around its neighbors. The demerit of this design is that it is restricted to planar mechanism.

2.3.7 Proteo

Bojinov *et al* [Bojinov *et al.*, 2000] proposed a metamorphic robot, Proteo as shown in Figure 2.2(b). The design of each module is such that it is a rhombic dodecahedron having twelve identical connection faces which allow it to attach with other modules. For connection of module electromagnets are used. Motion of proteo is quite simply consisting of a number of rotations about the edges of the faces and simulation of it is shown. The design of this robot includes homogeneous rhombus units. The demerit of this manipulator lies in that the twelve connecting faces make the design and working more complex and costly.

2.3.8 Crystalline

Rus and Vona [Rus and Vona, 2000] described the concept of a Crystalline module as shown in Figure 2.2(c). Modules are having square cross- section. In square cross section a connection mechanism is modeled which helps in locking modules together. Each module has the capability of expanding and contracting with which the robotic system gets actuated. Each module has capability of expanding its size to twice the original size. The module is controlled by an on-board CPU, IR communication and power supply.

(a) (b) (c) (d)

Figure 2.2: (a) Metamorphic system [8] (b) Proteo [10] (c) Crystalline [11] (d) Fractal robot [12]

2.3.9 Fractal Robot

A novel polymorphic robot termed as "Fractal robot" as shown in Figure 2.2(d) was proposed by Michael [Michael, 1994]. The design of Fractal robot consists of homogeneous cubes with screw and groove mechanisms at each cubic face which allow it to undergo geometry changes and tasks. By sliding one or a group of cube to another location along attached face(s) the structure of robot is formed. The mechanism of this robot looks complex to implement and the results are seen in simulation. In this robot, the merit of each module is that it can fasten special devices like gripper, camera.

2.3.10 Fractum

A 2D homogeneous system named as Fractum was developed by Tomita *et al* [Tomita *et al.*, 1999] as shown in Figure 2.3(a). Fractum has six arms, three permanent magnet female arms and three electromagnet male arms. This model works on basis of magnetic. When the polarity of electromagnet male is same as the polarity of permanent magnet female then, connection takes place. If the polarity is opposite the disconnection occurs. Every unit consists of its own processor and optical communication. The merit of Fractum robot is that it has simple mechanism but the demerit is that it is having a planer work envelop (2D).

2.3.11 Miniaturized Self-reconfigurable System

Yoshida *et al* [Yoshida *et al.*, 1999] presented the miniaturized self-reconfigurable robot as shown in Figure 2.3(b). In this approach, a male and female connection is used to combine the modules together with the help of locking pins. The lock between modules is released by a shape memory alloy (SMA) spring. The size of system is minimized by using novel SMA actuators in this robot. However, disadvantages of it are limited torque and a short range of movement.

(a) (b) (c) (d)

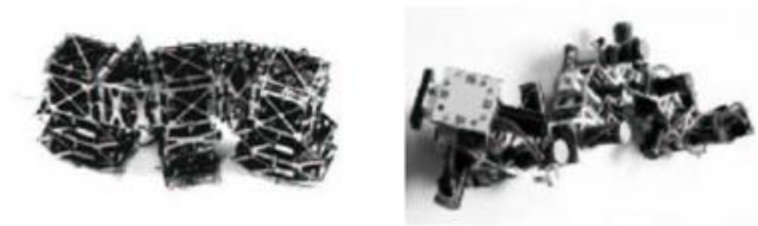
Figure 2.3: (a) Fractum [13] (b) Miniaturized unit of Yoshida [13] (c) CONRO [14] (d) I-Cubes structure [15]

2.3.12 CONRO

CONRO [Shen *et al.*, 2000], is a self-reconfigurable robot formed by two degree of freedom homogeneous modules. Each module as shown in Figure 2.3(c) has 108mm length and weight 115g. Modules are connected to each other with docking connectors which has locking mechanism that works with pin and holes. Each module consists of two batteries, two motors, an IR communication system and a micro-controller. The design of homogeneous CONRO robot has self-reconfiguration capability. It is having compact size which can reconfigure.

2.3.13 I-Cubes

I-Cubes (or ICES-Cubes) presented by Unsal and Khosla in 2000 is a modular self-reconfigurable robot as shown in Figure 2.3(d). I-Cube is a bipartite system consists of a link having three degree of freedom and a connector which acts as passive element. The link has a length of 80mm and weight 370g. The connector has cubic shape which has six faces for connection. A novel mechanism is used which results in an inter-module attachment and detachment to perform various applications such as moving over obstacles.



(a) (b)

Figure 2.4: (a) Polypod [16] (b) PolyBot(G2) [17]

2.3.14 Polypod and PolyBot

A modular reconfigurable robot known as Polypod was proposed by Yim. It has two types of modules. The first has two degree of freedom segment consists two connection ports and second has a passive cubic node with six connection ports. The robot is assembled manually using modules and bolts in order to achieve flexibility [Yim, 1994]. Polypod is shown in Figure 2.4(a). Each module is cube of 60mm. Another type is polybot as shown in Figure 2.4(b).

2.4 Modular Robot for Industrial Application

The Modularity in robot came into picture in 2000 when Dahmus and Stone have thought to make the link of robot reconfigurable. There are number of definitions given by researchers in past. Few are: “modules are a group of standard and interchangeable components” [Galsworth, 1994]; “a module is a complex group that allocates a function to the product and which could be changed and replaced in a loose way and be produced independently” [Wilhelm, 1997]; “a modular system is made of independent units which can be easily assembled and which behave in a certain way in a whole system” [Baldwin and Clark, 2000]. Basically the term Modularity denotes the independent parts or links that configure together to form different structure or robot as per the application. The development of modular robots is an interesting challenge for researchers as it is associated with remarkable potential benefits and application perspectives in industry. Modularity can be present at different levels i.e. at Design and Development phase, at Production, Operative modularity, modularity in retirement [Fixson 2003]. From all of these levels the operative modularity is treated more important as this helps in achieving good set of Robot configuration to match the requirement of application. One important advantage of modularity is that it helps in reducing the Mean Time To Repair (MTTR). Due to which the availability of the manipulator increases. Generally assembly of the robot is done manually but some researchers have given an idea to automate the process of reconfiguration by the robot itself [Murata et al., 2000, 2002; Rus and McGray, 1998]. The modular and self configurable robot has a great advantage as it can work in complex, unmanned and unknown environment.

Modular robots are economically desired in these conditions:

1. In industry where production changes rapidly which requires the reuse of the robots for different applications; and
2. Manufacturing processes where the availability of resources is critical.

Focusing the attention on modular manipulator, the operative modularity plays an important role as it allows achieving a great variety of robot configurations starting from a small set of modules, in order to match different operative requirements. Moreover, modularity drastically reduces the time-to-repair of the robot and consequently improves its overall availability, if a complete set of all modules are available; this is a fundamental requirement for modern industrial enterprises aiming at maximizing the resources availability. The assembly of the robot in most of the cases starting from the basic modules is generally performed manually; in order to improve the level of autonomy of the robots, some researchers have tried to design self-reconfigurable robots, capable of changing their configuration automatically [Murata et al., 2000, 2002; Rus and McGray, 1998]. Modular and self-reconfigurable robots are most effective in complex, unknown environments, or in unmanned environments for self-repair. The demerit of this approach is the lower mechanical performance, due to complex and heavy structure of the modules.

In space applications modular serial manipulator are generally used [Yim et al., 2003; Hirzinger et al., 2004, 2002]. The links close to the base are not more loaded than the links close to the tool or end effectors due to absence of gravity. Therefore the possibility to use modular manipulator assembled with modules of equal length is good as the performance is not affected. On the other side, when the gravity is present each link supports the gravity force that acts on the following ones, therefore serial robots which are well designed are always characterized by links and motors with size decreasing from the base to the end-effector. Due to this reason, the design of the modular manipulator is complex and a good library of links is must.

In order to minimize the number modules in the library a set of different modules are designed [Acaccia et al., 2008]. Their study has been accomplished according to the following steps:

1. Conceptual design of the library consisting of robotic modules which are capable to fulfill the demands in common industrial applications, with consideration of the requirements mentioned in the previous section.
2. Architectural synthesis of the different modules types.
3. Detailed design of the modules through a concurrent engineering approach, by integrating FEM analysis and multibody simulation.

The aim of the work was to design a modular robotic system keeping in mind these general purpose requirements in order to obtain a technical solution suitable for widespread industrial applications:

1. possibility of composing a serial arm with good payload/weight ratio;
2. modules should have compact shape and capable of preventing accidental collisions;
3. connection of the modules must be quick and reliable; and
4. A library of modules with a comparatively limited number of elements, but sufficient to realize the most industrially important robotic architectures.

They proposed modular approach points at the design of a library of modules allowing the building up of a generic serial robotic architecture; this library consists of two categories of modules:

1. **Joint modules:** Composed of a joint, the corresponding actuator (motor and gearbox), a drive unit, a processing unit for the motion control.
2. **Link modules:** Not actuated, they can be inserted between two joint modules, between the base and the first joint module, and between the last joint module and the end effector (if necessary, two joint modules can be connected without the interposition of link modules).

The manipulator library is characterized by two levels of modularity:

1. **Mechanical modularity:** Different serial robots can be assembled starting from the elements of the library.
2. **Control modularity:** The assembled robot is governed by an embedded distributed control system; more precisely, every joint module is equipped with a local processing unit for properly driving its motion.

The mechanical modularity is a feature that does not depend on the control modularity, and a centralized control unit is used to control a mechanically modular robot. The advantage of the proposed distributed control approach is that there is no need to program the control unit according to the kinematics of the specific assembled serial chain.

The different joint modules of the library have different mobility (revolute or prismatic); moreover, for each type of mobility various sizes are present, thus allowing:

1. Robots that can have different dimensions and function
2. Inside the same robot, the different size of modules is present to comply with the gravitational effects.

In a generic serial robot, revolute joint modules can be assembled with different orientations with respect to the rest of the chain; commonly, only two types of orientation are possible:

1. **Axial.** The joint axis is parallel to the longitudinal axis of the previous link as shown in Figure 2.5(a).
2. **Transversal.** The joint axis is orthogonal to the longitudinal axis of the previous link as shown in Figure 2.5(b).

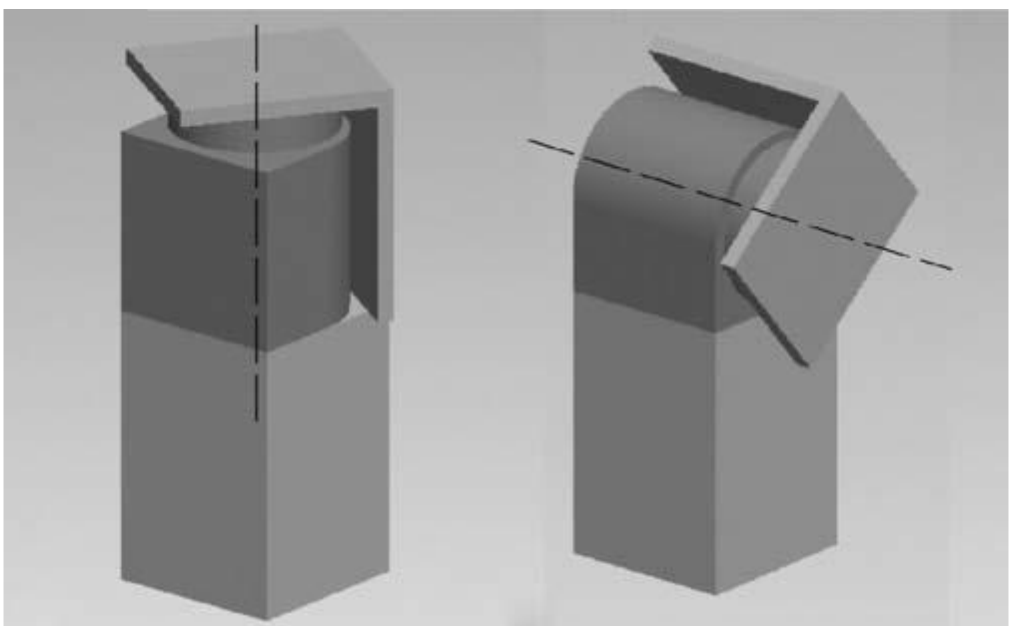
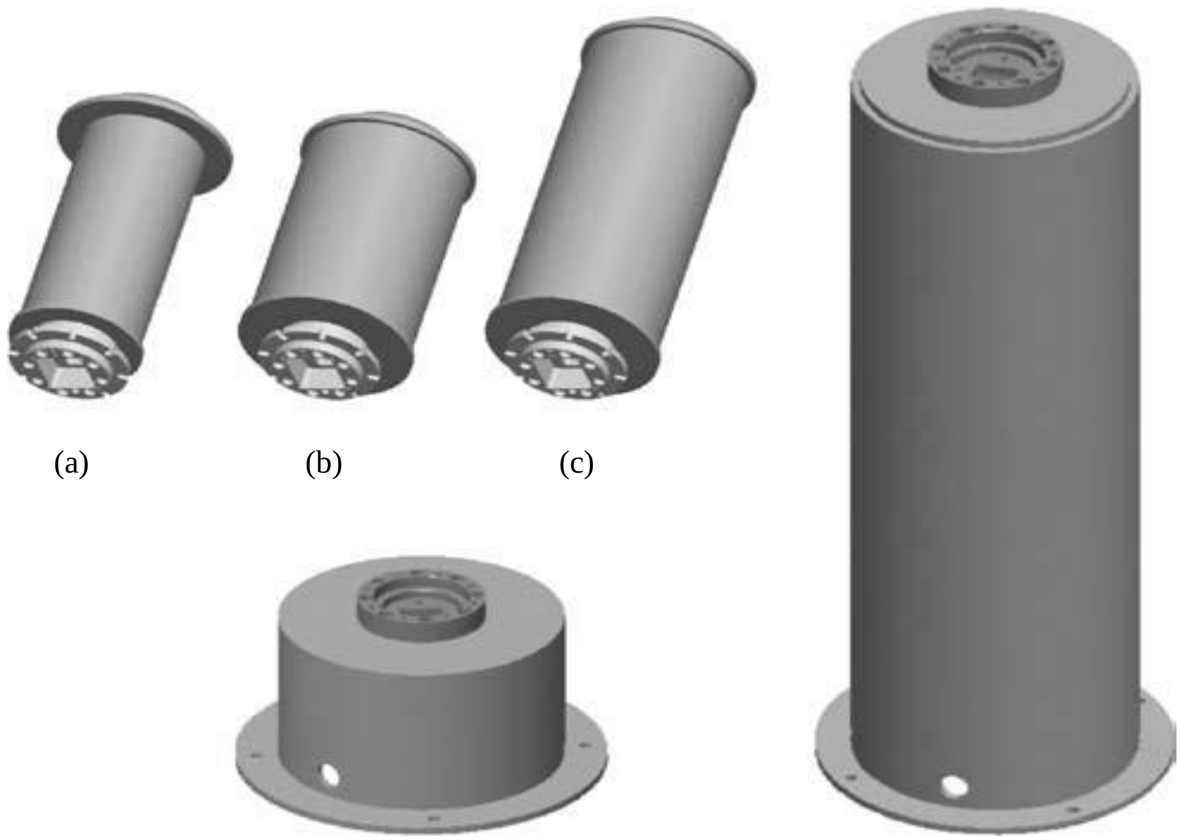


Figure 2.5: (a) Axial and (b) transversal assembly of a revolute joint module in a generic serial chain [28]

To improve the modularity of manipulator by reducing the number of elements of the library revolute joint modules are designed in such a way that it can be assembled both in axial and in transversal configuration. Therefore, they proposed library composed of four sets of modules: link modules (Figure 2.6) and three types of joint modules:

1. Revolute joint module (Figure 2.7(a));
2. Prismatic joint modules (Figure 2.7(b); and
3. Wrist modules (Figure 2.7(c)).

The design of the revolute joint modules has been modeled in such a way that mechanical features (torque, angular speed and structural strength) of the revolute joints of a wide range of medium-small general purpose serial robots. On this basis, it was decided to design, as first step, three sizes of revolute joint modules (small, S; medium, M; large, L).

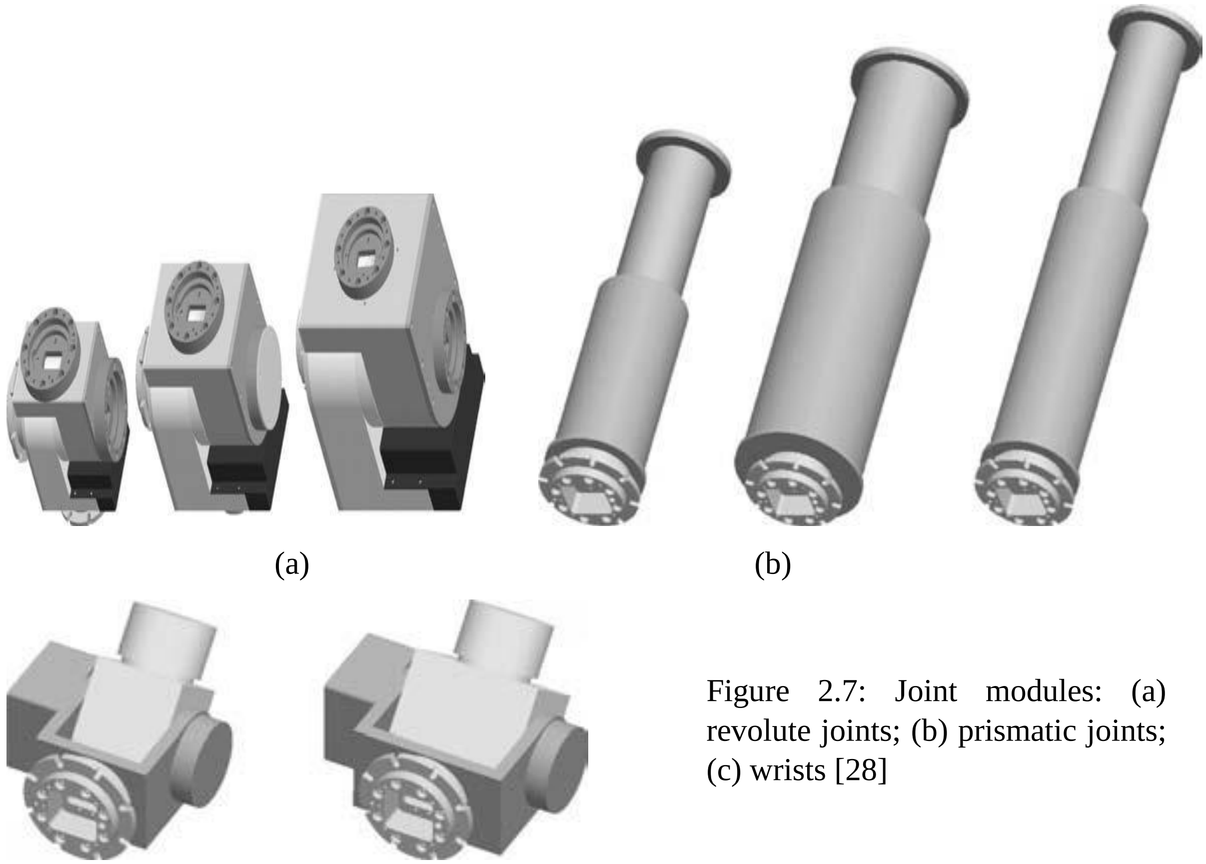


(a) (b) (c)

(d) (e)

Figure 2.6: Link modules: connections between link modules (a,b,c) and robot bases (d,e) [28]

Wrist modules are designed to have two degree of freedom devices characterized by two revolute joints with orthogonal axes; it is suitable for adding two rotations to the end effector. Three degree of freedom wrists having three intersecting axes and spherical motion can be obtained by assembling wrist module and revolute joint module in axial configuration is shown in Figure 2.8.



(a) (b)

(c)

Figure 2.7: Joint modules: (a) revolute joints; (b) prismatic joints; (c) wrists [28]

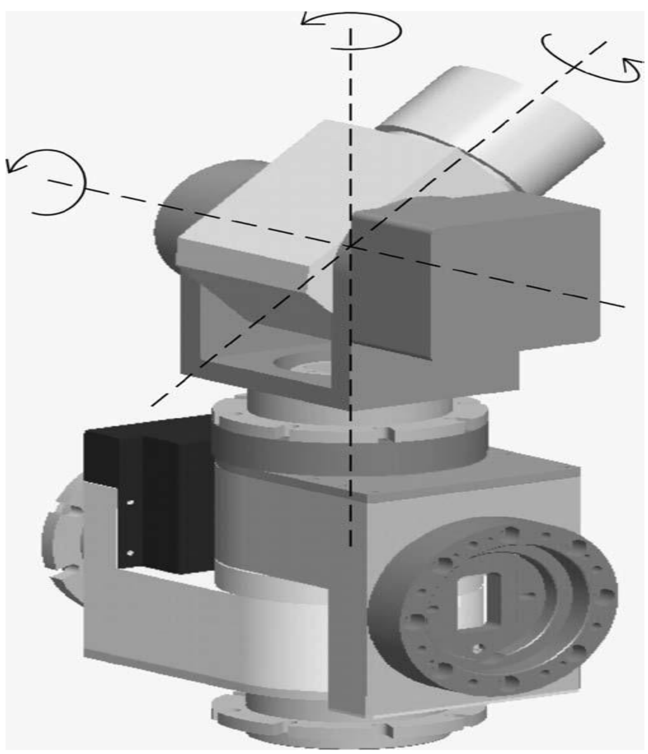
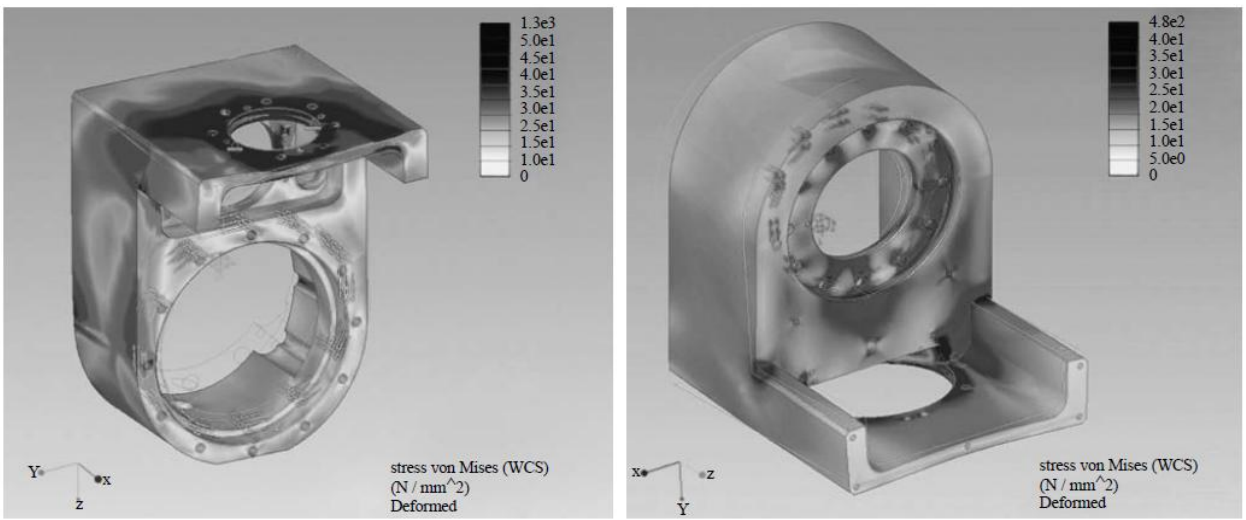


Figure 2.8: Assembly of a three-degree-of-freedom spherical wrist [28]

For the module joints and links, different materials were considered in this study. The requirement of the material are strength, resistance to shocks, lightness and manufacturing cost were considered. The carbon fiber was rejected due to the high manufacturing cost. From the list of lightweight metal alloys, the constructions in titanium and aluminium alloys were compared by FEM analysis (Figure 2.9). According to the results the masses of the inlet and outlet bodies can be slightly reduced (5-7 per cent) by using titanium instead of aluminium, but when aluminium was used the overall mass of module got reduced by 30 percent. Therefore aluminium was preferred as it also has lower cost and better machinability.



(a) (b)

Figure 2.9: FEM analysis of the revolute joint module: (a) von Mises stress of the inlet body (b) and of the outlet body in presence of combined moment [28]

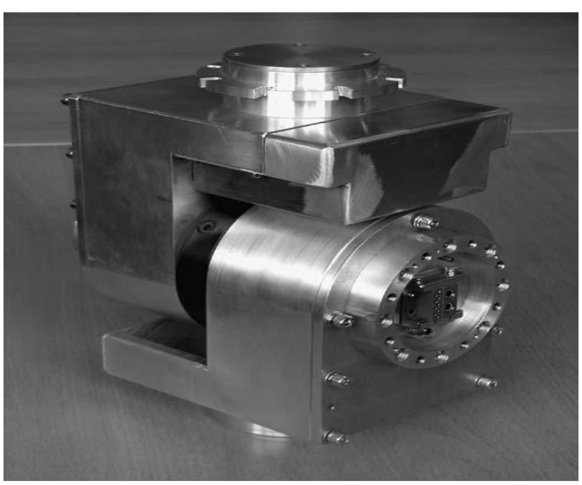


Figure 2.10: External view of the revolute joint Module [28]

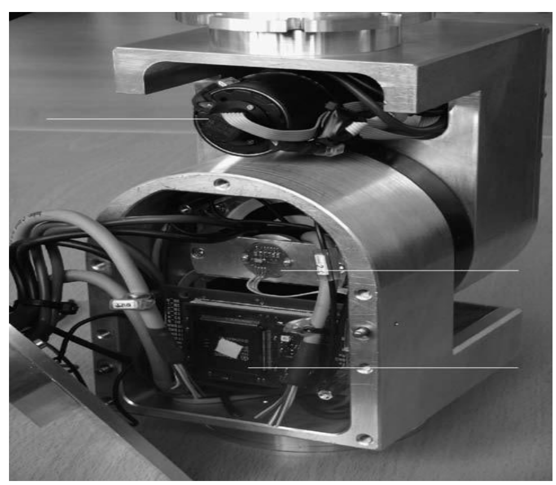
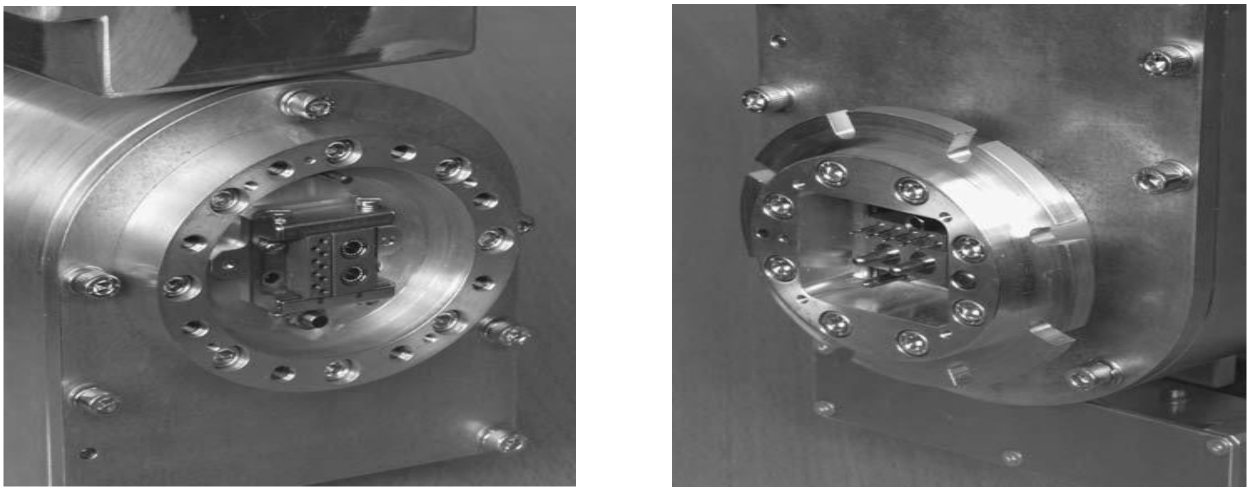


Figure 2.12: Internal view of the module [28]

The prototype of the revolute joint axis, size M, has been realized (Figure 2.10). Figure 2.11 shows the female interface (a) and the male interface (b). Figure 2.12 shows the internal view of the module.



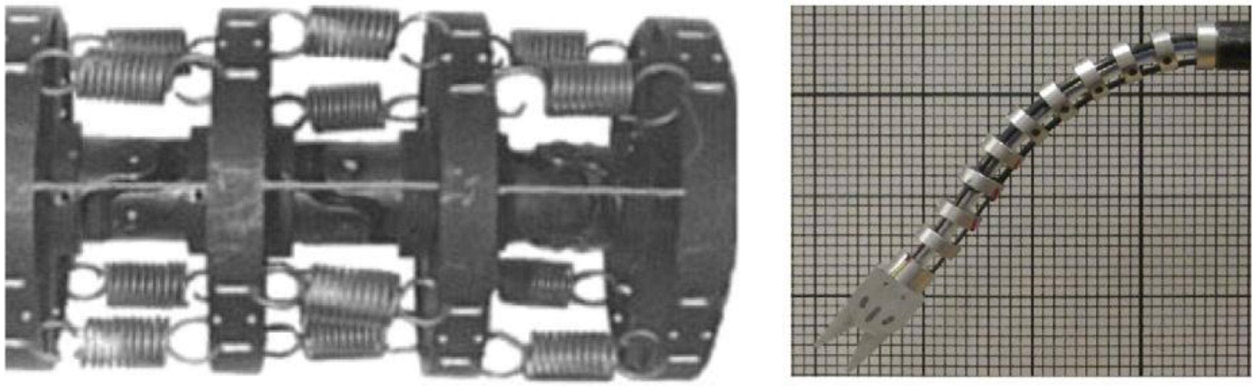
(a) (b)

Figure 2.11: (a) Female interface and (b) male interface [28]

2.5 Snake Arm Robot

Comparing with traditional rigid-link robots, snake arm robots have a continuous shape with multi-section construction. Snake robots have wide range of applications in medical surgery and industrial fields. A large number of snake arm robot designs have been presented in academic and industrial fields in past, but there is no such design of snake robot which can carry a relatively large payload, while having small diameter/length ratio, great flexibility and an actuation system. A new design of a snake arm robot was developed which has a unique twin actuation construction and maintains the cable tension in any arbitrary configuration [Dong et al., 2014]. Also, this design has a great flexibility and an appropriate stiffness enabled by compliant joint construction. Further, a kinematic model for this construction was introduced, which is among the most efficient method along the existing approaches.

In general the design of snake robot consists of backbone which enables the bending movement or support the structure, whenever it is flexible. The bending movement of the snake robots is achieved by rigid universal or spherical joints. All snake arm robots can be classified into two groups based on the backbone design. One group utilizes a rigid backbone connected by universal joints as shown in Figure 2.13(a) while others have flexible rod/tube as a backbone as shown in Figure 2.13(b), which is made up of elastic material.



(a) (b)

Figure 2.13: Two different concepts for snake arm robot construction (a) universal joints (b) flexible backbone. [29]

Disadvantages of existing snake arm robots

1. Flexibility and stiffness

Depending on the bending shape/angle of each section, which determines the obstacle avoidance capability of the system, the flexibility of snake arm robots changes. The flexibility is determined by the number of joints in a single section in case of rigid backbone snake arm robots. Specifically, a snake arm robot having multi-joints in each section is shown in Figure 2.14(b) has greater bending ability to access confined spaces, when it is compared with one with a single joint in each section as shown in Figure 2.14(a). In order to have two degree of freedom at single section the snake robots generally have universal joints in each section. Elastic rod/tube are used to obtain an evenly distributed bending shape/angle for each section as shown in Figure 2.14(c) and acts as the backbone instead of a multi-joint rigid backbone concept.

2. Actuation

There are two different concepts used in actuation, one uses three independent cables and actuators for driving a single section as shown in Figure 2.15(a) while the second utilizes two actuators and pairs of cables as shown in Figure 2.15(b). The former concept is applied in most of the existing designs of snake arm robots, while the only design which applies the latter concept has to employ a pulley system for compensating the internal tension of the cables, which makes the actuation system complex and bulky. Although the twin actuation design concept as shown in Figure 2.15(b) can significantly minimize the weight and size of the actuation packing system, neither the flexible backbone as shown in Figure 2.14(c) nor the rigid universal joint snake arms as shown in Figure 2.14(a) and (b) can apply the twin actuations for one section solution directly, due to the kinematic problem caused by the cable tension problem.

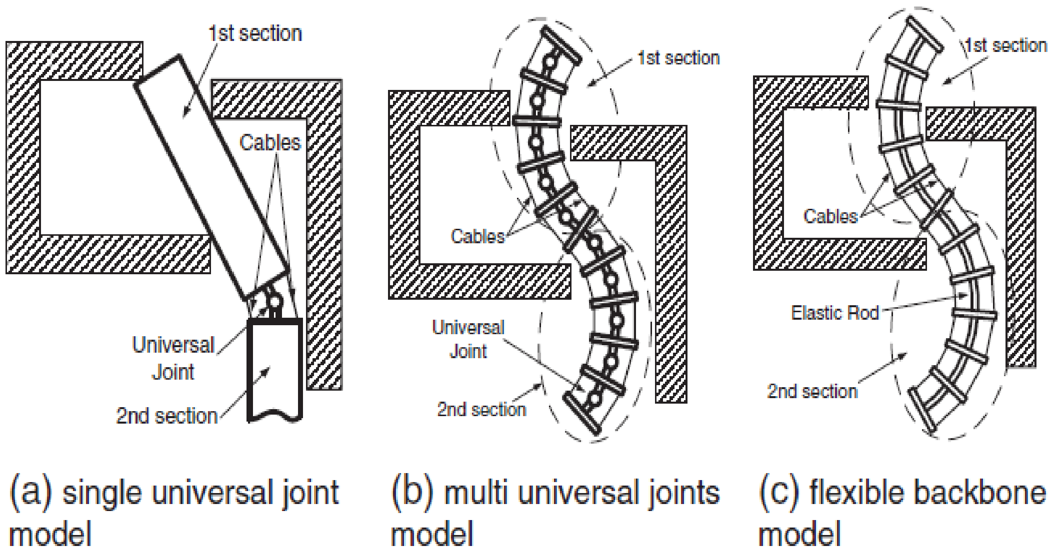


Figure 2.14: Flexibilities of different snake arm robots: (a) single universal joint model (b) multi universal joint model (c) flexible backbone model. [29]

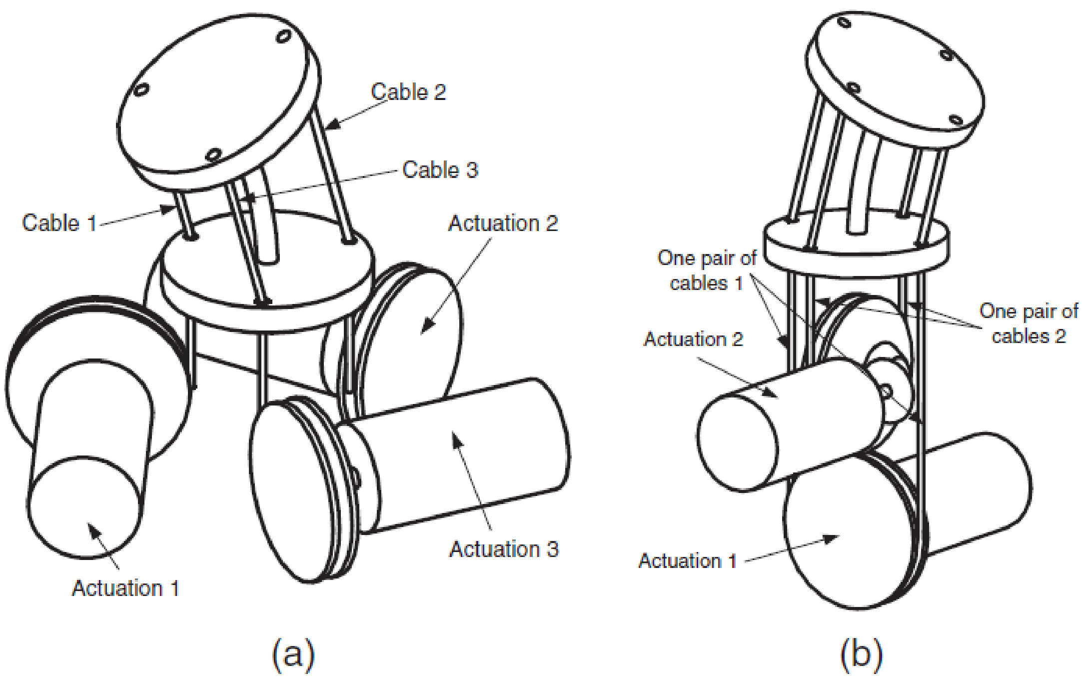


Figure 2.15: Different actuation types of snake arms: (a) triple actuation and (b) twin actuation concepts. [29]

New concept for snake arm robot construction

To overcome the disadvantages in previous designs, a novel snake arm robot construction was presented, which has improved flexibility and stiffness and can employ two actuations for each section.

As shown in Figure 2.16(a), the snake arm composed of disks, actuation cables, compliant joints and rigid rods/tubes. The disks are connected with the help of compliant joints and rigid rods/tubes; the bent in snake arm is due to the torque generated by actuation cables.

The construction of a snake arm robot as shown in Figure 2.16(b) consists of the following elements:

• A material which is flexible and able to be bent with little residual plastic deformation is used in manufacturing of Compliant joint. The compliant joint can be made by a single elastic rod/tube, or a universal joint construction connected by elastic rods or tubes as shown in Figure 2.16. This design facilitates rotation axes of these two pairs of elastic rods to coincide with each other. Thus, this functions as a universal joint.

• A material which is significantly stiffer when compared with the elastic rod is used to manufacture rigid rod/tube.

• Disks are used for constraining the cables; note that the middle point (pivot point) of compliant joint is on the top plane of the disk bulge.

• Cables are present in two pairs (1A and 1B; 2A and 2B) each one is actuated by a single motor.

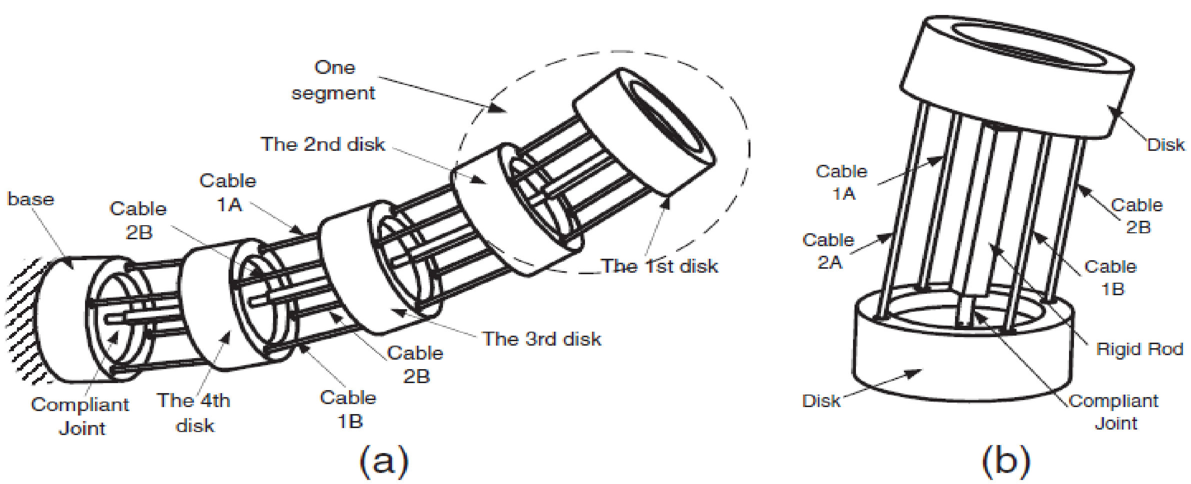


Figure 2.16: Snake arm construction using two actuations concept: (a) general view; (b) one segment. [29]

2.6 Slider Crank Mechanism Based Robot

Industrial manipulators are generally open kinematic chain arm like structure and are generally composed of serial links interconnected to each other by means of revolute and prismatic joints. As open kinematic chain robot arms are relatively simple structures, they generally do not have sufficient mechanical stiffness and have undesired elastic behavior that decreases the level of performance of robot under high speed and heavy operation conditions. On the other side, closed kinematic chain type manipulators are preferable in many industrial applications because of their high structural stiffness.

Parallelogram mechanism as a robot arm is one of the most powerful alternatives providing high structural stiffness as it is a closed chain mechanism. As it can be seen that closed kinematic chain robot manipulators are generally massive structures, but they have many ideal features such as high mechanical stiffness, lower power requirements and positioning error, direct drive facility, good force–velocity characteristics.

Slider crank mechanism is used as a close kinematic chain in the next study [koser, 2003]. In this study, a new type closed kinematic chain robot arm is introduced. In plane manipulability and transmission characteristics of the robot arm are examined by means of Jacobian matrix. To demonstrate the effectiveness of the proposed design of robot arm, kinematic performance of proposed robot is compared with general conventional two link 2R open chain robot arm.

Figure 2.17 shows side view drawing of the slider crank mechanism based robot arm. Its numbered components are: (0) robot base, (1) robot waist, (2) arm, (3) crank, (4) slider, (5) coupler, (6) wrist, (7) end-effector. A revolute joint is located robot waist and robot base and robot waist can rotate freely about a fixed axis with respect to the robot base. A revolute joint is present between Arm and the robot waist. Arm and crank are connected together by means of a revolute joint. The arm supports slider with the help of a prismatic joint. Coupler is connected to the crank by a revolute joint. The wrist is connected to Slider and coupler by revolute joints. Coupler or slider locks the motion of Wrist. The degree of freedom of fundamental structure of slider crank mechanism based robot arm is four. Degree of freedom gets reduced to three if slider or coupler is locked to the wrist, then structure transforms to a basic robot arm. Due to this, the robot arm can be employed as both redundant and nonredundant manipulator. The structural properties of both spherical and anthropomorphic robot arms can be combined using this closed chain basic robot and can be alternatively transformed from one another whenever required. The kinematic performance of robot arm having closed chain is analyzed by considering the wrist link length as zero. This helps in understanding kinematic characteristics of the robot arm in a global sense.

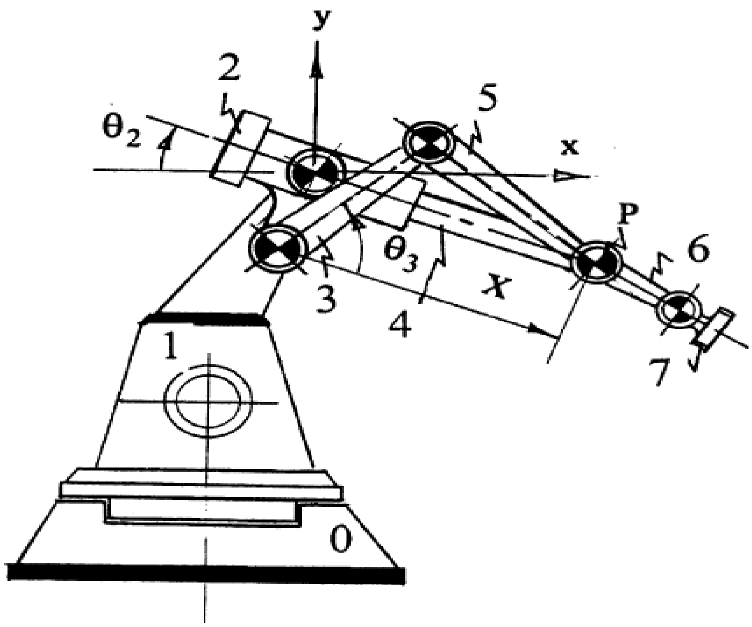


Figure 2.17: Structure and joint variables of slider crank based robot arm. [30]

He has derived the equations of motion for an idealized SC robot arm using L-E formulation together with D–H matrix representation. For an effective control of a robot arm, one would like to obtain a simplified and explicit set of closed-form equation of motion. In order to achieve a compact formulation and eliminate iterative constraint equation, joint parameters are minimized and kinematic solution of the closed kinematic chain mechanism is simplified by using equal crank and coupler link length. A long wrist is assembled which is locked to the coupler in the structure of robot arm in order to realize more effective manipulator. The arm matrix is given by

$$A_5^0 = \begin{bmatrix} C_1 C_{23} & -C_1 S_{23} & -S_1 & C_1(LC_{23} + rC_{32}) \\ S_1 C_{23} & -S_1 S_{23} & C_1 & S_1(LC_{23} + rC_{32}) \\ -S_{23} & -C_{23} & 0 & d_1 - LS_{23} - rS_{32} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

By using Lagrange formulation, generalized torque τ_i for joints i actuator

$$\tau_i = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{\theta}_i}\right) - \frac{\partial L}{\partial \theta_i} = \sum_{j=1}^{3} M_{ij}(\theta)\ddot{\theta}_j + \sum_{j,k=1}^{3} \Gamma_{ijk}(\theta)\dot{\theta}_j\dot{\theta}_k + g_i(\theta)$$

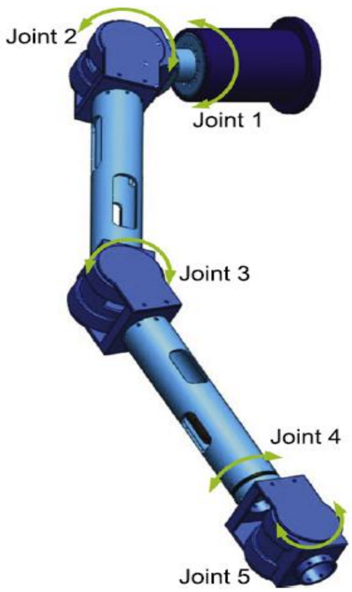
2.7 Drive Optimization for Robot

While designing the robot the drive optimization is also necessary. An optimization technique is used to optimize the drive including gearbox and motor for a light weight robotic arm [Zhou et al., 2011]. The drive train is the core part of a robotic system which has significant impact on the performance and cost of the whole system. In order to achieve a light-weight design, drive train optimization plays a vital role. A number of methods have been proposed for motor and gear selection in mechatronic systems.

While designing of robotic drive train consisting of multiple joints, the challenge is that not only the characteristics of motor and gearbox at a single joint, but also the dynamics of the robot should be taken into account and it varies with the selection of components and link dimensions. The technique adopted for optimization should be capable of handling discrete design variables as the transmission is typically composed of commercially available components. For entire drive train only few methods are available for the optimization.

The optimization method presented is applicable to serial robotic arms which aim for minimizing weight of the arm. In the method, the optimization is carried out for a prescribed trajectory of the end-effector, generated within the robotic arm's workspace. ADAMS is used for the inverse kinematic analysis to verify that the trajectory is within the joint space. A dynamic model of the robotic arm is taken which is used to formulate an optimization problem. A co-simulation platform is used to implement this method where robotic dynamics of robot is found with the help of MSC.ADAMS™, and the complex optimization is performed using Matlab™.

For optimization a light-weight robotic arm is taken having five degrees of freedom, with two at the shoulder, one at the elbow, and two at the wrist, as depicted in Figure 2.18. In this robot, harmonic drives are used as gearing elements. The joints consist of motors and harmonic drive gearboxes which are mounted inside it. The joint axes coincide with the axes of rotation. The physical realization of Joint 2 is illustrated in Figure 2.19. The same conceptual design was used for all 5 joints. The optimization was performed for this robot and significant results were obtained.



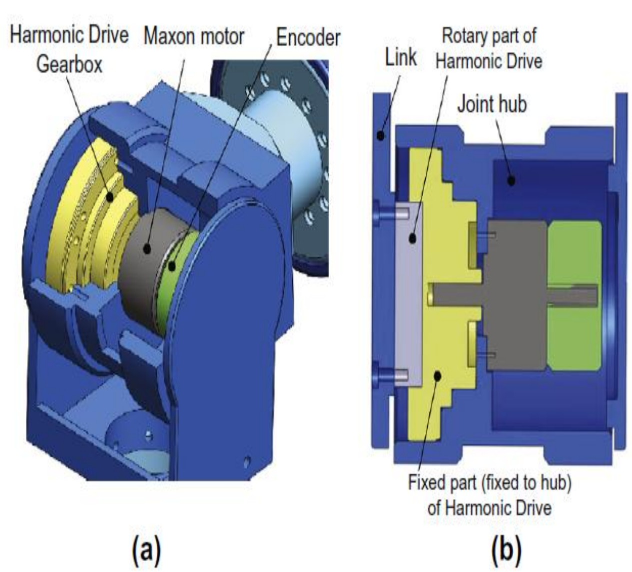


Figure 2.18: A 5-DOF light-weight robotic arm. [31]

Figure 2.19: Joint mechanism for Joint 2, (a) 3D view, (b) section view. [31]

2.8 Summary

The discussions on the different designs have been done in this chapter and it is seen that several types of approaches can be followed to design a robot. The flexibility of the manipulator can be increased by use of different modules having different size. By using a closed kinematic chain the performance of manipulator can be improved. The snake robots have great flexibility but these are more complex compared to other robots. It has been seen that drive unit in robotic system also plays a vital role thus an optimal drive unit is necessary to reduce the overall mass of robot. If the manipulator is a modular type with good set of modules in library it add to the flexibility in the system by performing different applications.

Chapter 3

Design and Assembly of Modular Manipulators

3.1 Introduction

In Chapter 2 different designs of the modular manipulator are discussed. Based on the discussion two different approaches for the design of modular manipulators are presented in this Chapter. In the first technique i.e. *bevel gear approach* two bevel gears are used to change joint angle and a subassembly of shaft and base is used to change the link twist angle. Whereas in the second technique i.e. *helical gear approach*, two helical gears are used to change joint angle and a subassembly of shaft and base is used to change the link twist angle. Designs and workings of the joints and links are discussed. Later the assembly of the joints and links are done in order to show 2-link and 4-link modular manipulators.

3.2 Bevel Gear Approach

The first approach used is based on the bevel gear and it is named as bevel gear approach. In this approach, two bevel gears are meshed and one of them is been driven by a motor and rotates the link resulting in change of joint angle. The second rotation i.e. link twist angle is changed by assembly of the shaft coupled to the base and this is done manually. The complete detailed assembly is discussed in the next sections.

In the following sections the design of module joints and module links are discussed. There after the module joints and links are assembled in order to show the assembly of the modular manipulators.

3.2.1 Design of Joints

The joint plays a vital role in the modular manipulator as the flexibility of the modular manipulator depends on joints. The joint should be designed in such a fashion that the strength of the structure of the modular manipulator will not get affected much by making them flexible to have multiple degree of freedom. While designing a joint care must be taken in case of the modular manipulator that it can be assembled with different links available in the library. While assembling the manipulator it becomes necessary to check that the links should have smaller size towards the tool tip when approaching from the base of manipulator. The joint consists of several parts that perform some specific tasks while moving a manipulator. The working and construction of the parts are explained below:

(a) **Base:** The base of the joint have eight holes on the top surface which will help in fastening it with the foundation as shown in Figure 3.1. The slots are provided on the circumference of the base in order to change the link twist angle. The accuracy of the angle increases with the number of slots. A shaft is mounted on the base which holds the rest of the structure. For the present design the numbers of slots are kept 8 and therefore by rotating the shaft to next adjacent slot the variation in link twist angle is 45^o.

(b) **Shaft for Base:** The shaft also have eight slots on its circular surface as shown in Figure 3.2 and it is chamfered in order to hold the rest of the structure of the joint. The motion between the shaft and the base are locked by the locking pins which are inserted in all eight slots provided on both base and shaft. The slots are made at an angle of 45^o and the shaft can be rotated on the circular cross section in the base so as to change the angle. After changing the angle between the shaft and the base they are locked together with the help of locking pins. As the rotation is about the x-axis it is variation in the link twist angle. Therefore the variation in the link twist angle is achieved by relative motion of the shaft and the base. The link twist angle is changed manually.

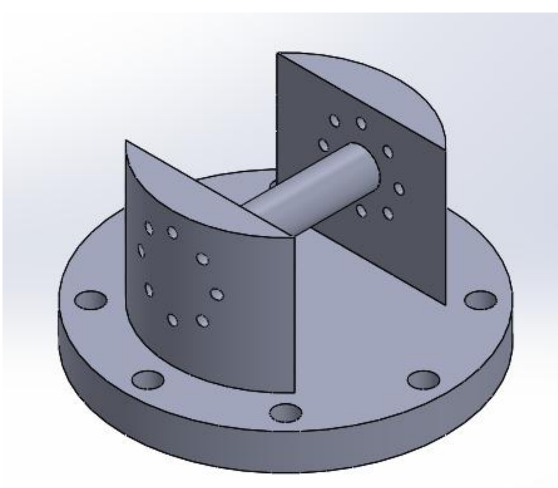


Figure 3.1: Base

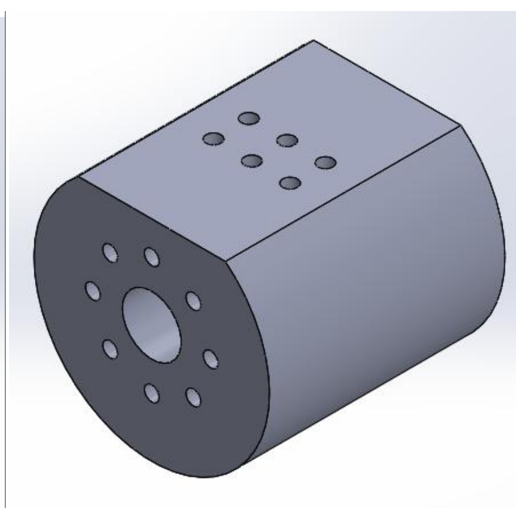


Figure 3.2: Shaft for base

(c) **Mounting Stationary:** The mounting stationary has U-shaped structure as shown in Figure 3.3. Mounting Stationary is coupled to the shaft for base using bolts. On other side the mounting stationary is fastened using bolts to stationary shaft which holds the rest of the joint structure.

(d) Shaft Stationary: The shaft stationary has two through holes at either ends as shown in Figure 3.5(b). These holes are used to mount the shaft to the mounting stationary and to lock the rotation of the shaft using bolts. One more through hole is created on the circumference of the shaft in order to attach bevel gear. The shaft also holds two bearings that are used for the motion between moving mounting and shaft.

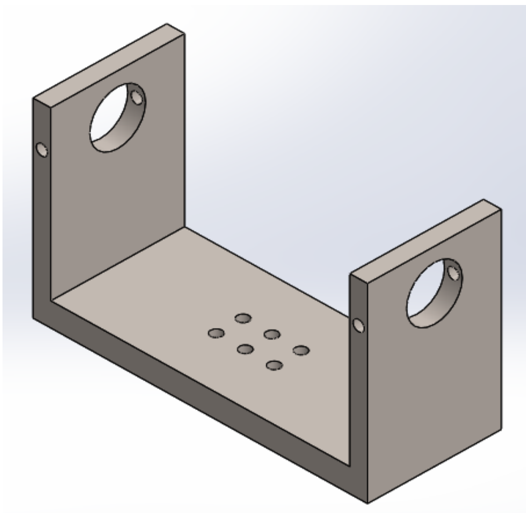


Figure 3.3: Mounting stationary

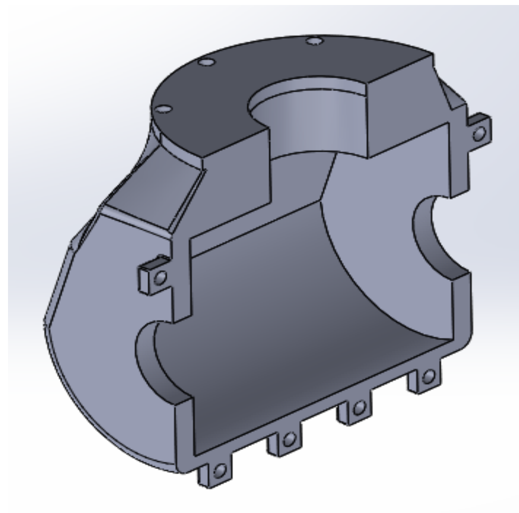


Figure 3.4: Mounting Moving

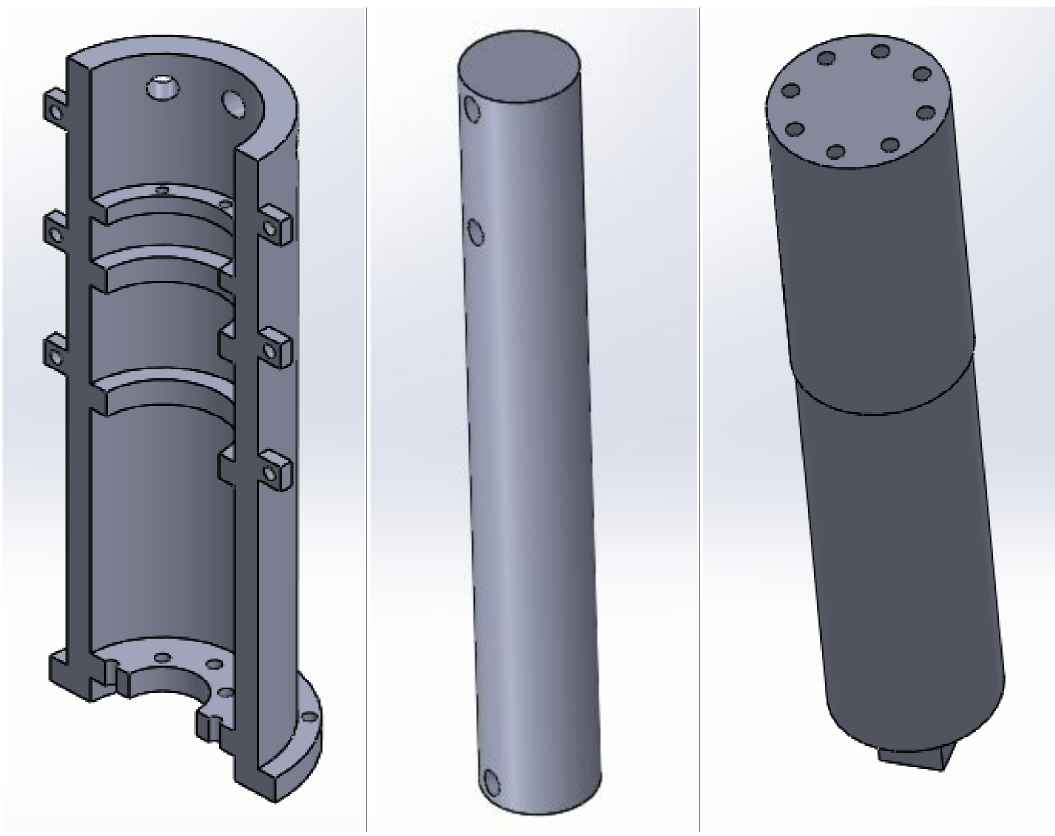
(e) Bevel Gear (driven): The driven gear is mounted on the shaft stationary and it is made stationary using bolts. Another driver gear is meshed with the driven gear. The specifications of the driven gear are given in Table 3.1.

(f) Bevel Gear (driver): The driver gear is coupled to the motor placed vertically. The driver gear is meshed with the driven gear but the rotation of the driven gear is restricted due to which the driven gear acts as a guide way to the driver gear. Therefore the driver gear rotates around the driven gear. This rotation takes place along the z-axis and therefore it is variation in the joint angle.

(g) Moving mounting: There are two moving mounting present in a pair that combines together with the help of bolts and serves as a base on which the rest of the joint is coupled as shown in Figure 3.4. As already discussed it also rotates around shaft stationary mounted using two ball bearings.

Table 3.1 Specifications of bevel gears

Specifications	Driver	Driven
Module (mm)	5	5
Number of Teeth	12	12
Pinion's / Gear's number of teeth	12	12
Mounting distance (mm)	75	45
Pressure angle (degrees)	20	20
Face width (mm)	20	20
Hub diameter (mm)	36	36
Nominal shaft diameter (mm)	22	25



(a) (b) (c)

Figure 3.5: (a) Link mounting (b) Stationary shaft (c) Motor

(h) Link mounting: Link mounting are also present in a pair joined together with the help of bolts as shown in Figure 3.5(a). Link mountings are coupled to the moving mounting and rotate with it. Link mounting also have holes at the end and used to hold the next link using bolts. Link mounting hold the motor which is used to rotate the gear.

- **(i) Motor:** Motor is placed concentric to the link mountings and it is held in place by link mounting. It holds the driving gear. It is used to provide the torque to driving gear which in turn rotates the joint about the z-axis. Motor is shown in Figure 3.5(c).
- **(j) Stop Ring:** Stop ring are fastened to the link mounting using bolts. The purpose of stop ring is to lock movement of the motor otherwise the motor will come out through the link mounting as the driven gear is stationary.

The parts discussed above are assembled to form a complete joint. In assembly of joint parts are marked in same sequence as described above. The complete assembly of joint is shown in Figure 3.6. Change of link twist angle is accomplished by relative motion between shaft and base. The variation of link twist angle is limited to 0^o, 45^o, -45^o. This is due to the slots present at every 45^o. The angle is changed manually by removing the locking pin and inserting again in the holes. The variation in the joint angle is achieved by rotation of gears. Driven gear is made stationary by locking it a stationary shaft and it serves as a guide way to the driving gear. As whole upper structure is fixed with motor and gear, thus it results in change of joint angle. The circular link is attached at end of link mounting to get manipulator. The base of joint can be replaced with a coupler (as shown in Figure 3.10(c)) when a joint is to be attached to a link at free end.

3.2.2 Design of Module Links

The links are attached to joints to form a complete modular manipulator. The number of links attached in the manipulator depends on requirement of application and layout of industry in which the manipulator has to do the task. The degree of freedom will depend on the number of joints and links assembled together. The links should be assembled in such a way that the longer links are towards the base side. The mass of the links are key feature as it gives a moment which affects the base. The length of the links is also an important factor as it decides the reach of the manipulator. There are four different links designed having same cross section but different lengths. The cross section of link is kept constant because these have to be fitted in joint. The link lengths of different links are 300 mm, 250 mm, 200 mm, and 150 mm. Figure 3.7 shows the links having different link lengths.

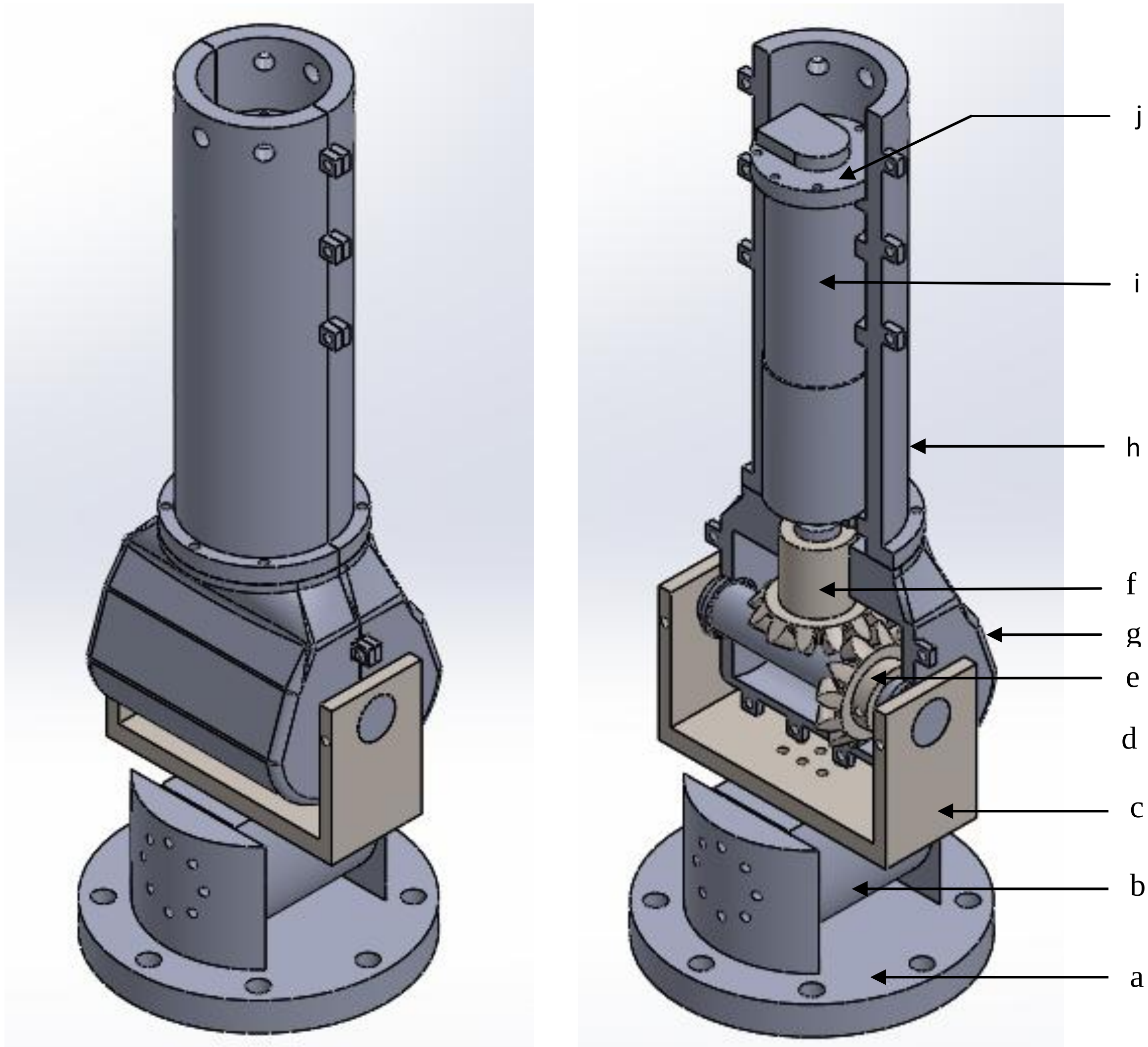


Figure 3.6: (a) Assembly of bevel gear approach (b) Assembly showing inner components

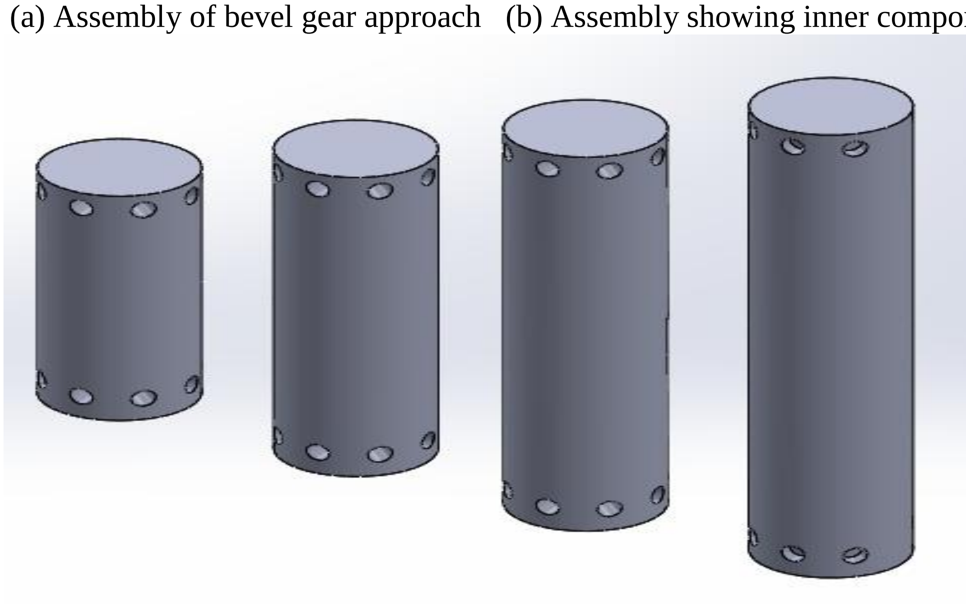


Figure 3.7: Links with different lengths

3.2.3 2-Link Modular Manipulator

The name 2-link modular manipulator itself gives an idea that two links are attached in the manipulator as shown in Figure 3.8. Starting from the basics, it has two links and two joints. First joint with base is fastened to the foundation of the manipulator using bolts. On the other end, a link of 300 mm in length is attached to the joint with the help of bolts. The first joint shown in the figure is currently having 90^o joint angle and the link twist angle is 45^o. The link is again attached to a second joint. In second joint, a coupler is used instead of base which is fastened to link using bolts. It can be seen that joint angle and link twist angle of second joint are 90^o and 45^o respectively. The line diagram of this manipulator is shown in Figure 3.9. Now a second link of length 250 mm is attached to second joint using bolts. The second link can be used to fasten the tool or end-effector based on the application. As from the discussion we can see that that manipulator have four degree of freedom i.e. two due to variation in link twist angle which is done manually and two more due to variation in joint angle with the help of motor. The link length of links in the manipulator can be varied by replacing different links in the library. Therefore the design is created in such a way that even a 2-link manipulator has four degree of freedom.

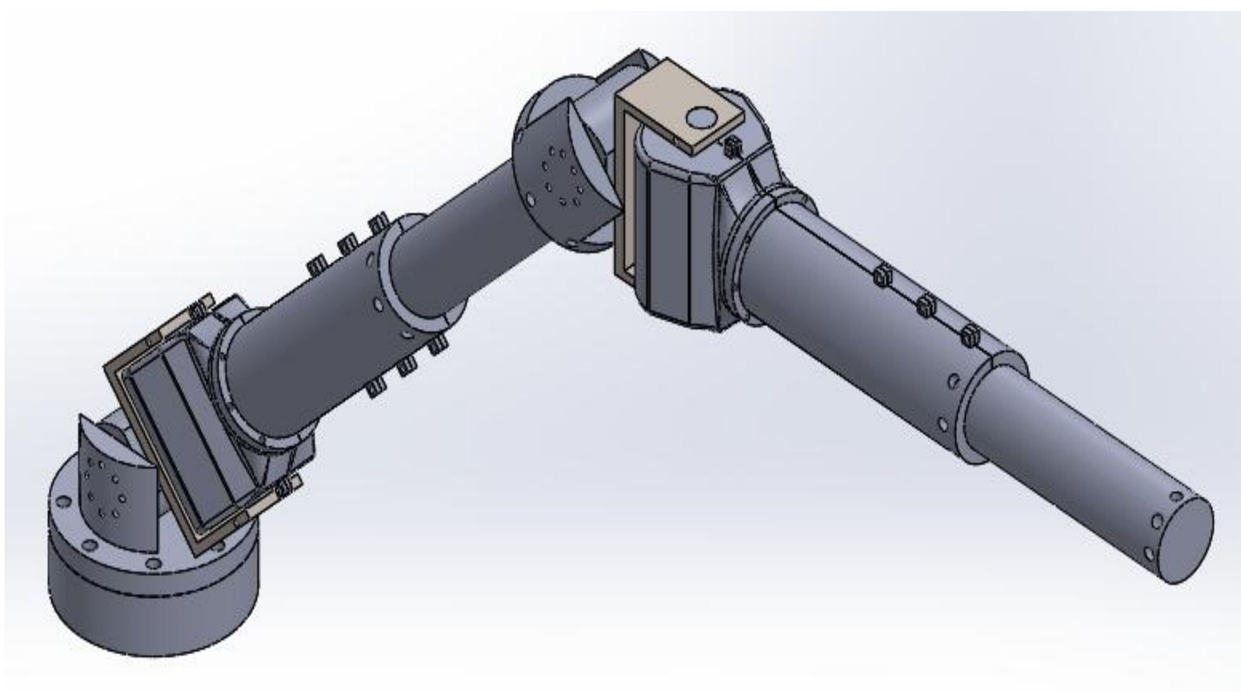


Figure 3.8: 2-link modular manipulator

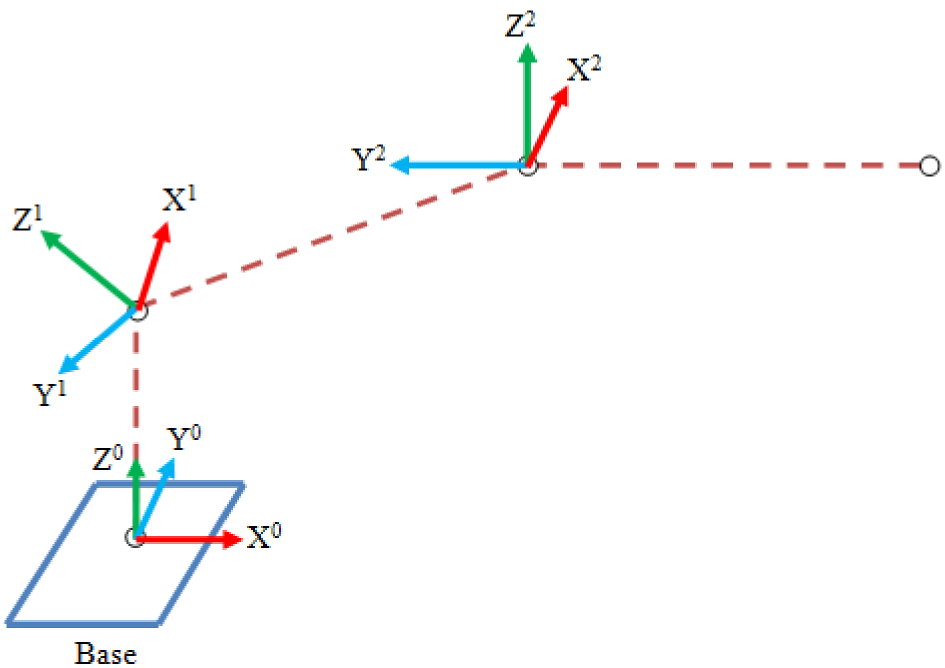


Figure 3.9: Line diagram of 2-link modular manipulator

3.2.4 4-Link Modular Manipulator

4-Link modular manipulator consists of four links and four joints as shown in the Figure 3.10. In this configuration, all four links with different link lengths are used. The link with the largest link length is attached to first joint and the link length decreases as we move to the last link in the manipulator. It can be seen that joint angle and link twist angle of first joint are 90^o and 45^o respectively. The second and fourth joints also have same angles as that of first joint. Whereas the third joint have 0^o link twist angle and joint angle is 90^o. From the discussion it can be noticed that the 4-link modular manipulator have eight degree of freedom i.e. four due to variation in link twist angle which is done manually and four more due to variation in joint angle with the help of motor. Therefore this manipulator is suitable for industries in which the work envelop requirement is more may be due to obstacles or depending upon application.

3.3 Helical Gear Approach

The second approach used is based on the helical gear and it is named as helical gear approach. In this approach, two helical gears are meshed and one of them is been driven by a motor and other rotates the link resulting in change of joint angle. The second rotation i.e. link twist angle is

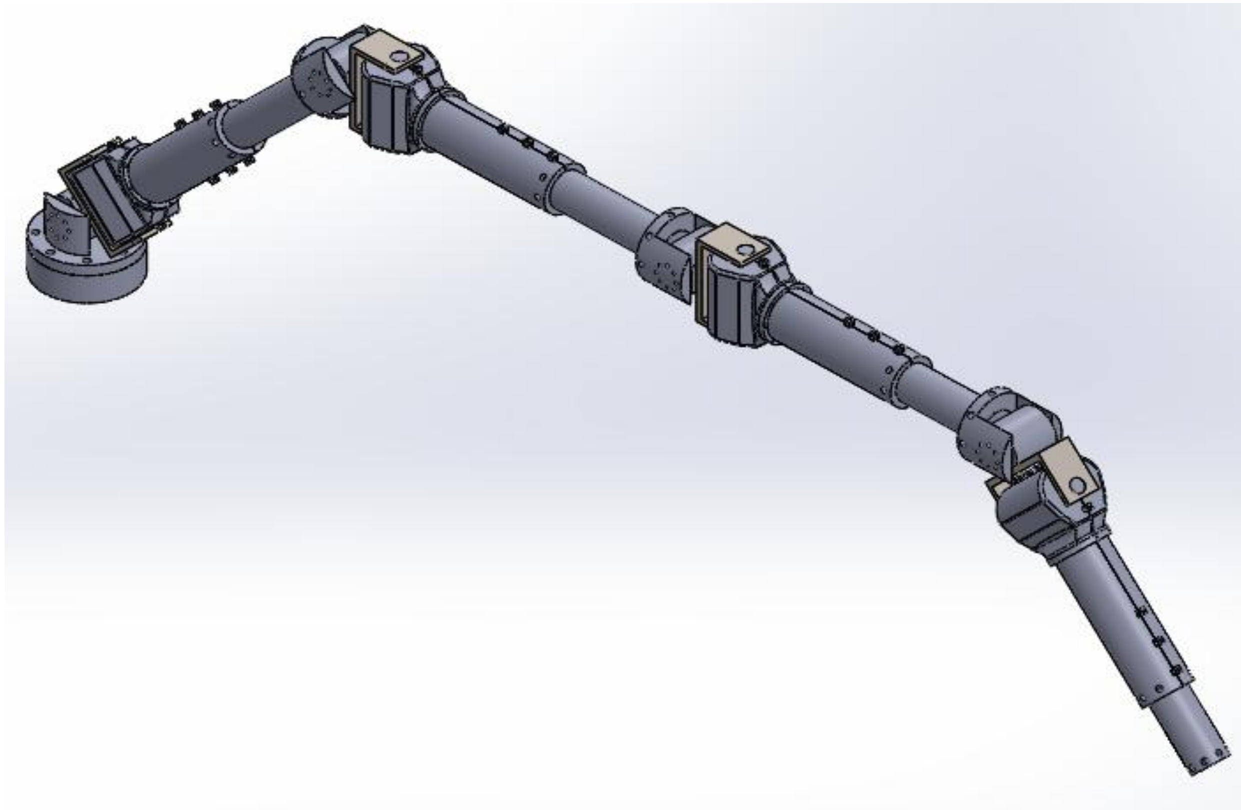


Figure 3.10: 4-link modular manipulator

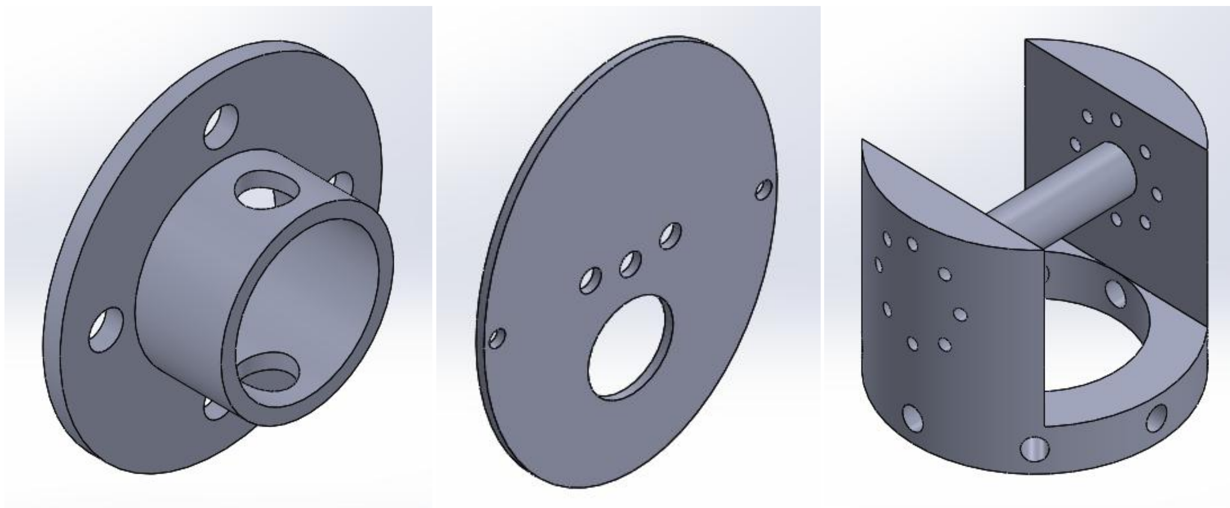
changed by assembly of the shaft coupled to the base and this is done manually. The complete detailed assembly of manipulator is discussed in the next sections.

In the following sections the design of module joints and module links are discussed. There after the module joints and links are assembled in order to show the assembly of the modular manipulators.

3.3.1 Design of Joints

As already discussed joint plays an important role in the modular manipulator as the flexibility of the modular manipulator depends on joints. The shaft and base design is similar to the design of the joint in bevel gear approach. In this joint also as shown in Figure 3.15 variation in link twist angle is done manually. The variation in the joint angle is achieved by rotating the helical gears.

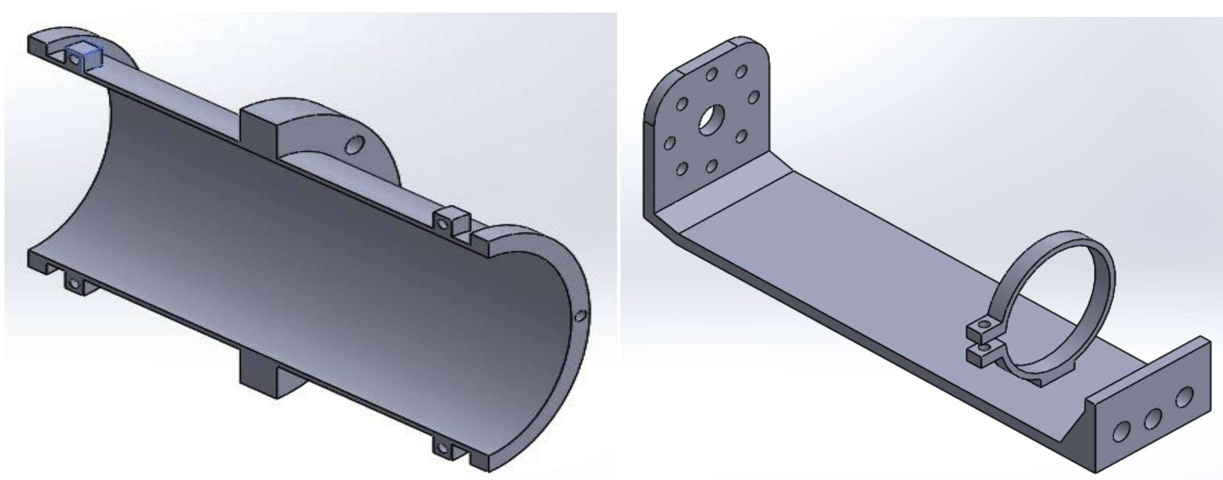
The shaft which is coupled to base has a chamfered surface on which two elliptical mounting are mounted. The elliptical mounting is shown in Figure 3.13(b). Two elliptical mountings combines together to form a base for the rest of the structure as shown in Figure 3.15. There are two gearbox casings (shown in Figure 3.12(a)) which combines together with the elliptical mounting using bolts. The gearbox covers (shown in Figure 3.11(b)) are clamped to the gearbox casing using bolts which in turn holds the motor mounting and the driven shaft. Two ball bearings are placed between the gearbox cover and driven shaft. The motor mounting (shown in Figure 3.12(b)) is coupled to the gearbox cover using bolts and holds the motor. The motor (shown in Figure 3.14(b)) provides torque to the helical gear which is meshed to a driven gear. The driven gear is mounted on the shaft (shown in Figure 3.14(a)). The driven shaft is coupled to the main link by means of connector (shown in Figure 3.11(a)). The main link (shown in Figure 3.13(a)) is



(a) (b) (c)

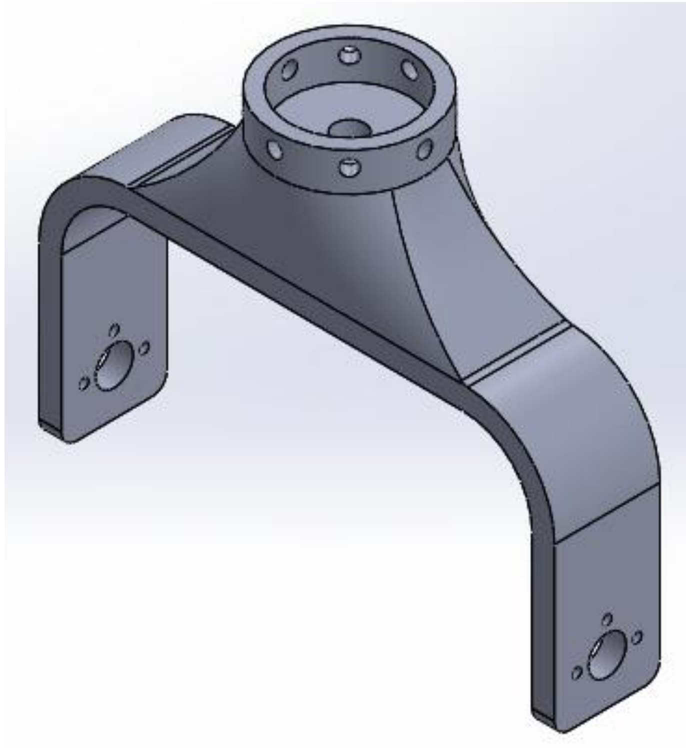
Figure 3.11: (a) Connector (b) Gearbox cover (c) Coupler

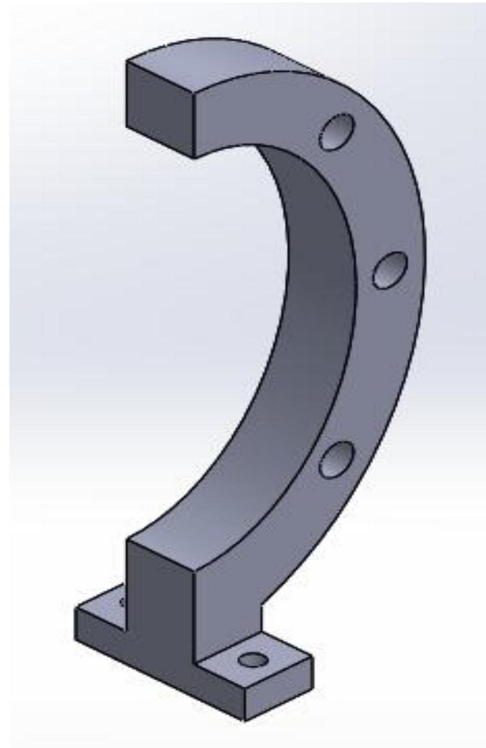
used to hold the link. Therefore the rotation of the main link rotates the link and it results in change of the joint angle. Thus two degree of freedom is achieved by this joint.



(a) (b)

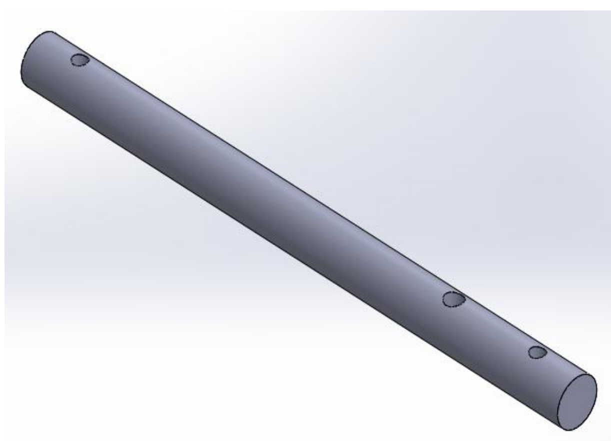
Figure 3.12: (a) Gearbox casing (b) Motor mounting

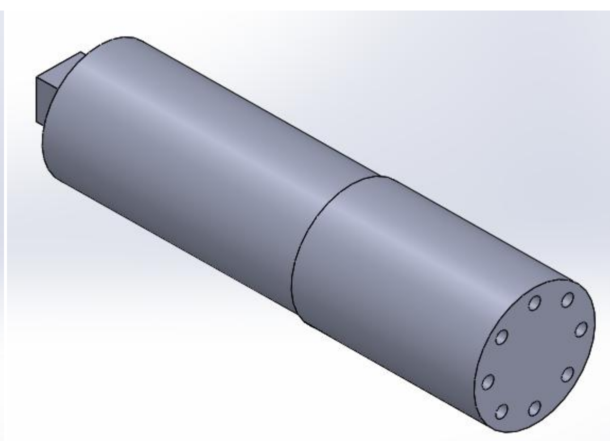




(a) (b)

Figure 3.13: (a) Main link (b) Elliptical mounting





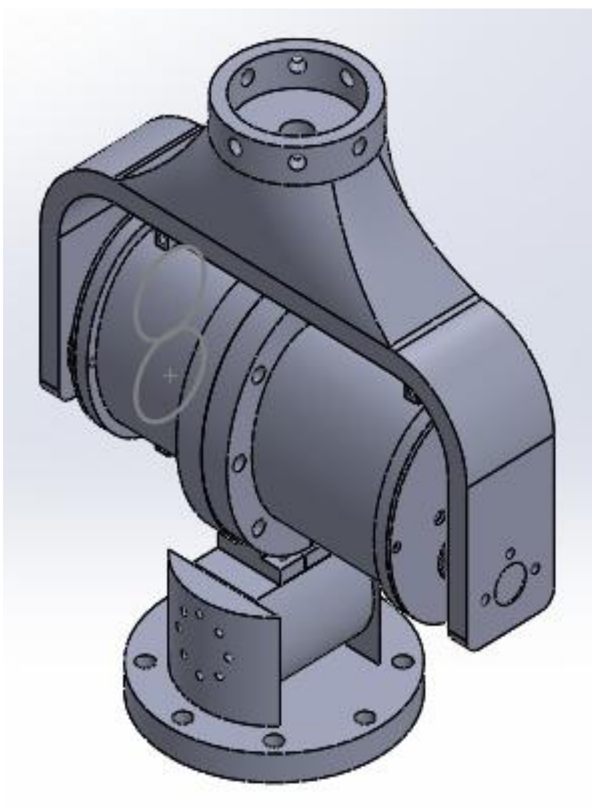
(a) (b)

Figure 3.14: (a) Shaft (b) Motor

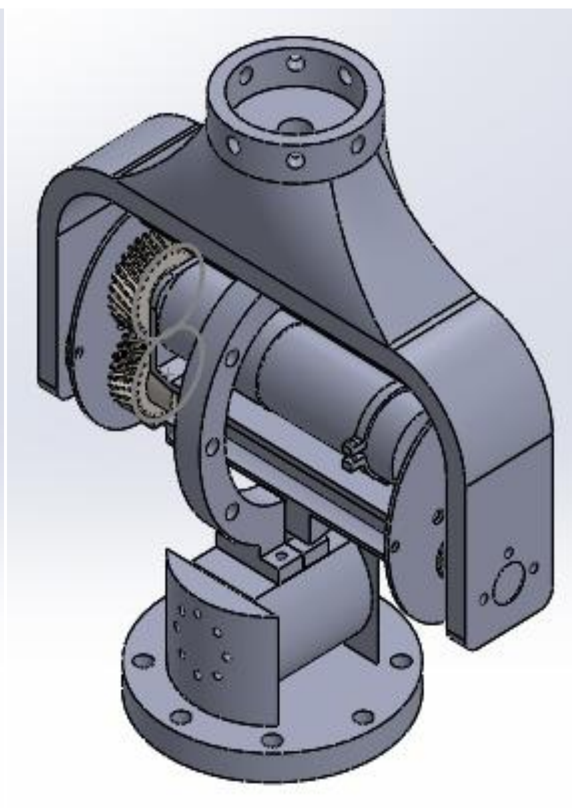
The assembly of the joint and its inner parts are shown in Figure 3.15(a) and Figure 3.15(b) respectively. The details of the helical gears are given in Table 3.2.

Table 3.2 Specifications of helical gears

Specifications	Driver	Pinion
Module (mm)	1.75	1.75
Helix direction	Left hand	Right hand
Pressure angle (degrees)	20	20
Hub style	One side	One side
Overall length (mm)	40	30
Number of teeth	28	28
Helix angle (degree)	20	20
Face width (mm)	20	20
Hub diameter (mm)	35	30
Nominal shaft diameter (mm)	25	12



(a)



(b)

Figure 3.15: (a) Assembly of bevel gear approach (b) Assembly showing inner components

3.3.2 Design of Module Links

The links are attached to joints to form a complete modular manipulator. The number of links attached in the manipulator depends on requirement of application and layout of industry in which the manipulator has to do the task. The degree of freedom will depend on the number of joints and links assembled together. The links should be assembled in such a way that the longer links are towards the base side. The mass of the links are key feature as it gives a moment which affects the base. The length of the links is also an important factor as it decides the reach of the manipulator. There are four different links designed having same cross section but different lengths. The cross section of link is kept constant because these have to be fitted in joint. The link lengths of different links are 400 mm, 350 mm, 300 mm, and 250 mm. Figure 3.16 shows the links having different link lengths.

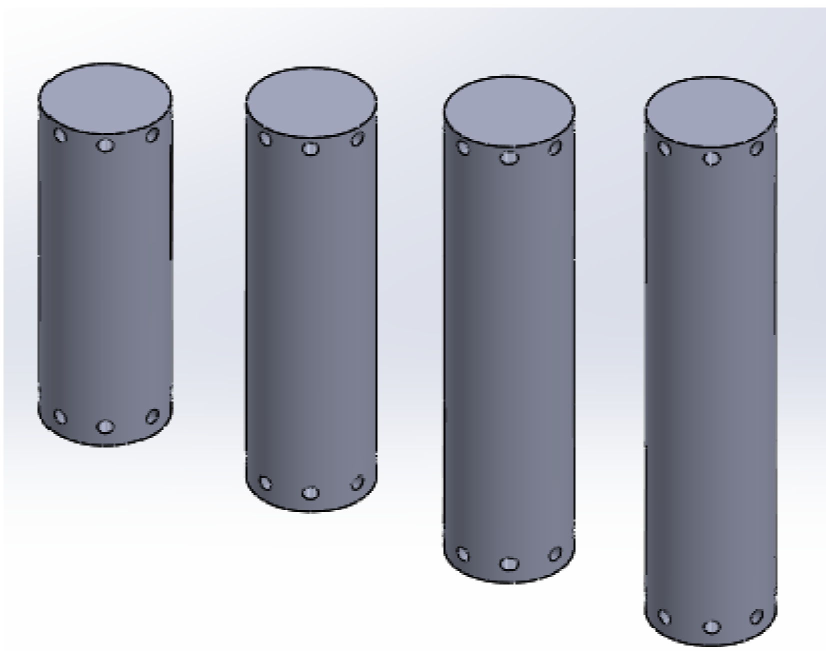


Figure 3.16: Links with different lengths

3.3.3 2-Link Modular Manipulator

The name 2-link modular manipulator itself gives an idea that two links are attached in the manipulator as shown in Figure 3.17. Starting from the basics, it has two links and two joints. First joint with base is fastened to the foundation of the manipulator using bolts. On the other end, a link of 300 mm in length is attached to the joint with the help of bolts. The first joint shown in the figure is currently having 90° joint angle and the link twist angle is 45°. The link is again attached to a second joint. In second joint, a coupler is used instead of base which is fastened to link using bolts. It can be seen that joint angle and link twist angle of second joint are 90° and 45° respectively. Now a second link of length 250 mm is attached to second joint using bolts. The second link can be used to fasten the tool or end-effector based on the application. As from the discussion we can see that that manipulator have four degree of freedom i.e. two due to variation in link twist angle which is done manually and two more due to variation in joint angle with the help of motor. The link length of links in the manipulator can be varied by replacing different links in the library. Therefore the design is created in such a way that even a 2-link manipulator has four degree of freedom.

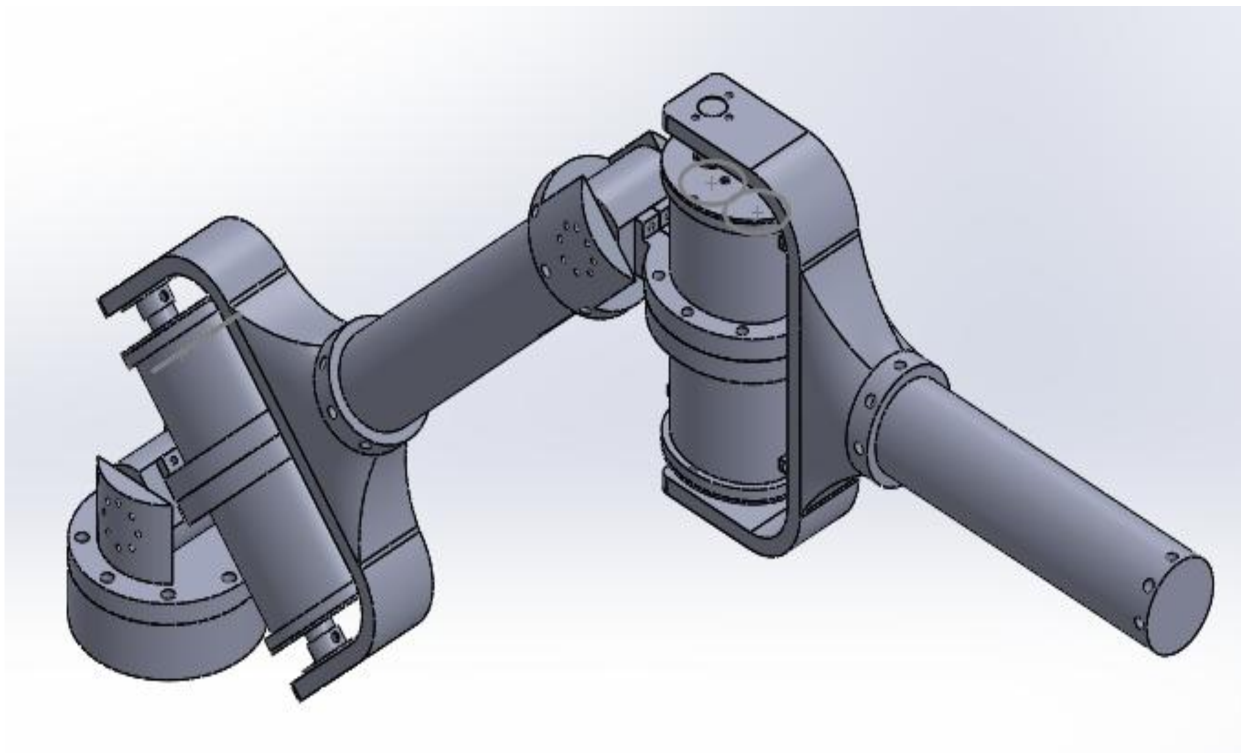


Figure 3.17: 2-link modular manipulator

3.3.4 4-Link Modular Manipulator

4-Link modular manipulator consists of four links and four joints as shown in the Figure 3.18. In this configuration, all four links with different link lengths are used. The link with the largest link length is attached to first joint and the link length decreases as we move to the last link in the manipulator. It can be seen that joint angle and link twist angle of first joint are 90° and 45°

respectively. The second and fourth joints also have same angles as that of first joint. Whereas the third joint have 0o link twist angle and joint angle is 90o. From the discussion it can be noticed that the 4-link modular manipulator have eight degree of freedom i.e. four due to variation in link twist angle which is done manually and four more due to variation in joint angle with the help of motor. Therefore this manipulator is suitable for industries in which the work envelop requirement is more may be due to obstacles or depending upon application.

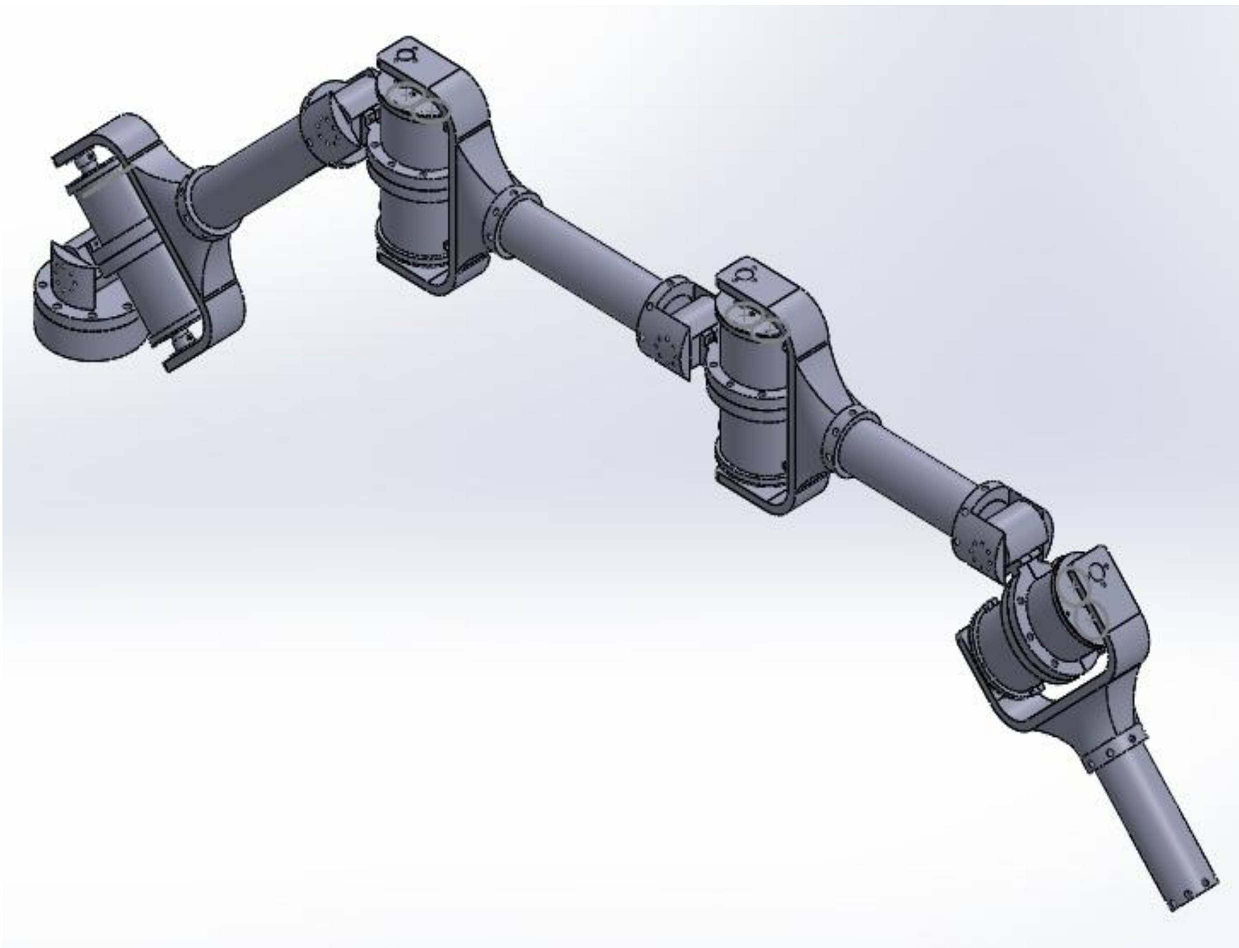


Figure 3.18: 4-link modular manipulator

3.4 Summary

In this Chapter, two different approaches of design have been discussed one is bevel and other is helical gear approach. The designs of the joints and links have been discussed for both approaches. The working of joints has been explained. With combination of these types of joints the variation in the link twist angle of modular manipulators has been achieved. Four links with different lengths have been designed which helps in varying the link length of the modular manipulators. The assemblies of the links and joints have been performed in order to realize modular manipulators. 2-link modular manipulator has been which have four degree of freedom. 4-link modular manipulator having eight degree of freedom has been discussed. The manipulators can be assembled based on the requirement of the applications.

Chapter 4

Static Analyses of Modular Manipulators

4.1 Introduction

In Chapter 3, the design of modular manipulator and working has been discussed. The focus of this chapter is on analyzing the structure of the modular manipulators. The manipulators with different link twist angle and joint angle are analyzed in different loading conditions. In this Chapter, the static analyses of 2-link modular manipulator with different configuration and loading condition are performed using ANSYS software. The deformation and stress in each configuration is noted.

4.2 Analysis of Bevel Gear Approach

A 2-link modular manipulator is made using two joints and two links. The joints used here follow the bevel gear approach. The link lengths of the link are 300 mm and 250 mm of first and second link respectively. Different configurations are tested by varying the link twist angles and joint angles. The load at last link is varied in order to see the behavior of the manipulator. The material taken for testing of manipulator is aluminum alloy.

4.2.1 Worst Configuration

In the worst configuration, the joint angle of joint 1 and joint 2 are 0^o and 90^o respectively. The link twist angle of both the joints is kept 0^o. The configuration of manipulator is shown in Figure 4.1. The gravity in –y direction is applied to the manipulator as shown in Figure 4.1. The foundation of the manipulator is made fixed as shown in Figure 4.3. One analysis is done under gravity only to check the stress and deformation of the manipulator. Three more analyses are done under a loading condition of 20 N, 40 N, and 50 N which is applied in –y direction at the surface of last link. During all three analyses the manipulator is under the effect of gravity also. The stress and deformation of the manipulator are noted in each analysis and are listed in Table 4.1. Figure 4.2 shows a load of 50 N which is applied at surface of last link. When a load of 50 N is applied in presence of gravity, the resulting deformation and the stress of manipulator are shown in Figure 4.4 and Figure 4.5 respectively. Figure 4.6 shows the zoomed view of the manipulator where maximum stress has occurred.

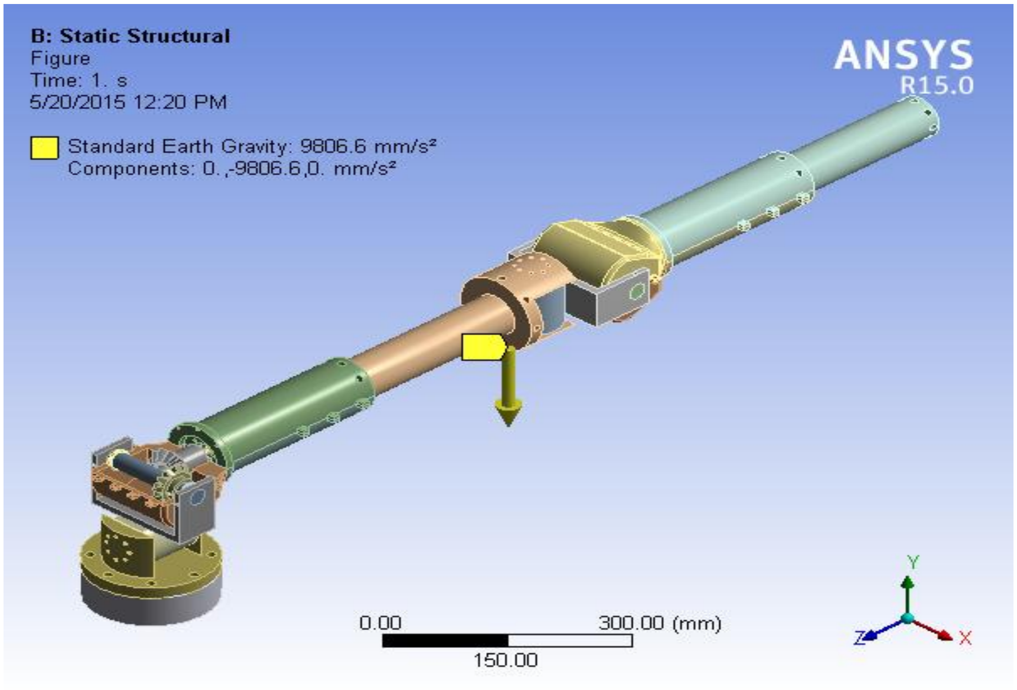


Figure 4.1: Manipulator under gravity

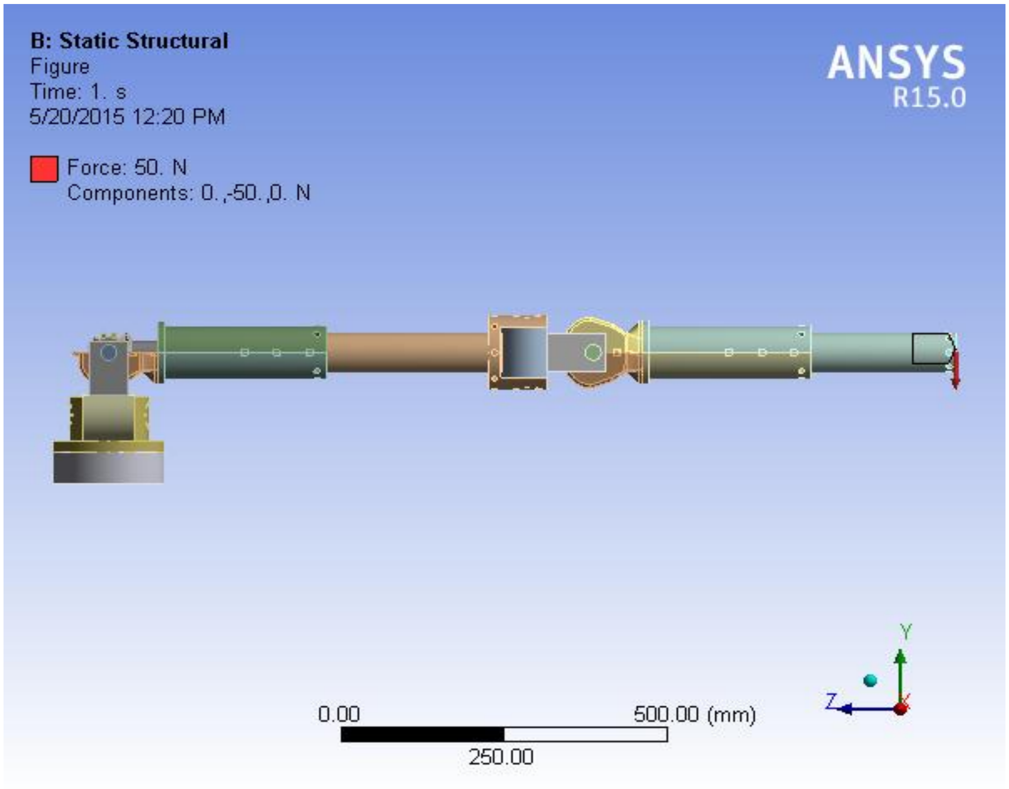


Figure 4.2: Load applied on manipulator

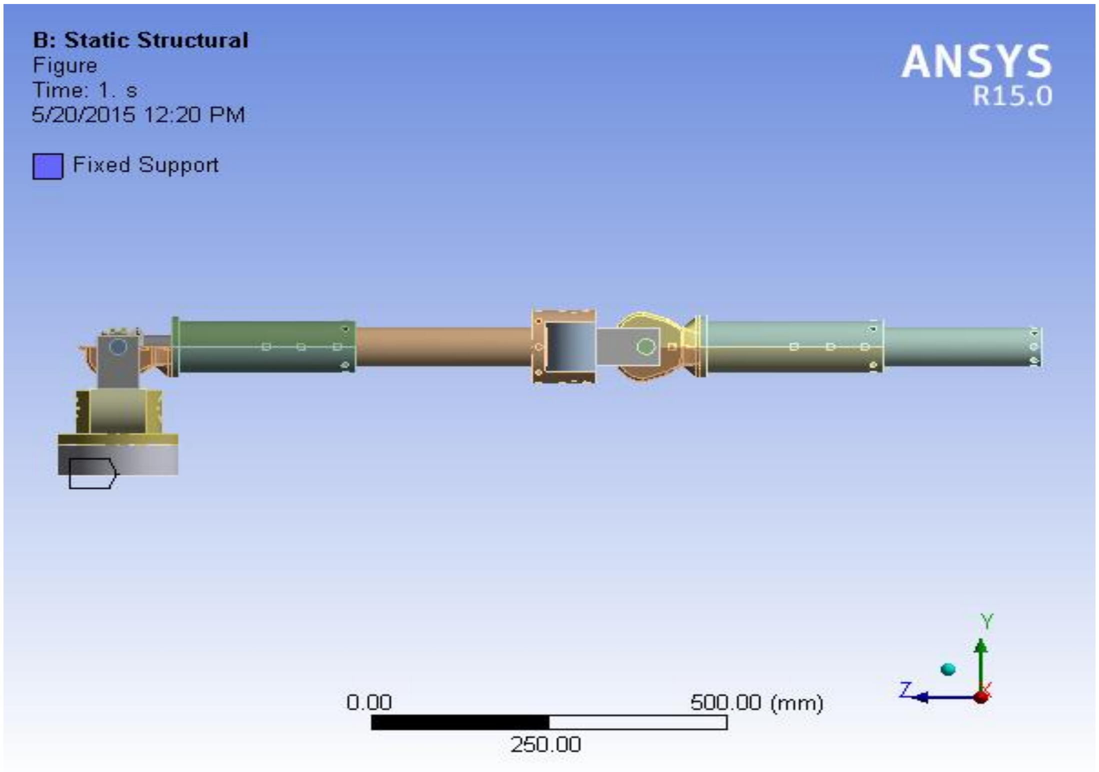


Figure 4.3: Foundation of manipulator is fixed

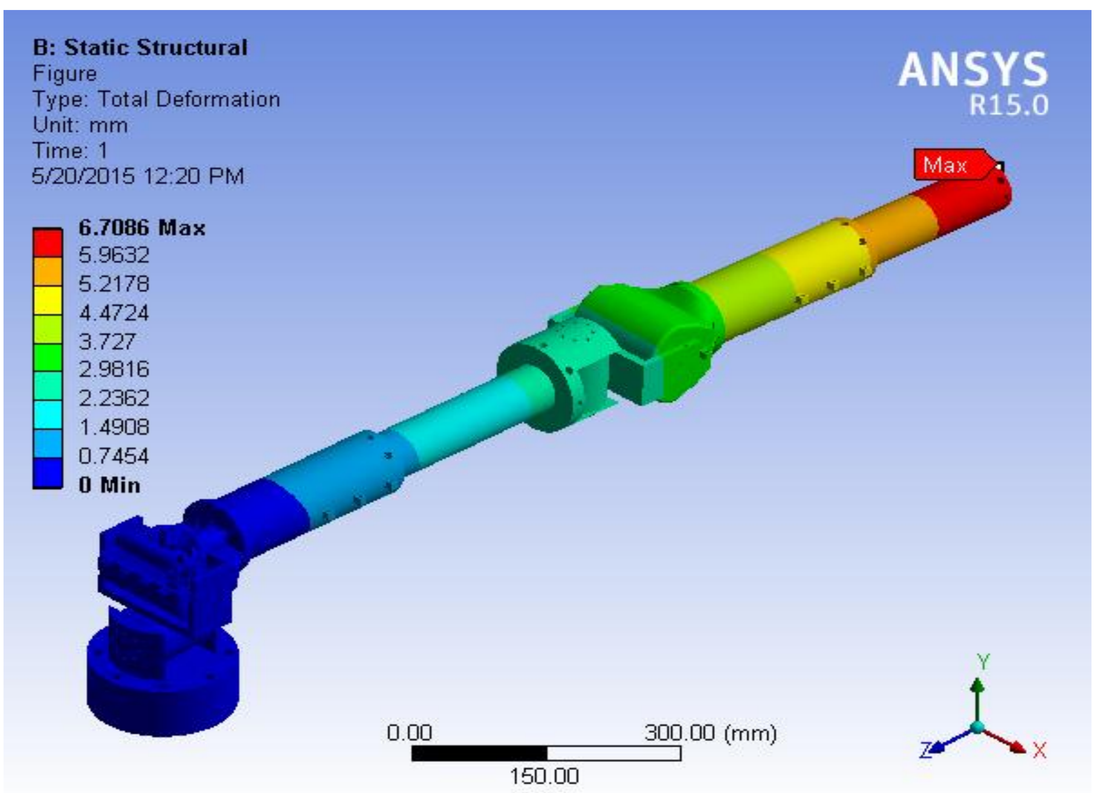


Figure 4.4: Deformation of manipulator

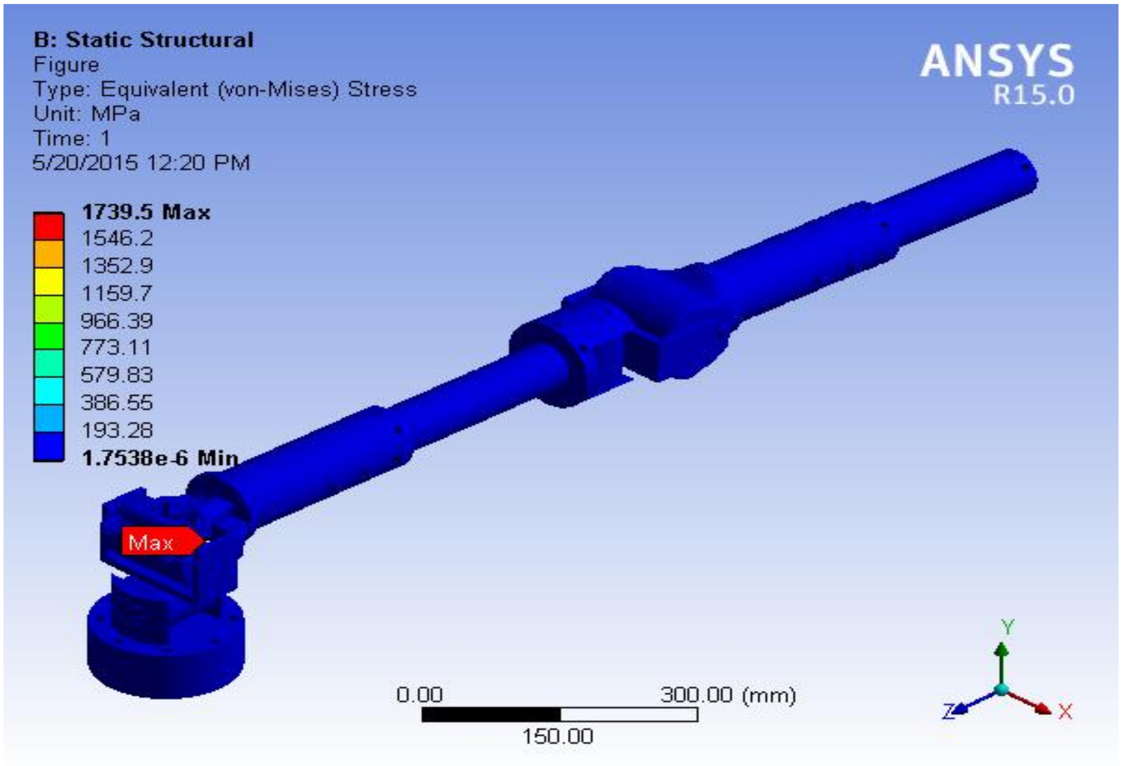


Figure 4.5: Stress developed in manipulator

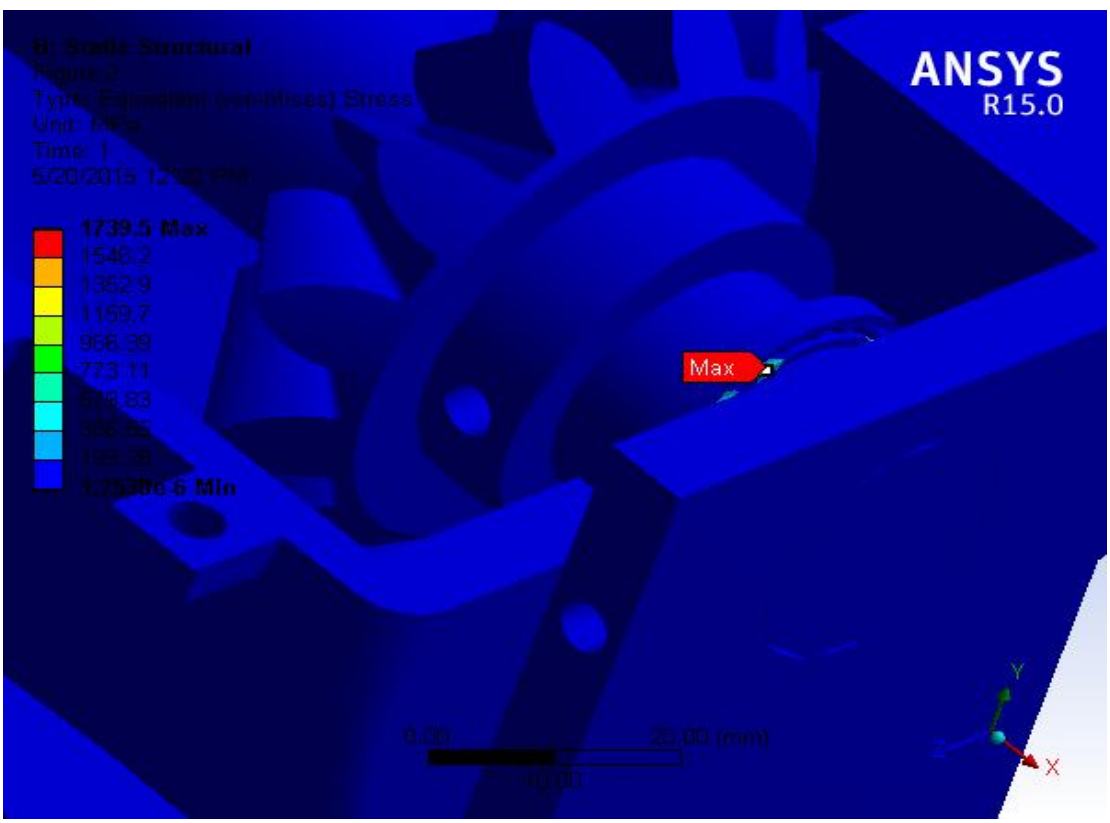


Figure 4.6: Zoomed view of maximum stress

Table 4.1 Results of 2-link modular manipulator under worst configuration

	Under gravity and 50 N load	Under gravity and 40 N load	Under gravity and 20 N load	Under gravity
Stress (MPa)	1739.5	1600.8	1323.5	1046.2
Deformation (mm)	6.71	6.11	4.91	3.72

4.2.2 Second Configuration

In the second configuration, the joint angle of joint 1 and joint 2 are 45^o and 45^o respectively. The link twist angle of both the joints is kept 0^o. The configuration of manipulator is shown in Figure 4.7. The gravity in –y direction is applied to the manipulator. The foundation of the manipulator is made fixed. One analysis is done under gravity only to check the stress and deformation of the manipulator. Three more analyses are done under a loading condition of 20 N, 40 N, and 50 N which is applied in –y direction at the surface of last link. During all three analyses the manipulator is under the effect of gravity also. The stress and deformation of the manipulator are noted in each analysis and are listed in Table 4.2. When a load of 50 N is applied in presence of gravity, the resulting deformation and the stress of manipulator are shown in Figure 4.7 and Figure 4.8 respectively.

Table 4.2 Results of 2-link modular manipulator under second configuration

	Under gravity and 50 N load	Under gravity and 40 N load	Under gravity and 20 N load	Under gravity
Stress (MPa)	298.35	272.89	221.97	171.06
Deformation (mm)	5.35	4.86	3.87	2.88

4.2.3 Third Configuration

In the third configuration, the joint angle of joint 1 and joint 2 is kept 90^o. The link twist angle of both the joints is kept 0^o. The configuration of manipulator is shown in Figure 4.9. The gravity in –y direction is applied to the manipulator. The foundation of the manipulator is made fixed. One analysis is done under gravity only to check the stress and deformation of the manipulator. Three more analyses are done under a loading condition of 20 N, 40 N, and 50 N which is applied in –y direction at the surface of last link. During all three analyses the manipulator is under the effect of gravity also. The stress and deformation of the manipulator are noted in each analysis and are listed in Table 4.3. When a load of 50 N is applied in presence of gravity, the resulting deformation and the stress of manipulator are shown in Figure 4.9 and Figure 4.10 respectively.

Table 4.3 Results of 2-link modular manipulator under third configuration

	Under gravity and 50 N load	Under gravity and 40 N load	Under gravity and 20 N load	Under gravity
Stress (MPa)	183.92	168.54	137.78	107.04
Deformation (mm)	2.31	2.11	1.69	1.27

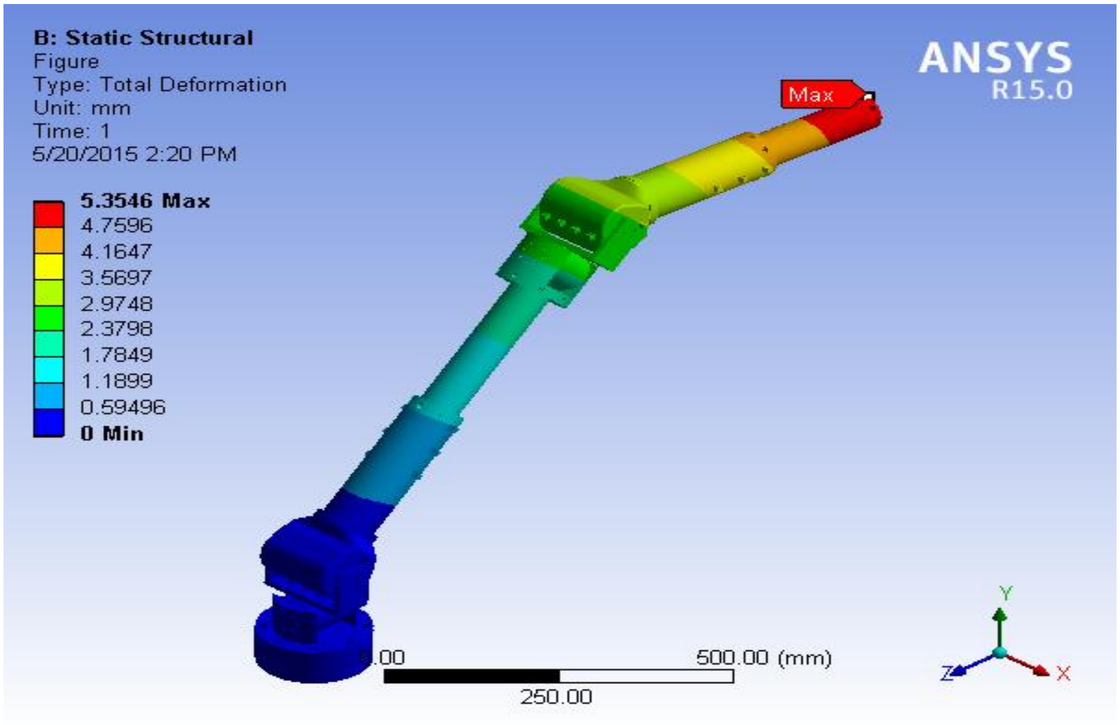


Figure 4.7: Deformation of manipulator

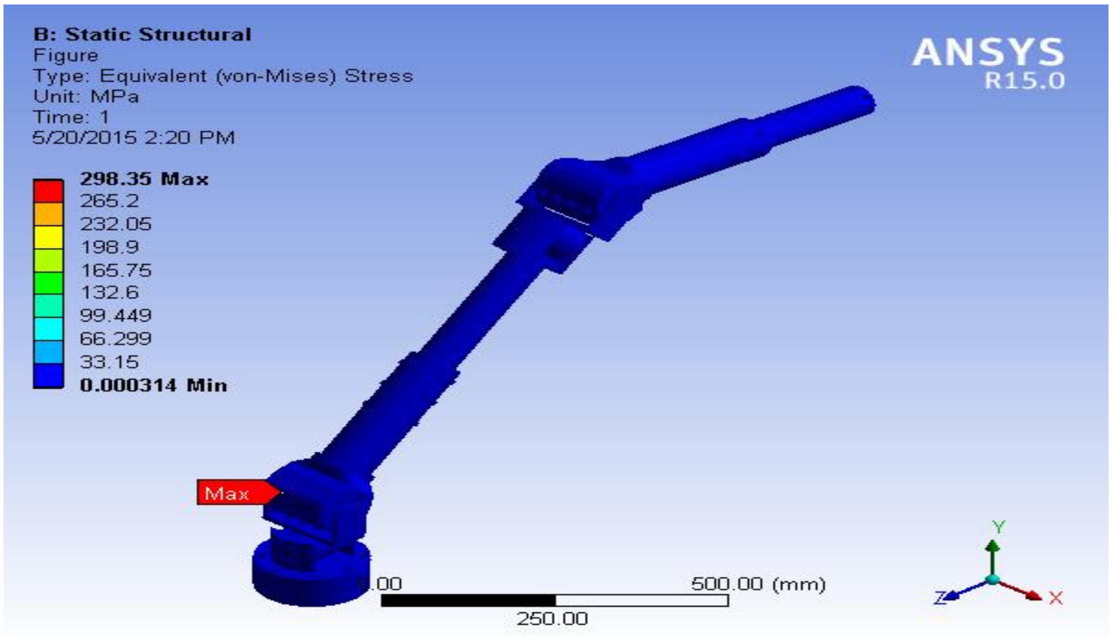


Figure 4.8: Stress developed in manipulator

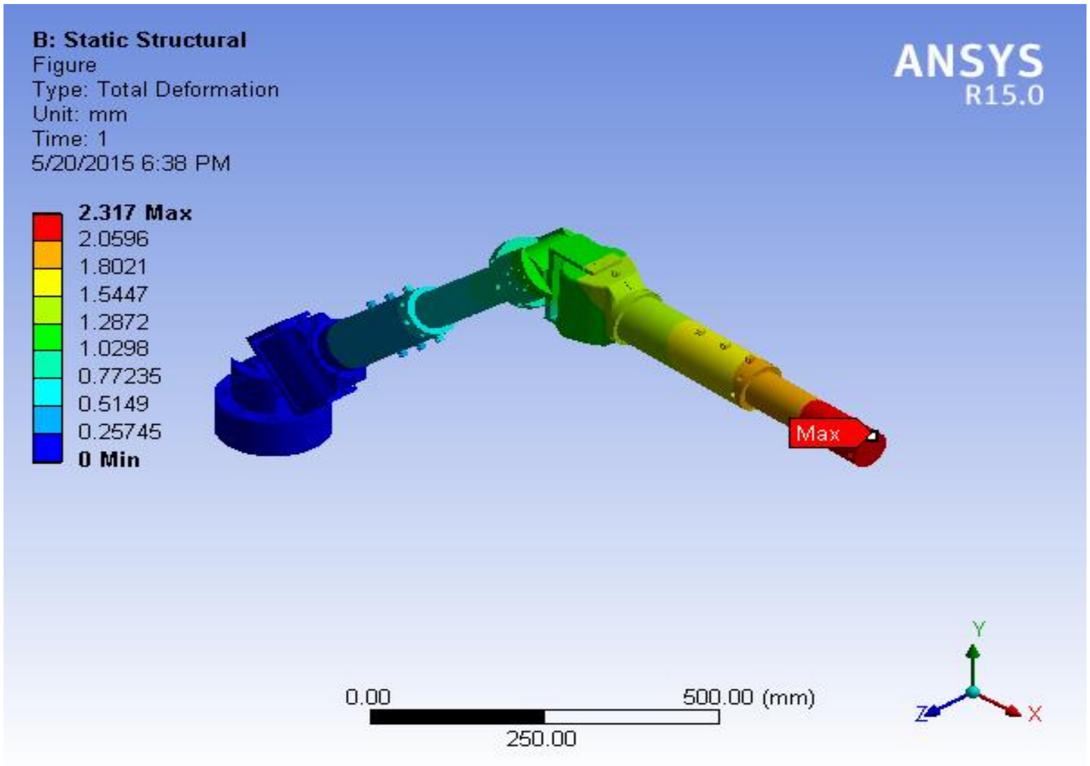


Figure 4.9: Deformation of manipulator

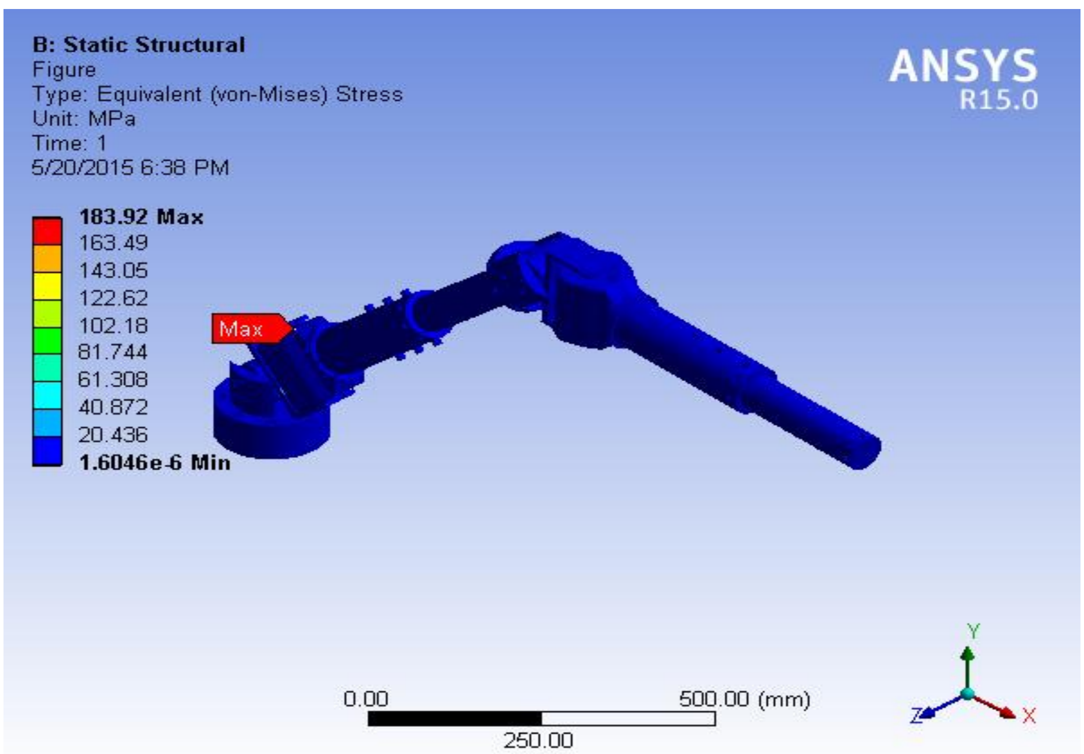


Figure 4.10: Stress developed in manipulator

4.2.4 Comparison of Results

The stress plot and deformation plot of all three configurations with variation in load are shown in Figure 4.11 and Figure 4.12 respectively. From the plot it can be seen that the maximum stress and deformation are 1739.5 MPa and 6.71 mm respectively in worst configuration when a load of 50 N is applied in presence of gravity. The results are within the allowable limit.

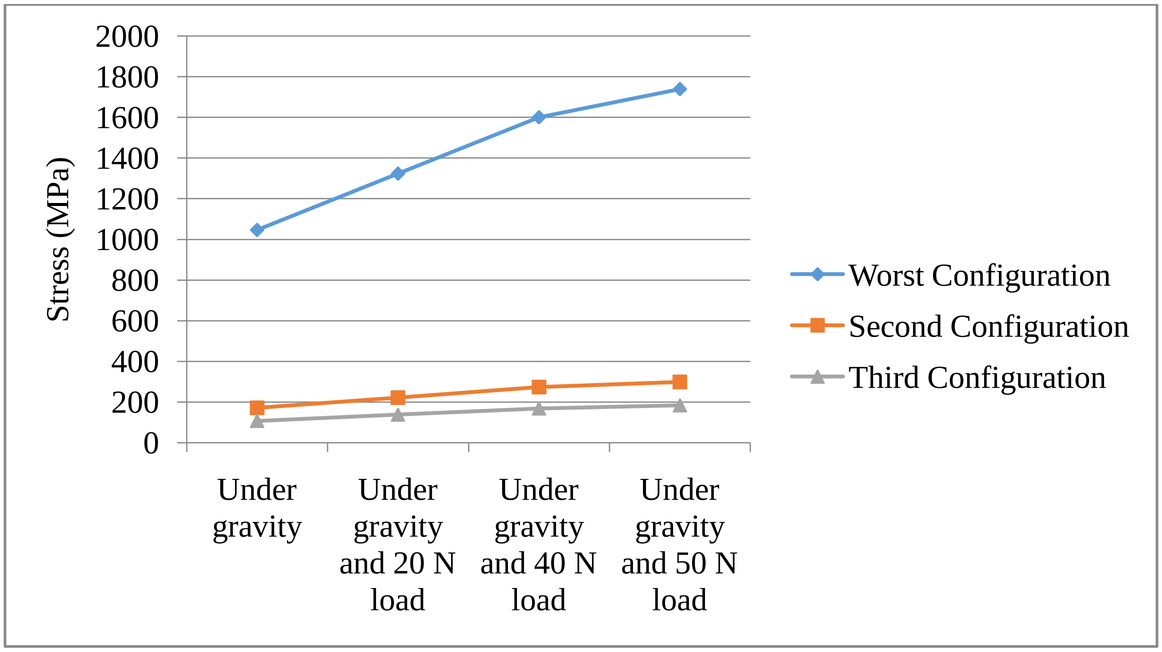


Figure 4.11: Plot of stress versus load for 2-link modular manipulator

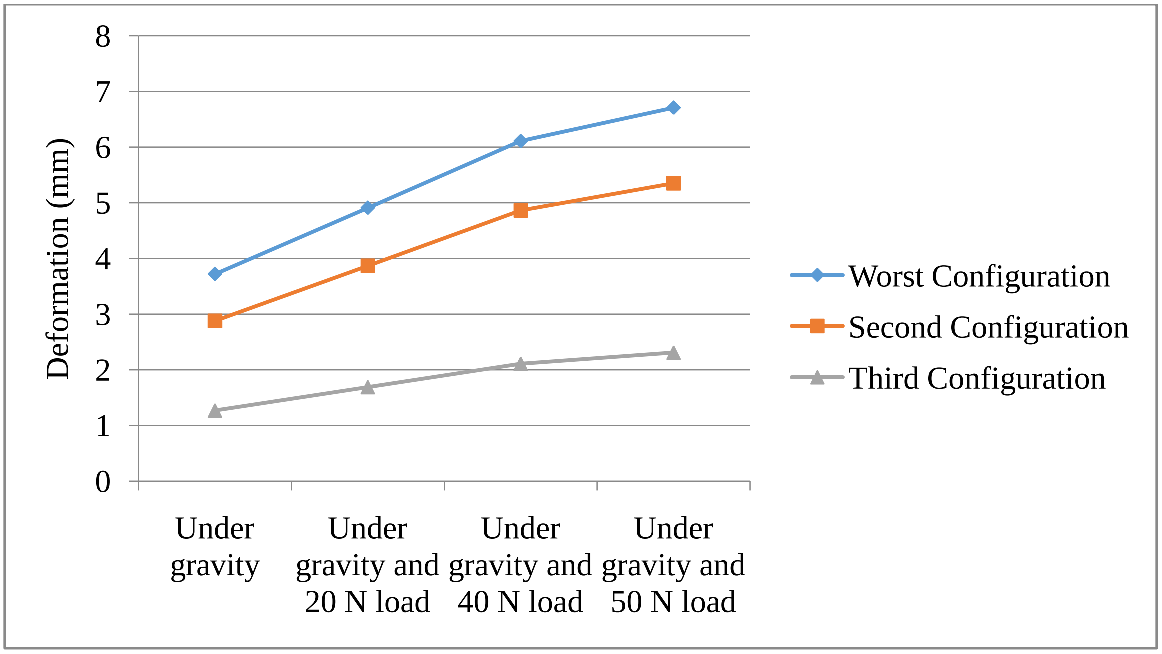


Figure 4.12: Plot of deformation versus load for 2-link modular manipulator

4.3 Analysis of Helical Gear Approach

A 2-link modular manipulator is made using two joints and two links. The joints used here follow the helical gear approach. The link lengths of the link are 400 mm and 350 mm of first and second link respectively. Different configurations are tested by varying the link twist angles and joint angles. The load at last link is varied in order to see the behavior of the manipulator.

4.3.1 Worst Configuration

In the worst configuration, the joint angle of joint 1 and joint 2 are 0^o and 90^o respectively. The link twist angle of both the joints is kept 0^o. The configuration of manipulator is shown in Figure 4.13. The gravity in –y direction is applied to the manipulator as shown in Figure 4.13. The foundation of the manipulator is made fixed. One analysis is done under gravity only to check the stress and deformation of the manipulator. Three more analyses are done under a loading condition of 20 N, 40 N, and 50 N which is applied in –y direction at the surface of last link. During all three analyses the manipulator is under the effect of gravity also. The stress and deformation of the manipulator are noted in each analysis and are listed in Table 4.4. Figure 4.14 shows a load of 50 N which is applied at surface of last link. When a load of 50 N is applied in presence of gravity, the resulting deformation and the stress of manipulator are shown in Figure 4.15 and Figure 4.16 respectively.

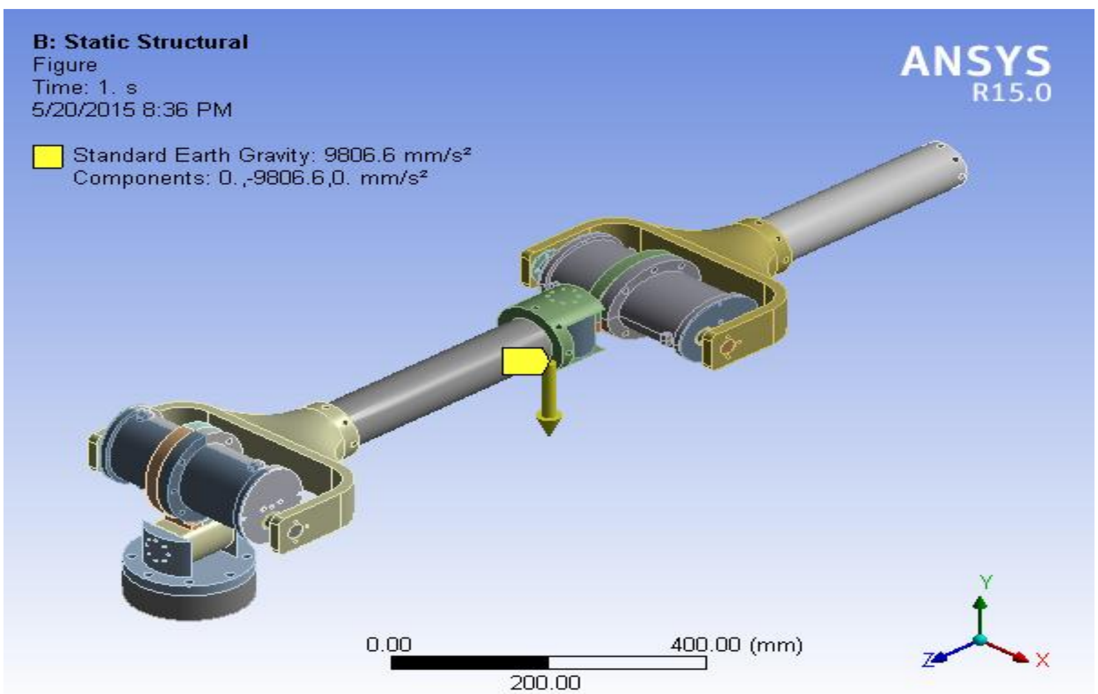


Figure 4.13: Manipulator under gravity

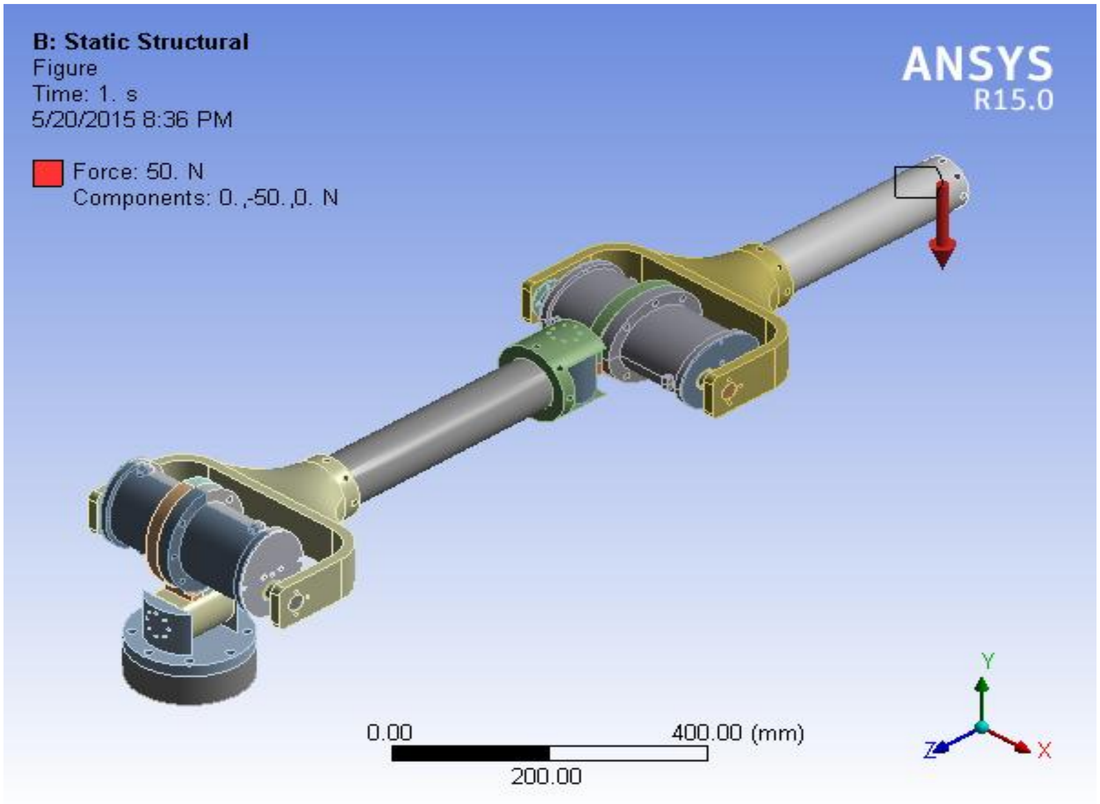


Figure 4.14: Load applied on manipulator

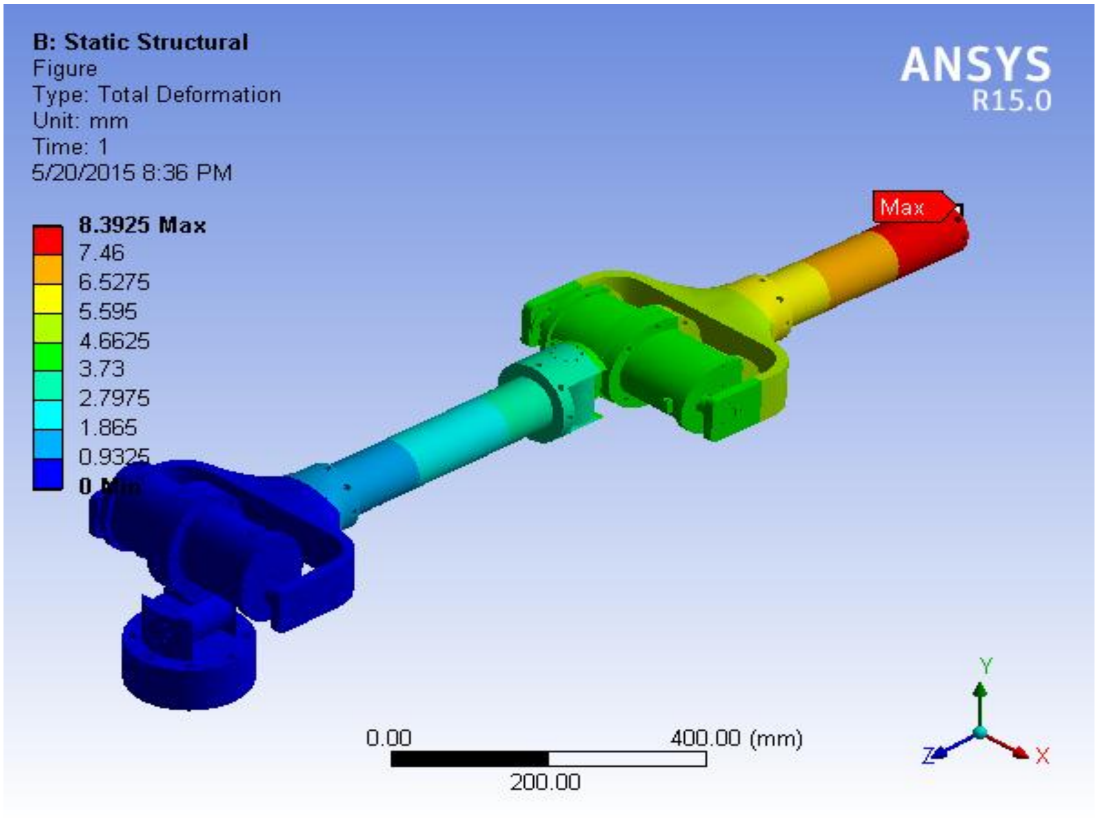


Figure 4.15: Deformation of manipulator

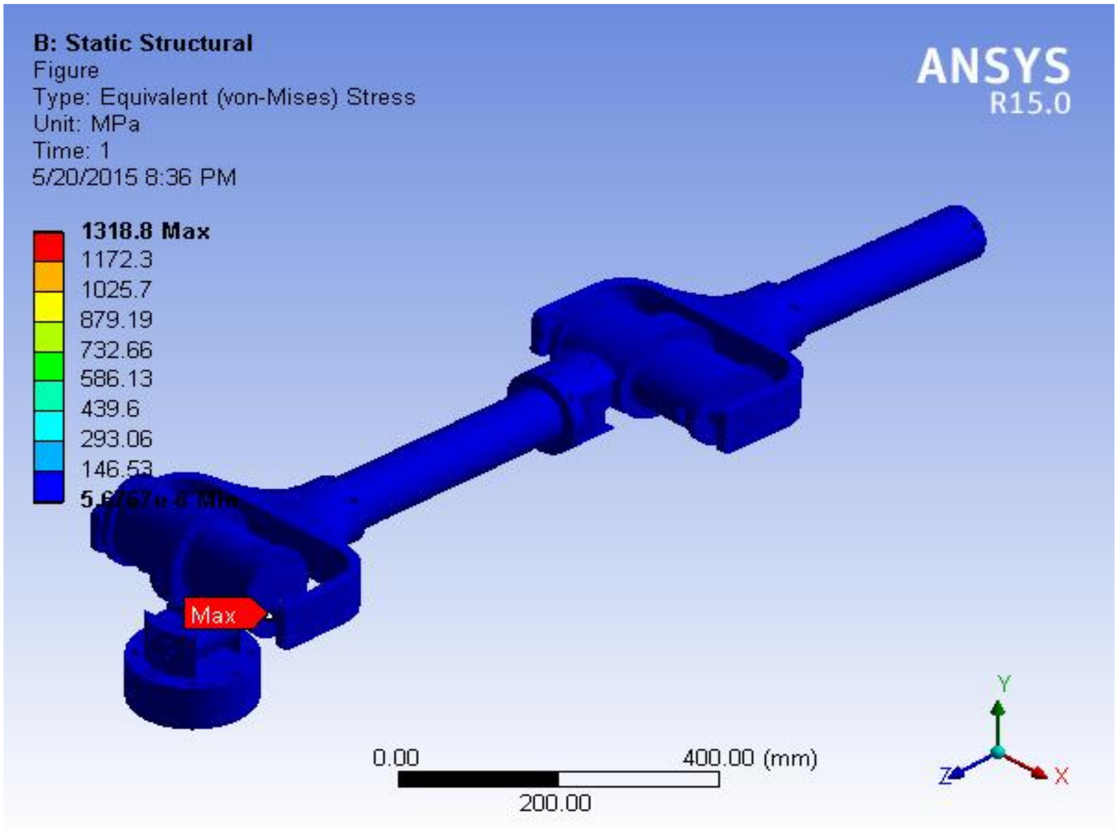


Figure 4.16: Stress developed in manipulator

Table 4.4 Results of 2-link modular manipulator under worst configuration

	Under gravity and 50 N load	Under gravity and 40 N load	Under gravity and 20 N load	Under gravity
Stress (MPa)	1318.8	1239.2	1080.1	920.9
Deformation (mm)	8.39	7.82	6.68	5.54

4.3.2 Second Configuration

In the second configuration, the joint angle of joint 1 and joint 2 is 45^o. The link twist angle of both the joints is kept 0^o. The configuration of manipulator is shown in Figure 4.17. The gravity in –y direction is applied to the manipulator. The foundation of the manipulator is made fixed. One analysis is done under gravity only to check the stress and deformation of the manipulator. Three more analyses are done under a loading condition of 20 N, 40 N, and 50 N which is applied in –y direction at the surface of last link. During all three analyses the manipulator is under the effect of gravity also. The stress and deformation of the manipulator are noted in each analysis and are listed in Table 4.5. When a load of 50 N is applied in presence of gravity, the resulting deformation and the stress of manipulator are shown in Figure 4.17 and Figure 4.18 respectively.

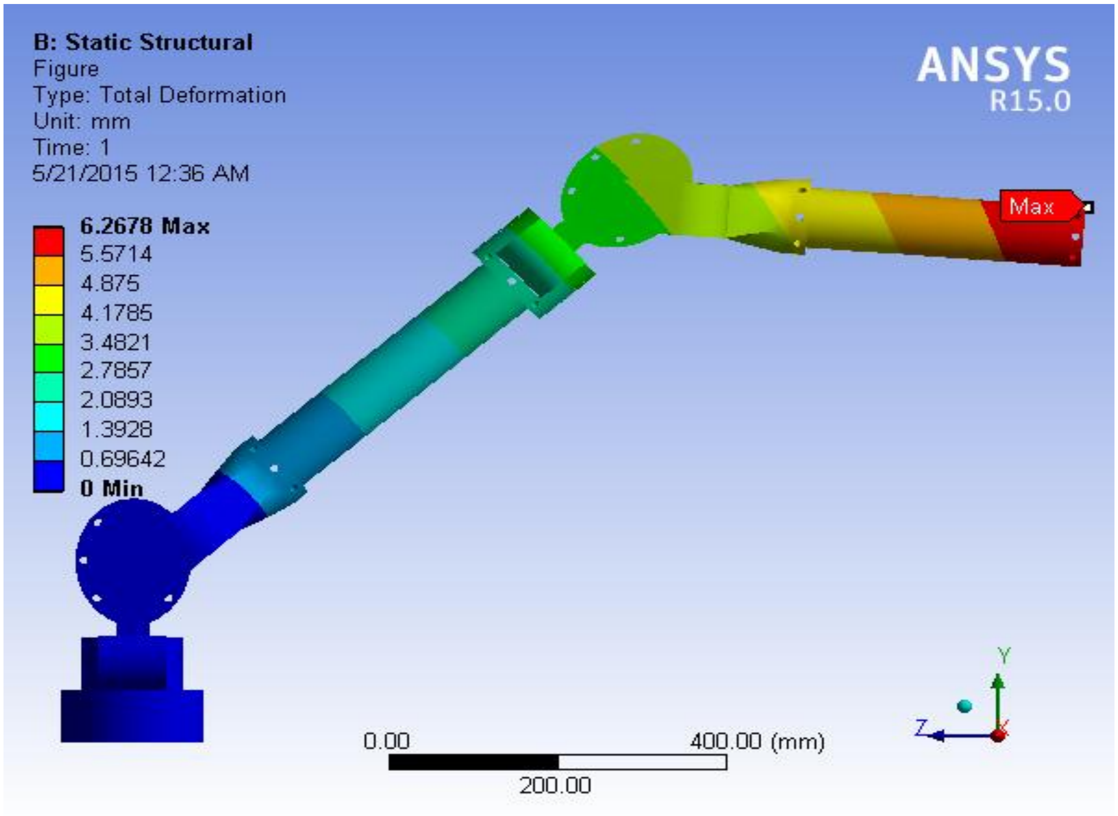


Figure 4.17: Deformation of manipulator

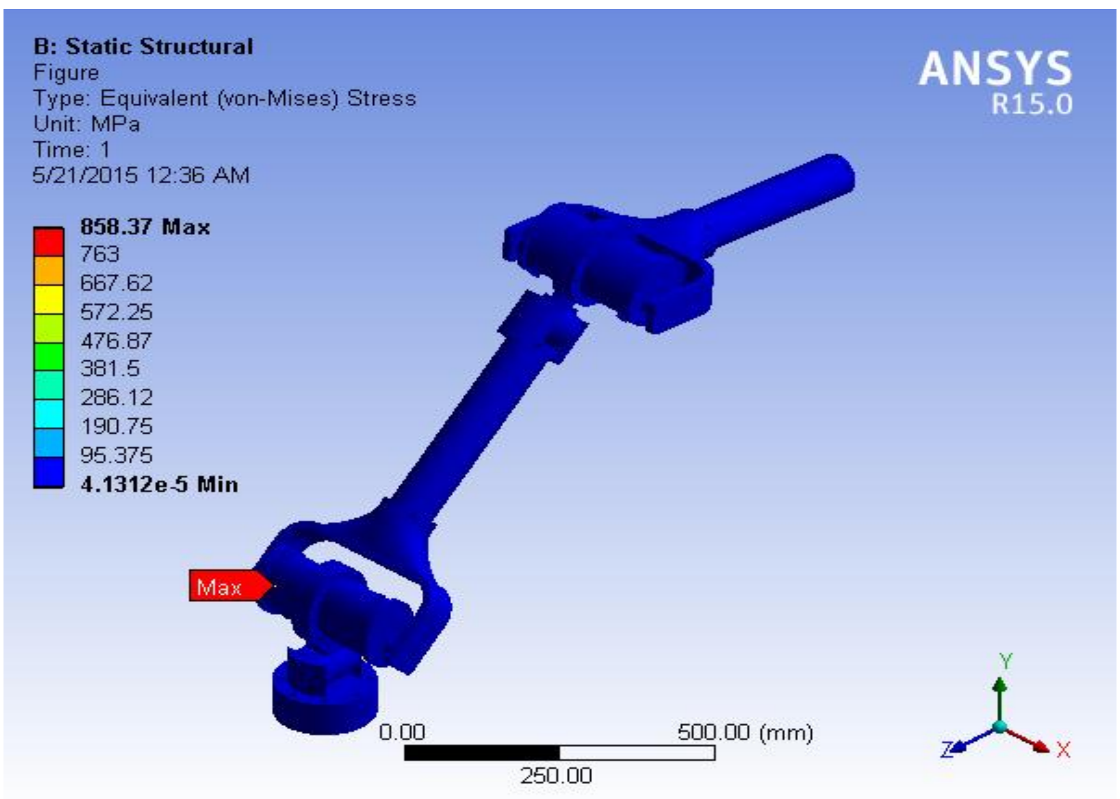


Figure 4.18: Stress developed in manipulator

Table 4.5 Results of 2-link modular manipulator under second configuration

	Under gravity and 50 N load	Under gravity and 40 N load	Under gravity and 20 N load	Under gravity
Stress (MPa)	858.37	802.88	691.9	580.92
Deformation (mm)	6.27	5.81	4.89	3.97

4.3.3 Third Configuration

In the third configuration, the joint angle of joint 1 and joint 2 is kept 90^o. The link twist angle of both the joints is kept 0^o. The configuration of manipulator is shown in Figure 4.19. The gravity in –y direction is applied to the manipulator. The foundation of the manipulator is made fixed. One analysis is done under gravity only to check the stress and deformation of the manipulator. Three more analyses are done under a loading condition of 20 N, 40 N, and 50 N which is applied in –y direction at the surface of last link. During all three analyses the manipulator is under the effect of gravity also. The stress and deformation of the manipulator are noted in each analysis and are listed in Table 4.6. When a load of 50 N is applied in presence of gravity, the resulting deformation and the stress of manipulator are shown in Figure 4.19 and Figure 4.20 respectively.

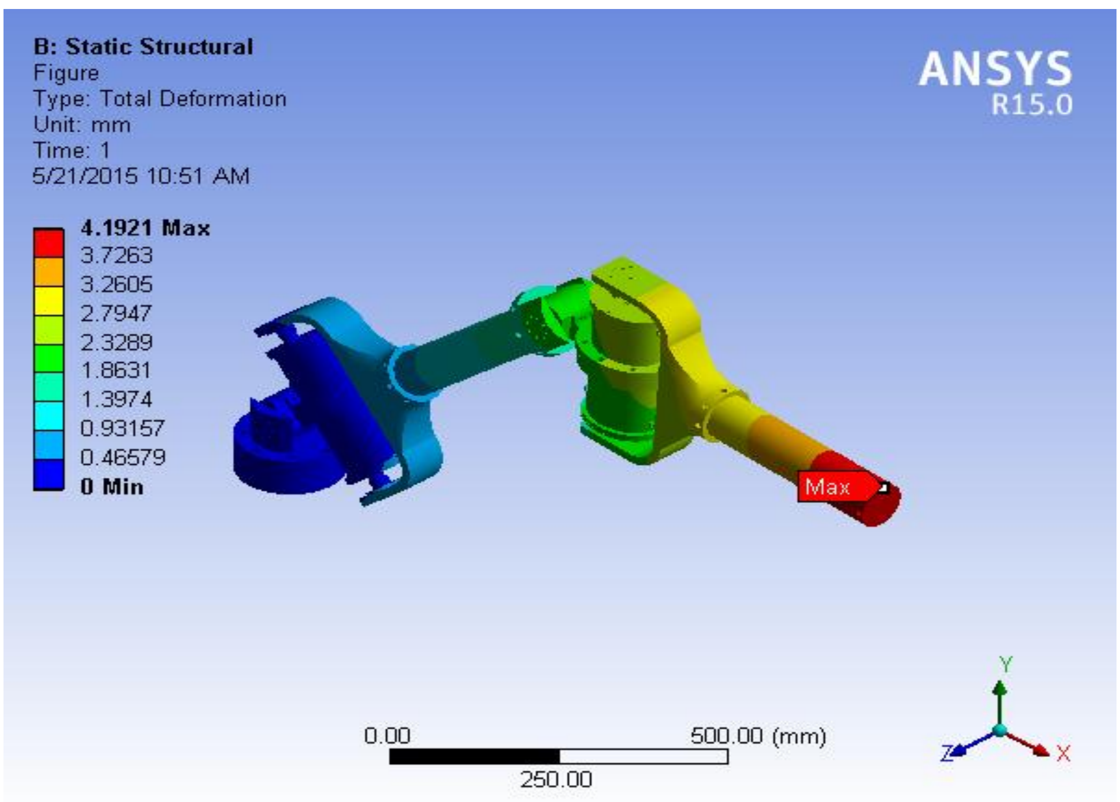


Figure 4.19: Deformation of manipulator

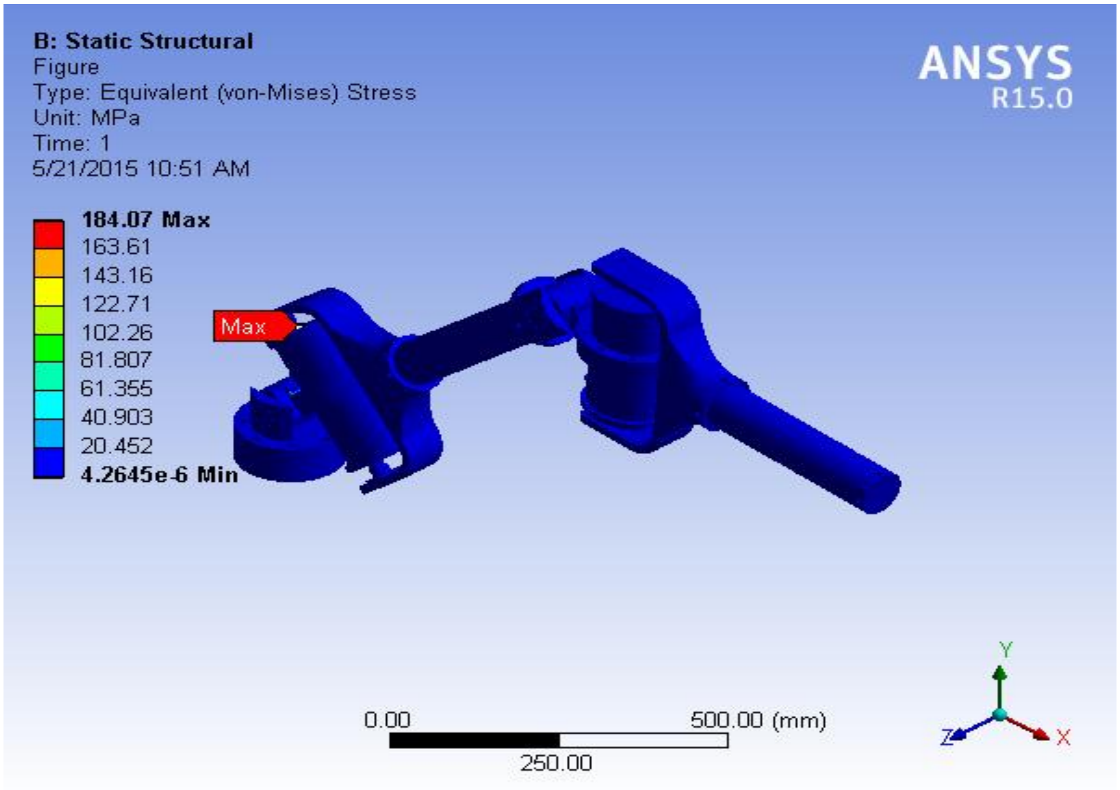


Figure 4.20: Stress developed in manipulator

Table 4.6 Results of 2-link modular manipulator under third configuration

	Under gravity and 50 N load	Under gravity and 40 N load	Under gravity and 20 N load	Under gravity
Stress (MPa)	184.07	172.64	149.78	126.92
Deformation (mm)	4.91	3.90	3.32	2.74

4.2.4 Comparison of Results

The stress plot and deformation plot of all three configurations with variation in load are shown in Figure 4.21 and Figure 4.22 respectively. From the plot it can be seen that the maximum stress and deformation are 1318.8 MPa and 8.39 mm respectively in worst configuration when a load of 50 N is applied in presence of gravity. The results are within the allowable limit.

4.4 Comparison of Different Approaches

Stress and deformation plot of 2-link modular manipulators with varying load are shown in Figure 4.23 and Figure 4.24 respectively. The solid line shows the variation for configurations of bevel gear approach while dashed lines are used for helical gear approach. From the plots it can be observed that the maximum stress occurred in the case of worst configuration of bevel gear

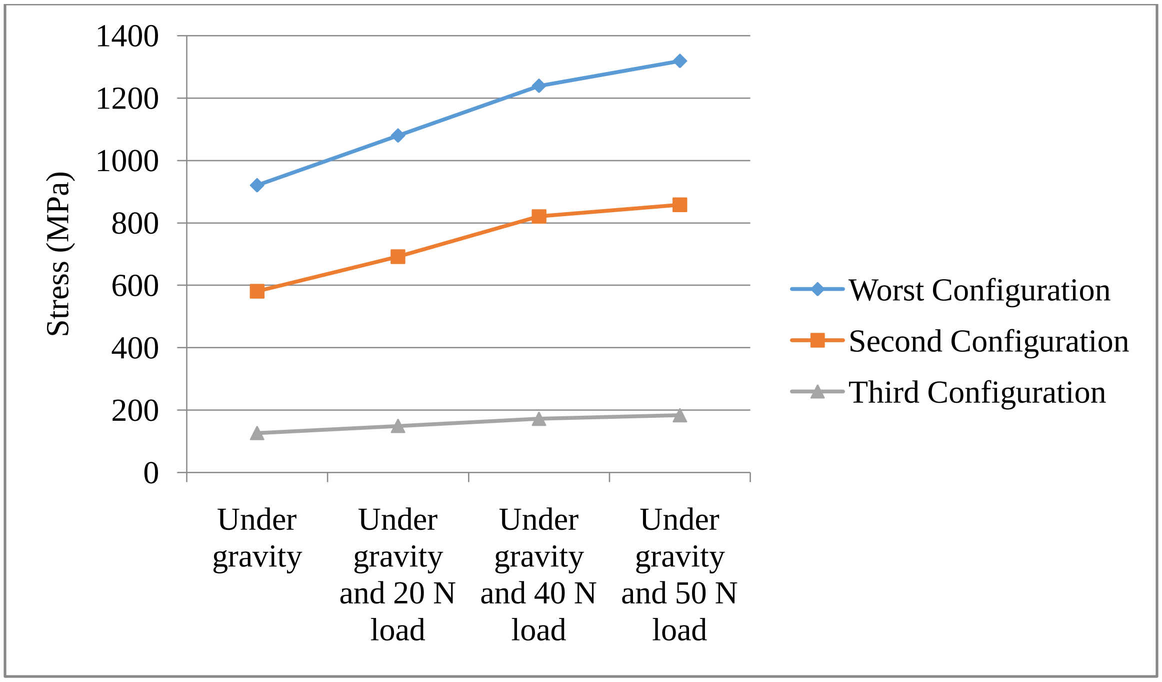


Figure 4.21: Plot of stress versus load for 2-link modular manipulator

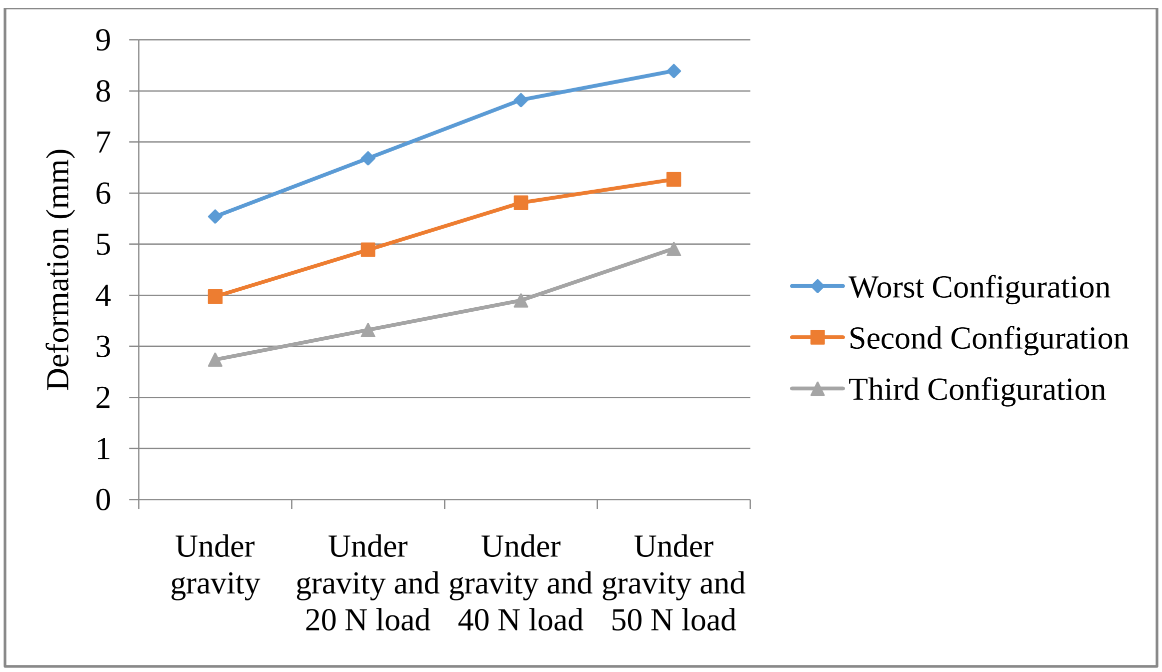


Figure 4.22: Plot of deformation versus load for 2-link modular manipulator

approach. The value is within the allowable limit. It is also observed that the maximum deformation observed is in case of worst configuration of helical gear approach. On basis of this we can conclude that the accuracy of bevel gear approach is more than the helical gear approach. The stresses developed in case of helical gear approach is less than the bevel gear approach.

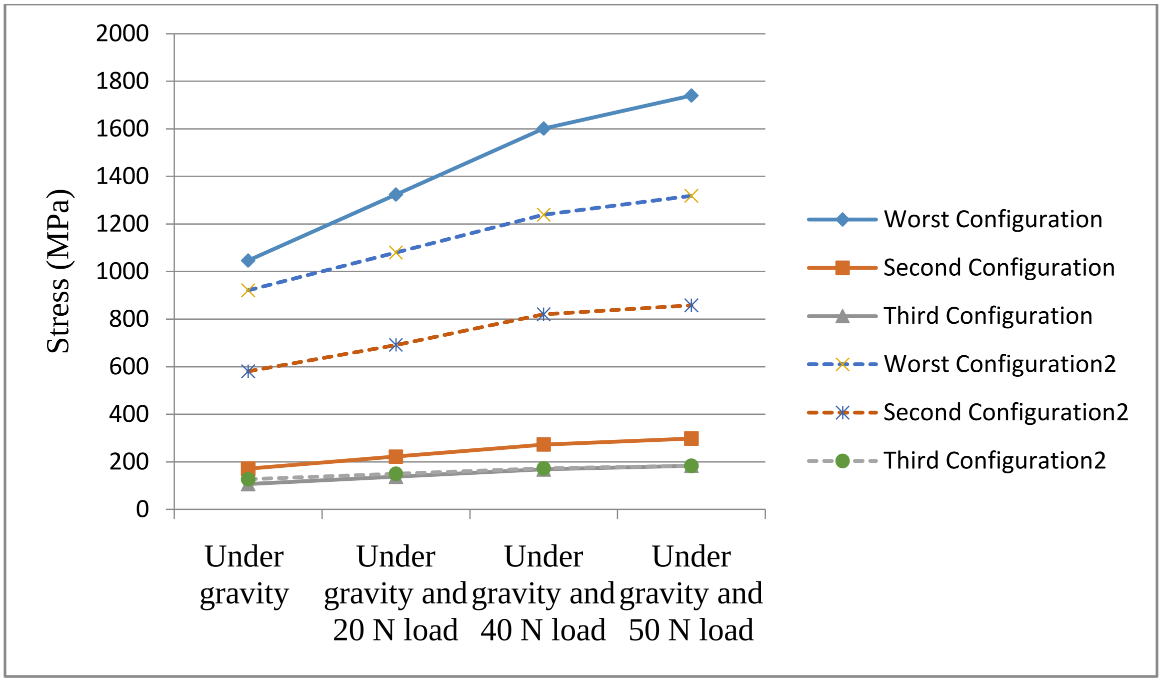


Figure 4.23: Plot of stress versus load for 2-link modular manipulator

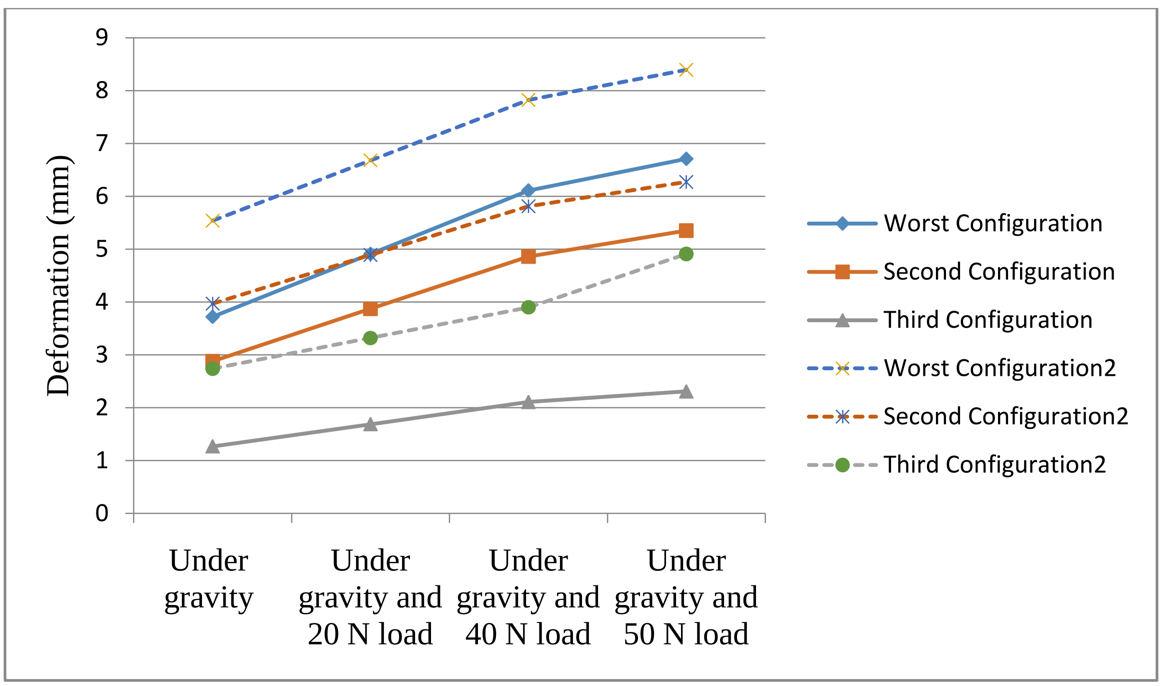


Figure 4.24: Plot of deformation versus load for 2-link modular manipulator

4.5 Summary

In this chapter the assemblies of 2-link modular manipulators have been presented in different configurations using both bevel gear and helical gear approaches. The static analyses of all the modular manipulators have been performed using ANSYS and the results have been tabulated. Form the results it has been seen that deformation occurs more in the helical gear approach compared to bevel gear approach. The stress and deformation decreases with the decrease in the load at the link. The variation in the link twist angles of manipulator is done and it can be seen that this change will not affect the working or performance of the manipulator.

Chapter 5

Dynamic Analyses of Modular Manipulators

5.1 Introduction

In Chapter 4, the static analyses of 2-link modular manipulator are discussed. In this Chapter, the dynamic behavior of the manipulators is discussed. The analyses of modular manipulators are performed using SimWise 4D. The discussion includes 2-link and 4-link modular manipulators. The variation in the stress and displacement of the manipulators are observed. Modification in the design of links is done to reduce the displacement and stress. At last the results are compared.

5.2 Analysis of Bevel Gear Approach

In this section, 2-link and 4-link modular manipulators are formulated using bevel gear approach. The manipulators are analyzed during the relative movement of the structure. The variation of link twist angle is done to check the strength of the structure. The manipulator is under motion for 6 seconds and plot of stress and displacement are plotted.

5.2.1 2-Link Modular Manipulator

2-link modular manipulator is assembled by using two joints and two links. The link lengths of link 1 and link 2 are 300mm and 250mm respectively. The manipulator is tested in three different configurations. In every configuration, a load of 50 N in –y direction at last link in addition to gravity is applied. The motors in the joints are made to rotate by giving an angular velocity which varies depending on configuration. The graphs of stress and displacement of the manipulators versus time are plotted for each configuration.

(a) Worst Configuration

In the worst configuration, the joint angles of joint 1 and joint 2 are 0^o and 90^o respectively. The link twist angle of both the joints is 0^o. The angular velocity of joint1 and joint 2 is 30 deg/s. The direction of the angular velocity of the joint 2 is reversed after 3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.2 and Figure 5.3 respectively. The configuration is shown in Figure 5.1.

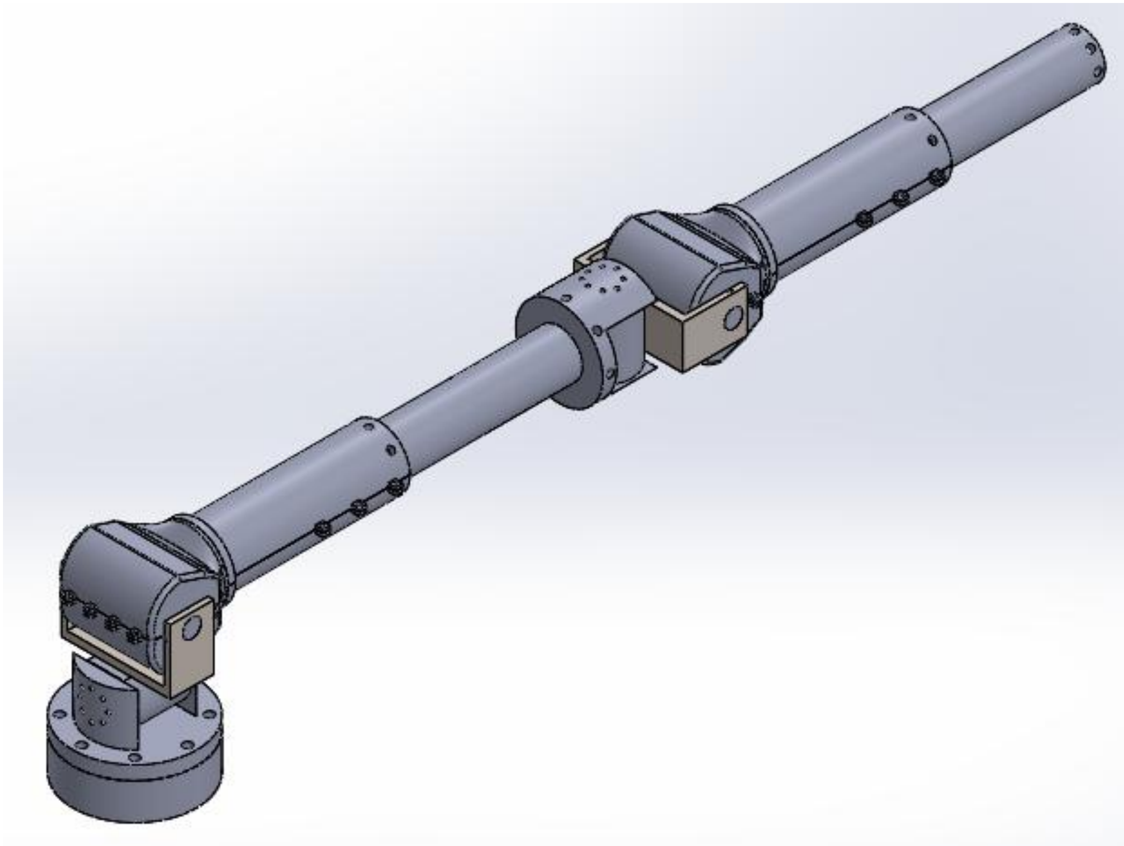


Figure 5.1: Worst configuration of 2-link modular manipulator

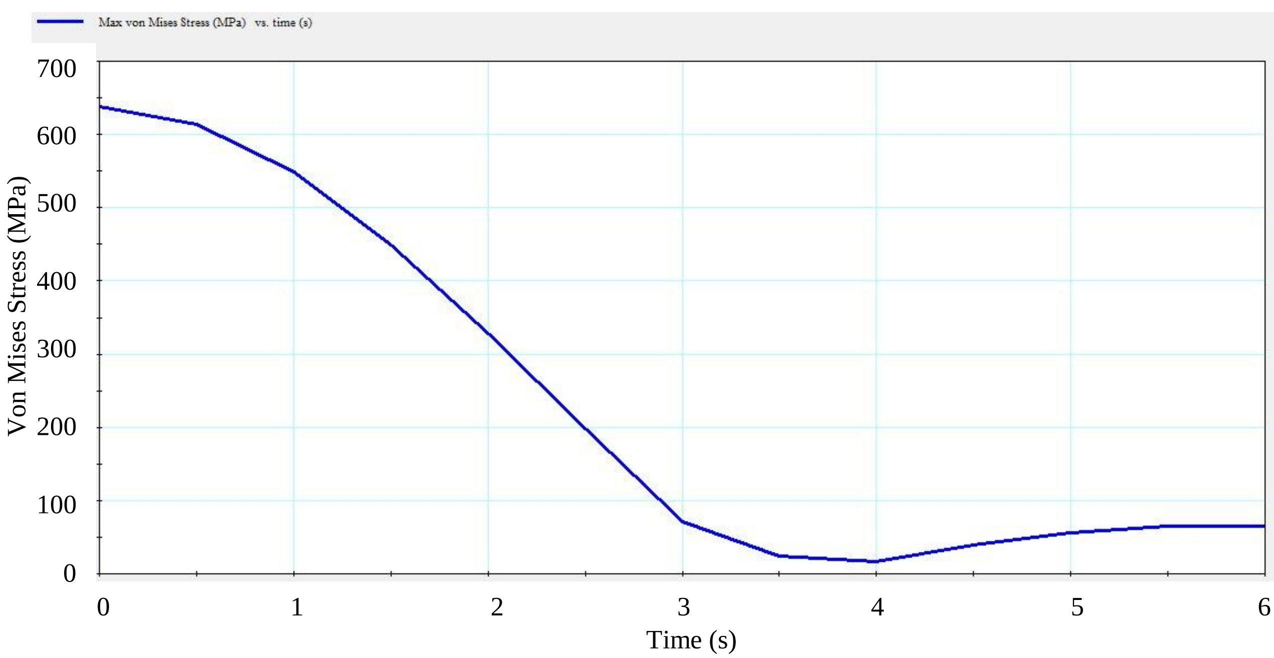


Figure 5.2: Stress versus time plot of manipulator under worst configuration

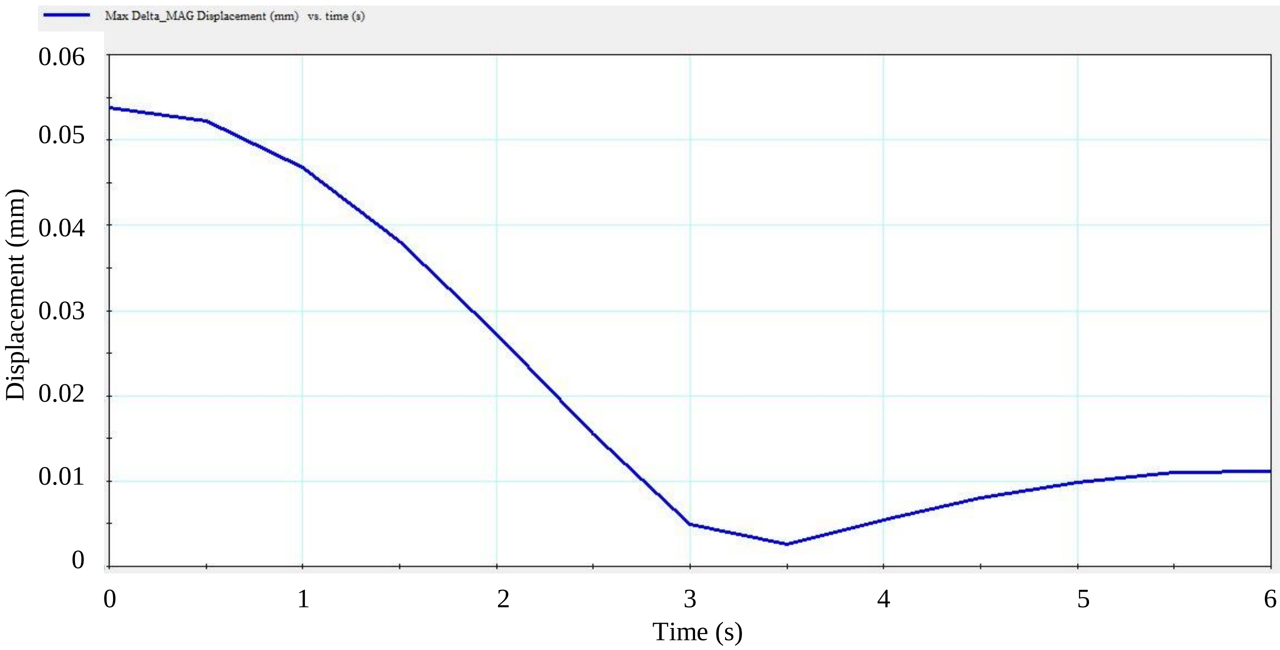


Figure 5.3: Displacement versus time plot of manipulator under worst configuration

(b) Second Configuration

In the second configuration, the joint angles of joint 1 and joint 2 is 45^o. The link twist angle of both the joints is 0^o. The angular velocity of joint1 and joint 2 is 15 deg/s. The direction of the angular velocity of the joint 2 is reversed after 3 seconds. The configuration is shown in Figure 5.4. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.5 and Figure 5.6 respectively.

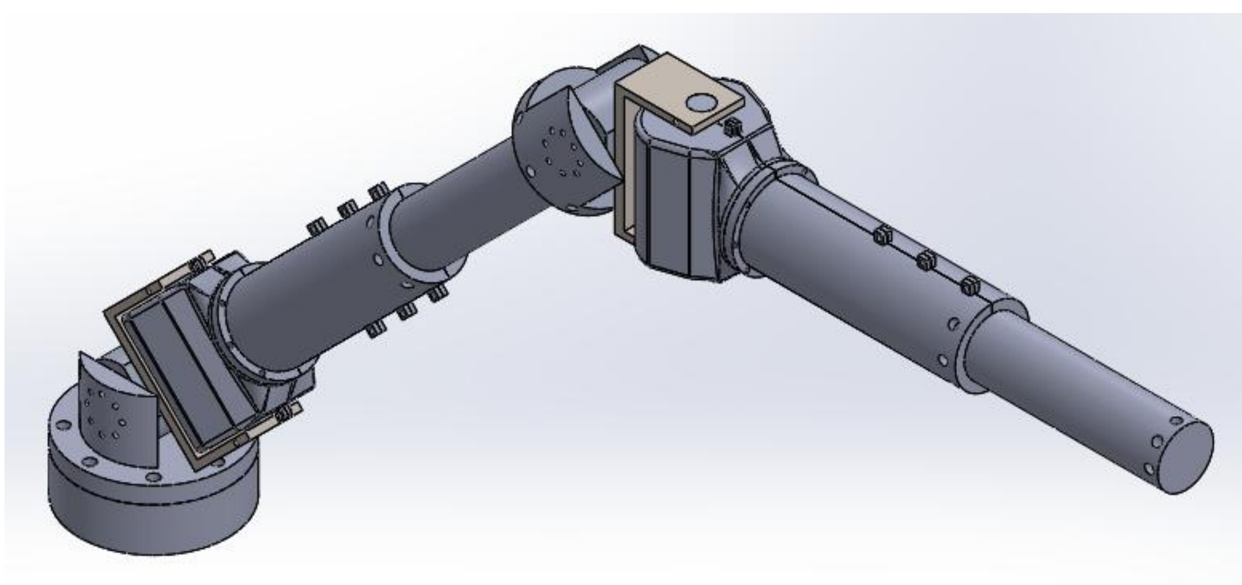


Figure 5.4: Second configuration of 2-link modular manipulator

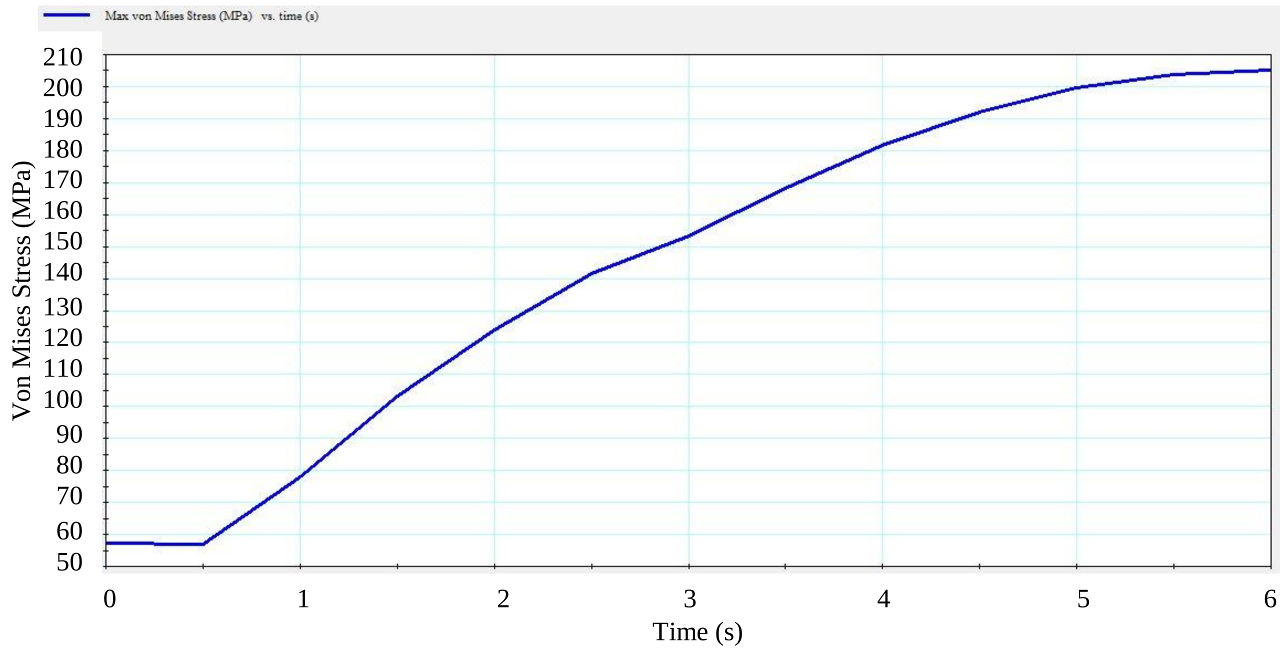


Figure 5.5: Stress versus time plot of manipulator under second configuration

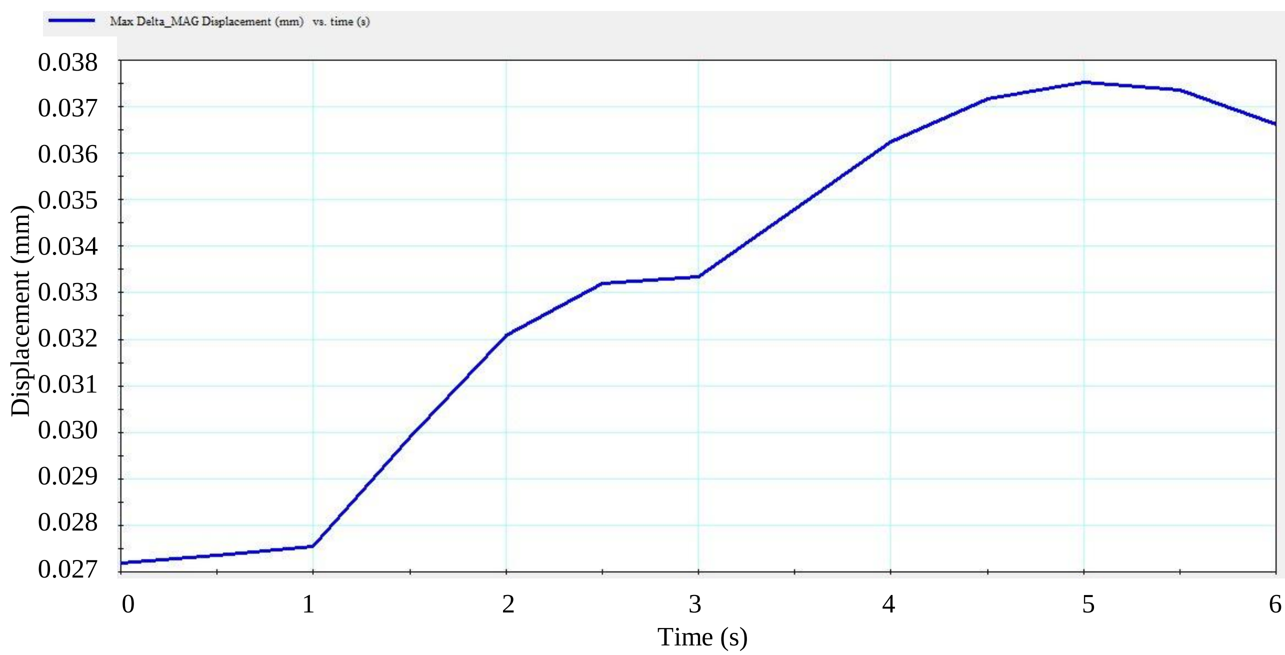


Figure 5.6: Displacement versus time plot of manipulator under second configuration

(c) Third Configuration

In the third configuration as shown in Figure 5.7, the joint angles of joint 1 and joint 2 is 90^o. The link twist angle of both the joints is 45^o. The angular velocity of joint1 and joint 2 are 15 deg/s and 30 deg/s respectively. The direction of the angular velocity of the joint is reversed after

3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.8 and Figure 5.9 respectively.

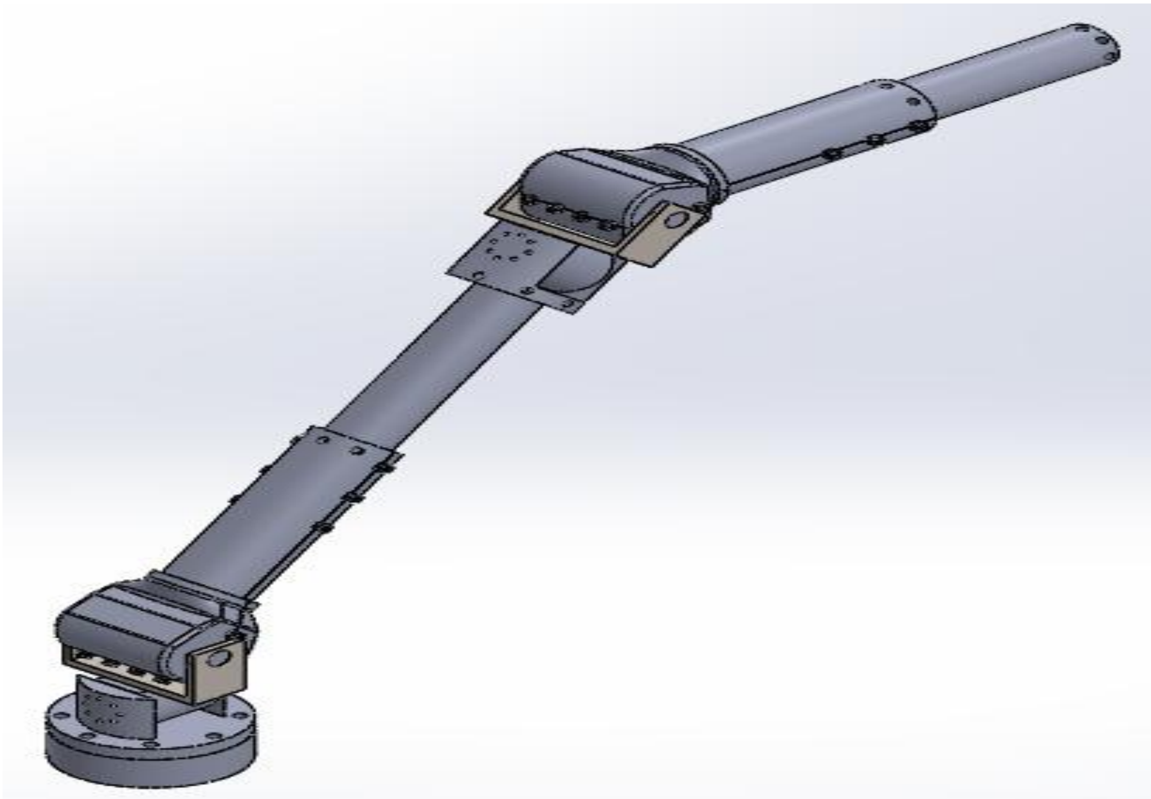


Figure 5.7: Third configuration of 2-link modular manipulator

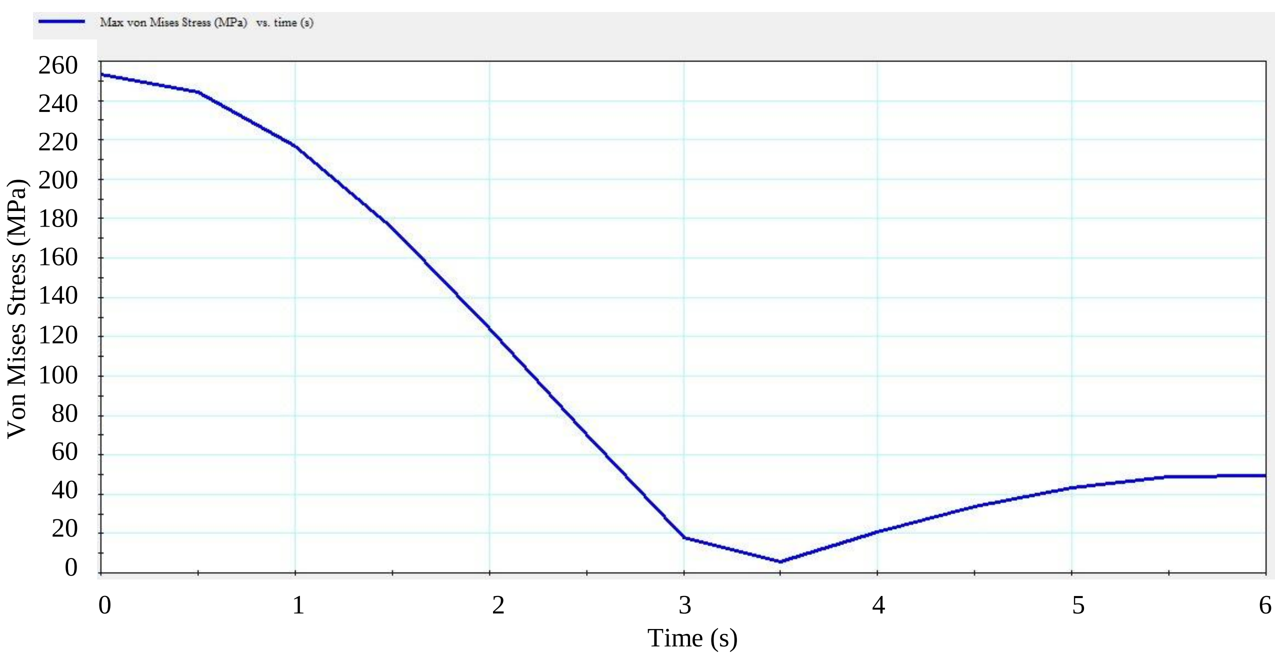


Figure 5.8: Stress versus time plot of manipulator under third configuration

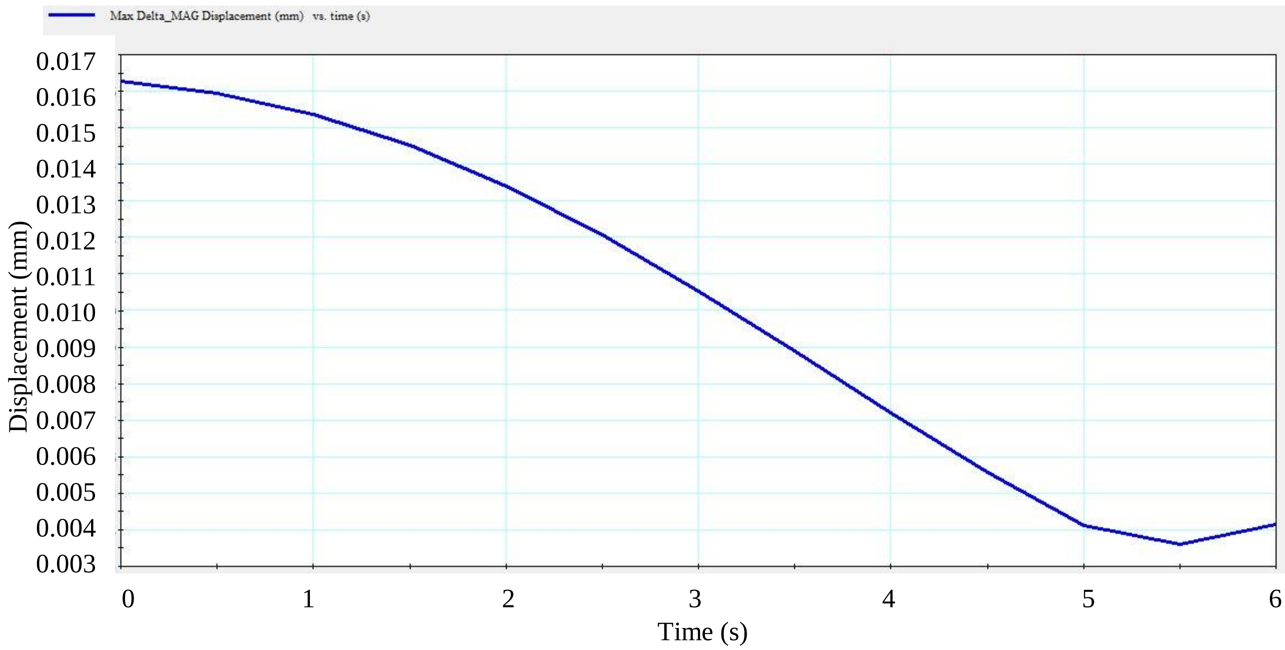


Figure 5.9: Displacement versus time plot of manipulator under third configuration

5.2.2 4-Link Modular Manipulator

4-link modular manipulator is assembled by using four joints and four links. The link lengths of link 1, 2, 3 and 4 are 300 mm, 250 mm, 200 mm and 150 mm respectively. The manipulator is tested in three different configurations. In every configuration, a load of 50 N in –y direction at last link in addition to gravity is applied. The motors in the joints are made to rotate by giving an angular velocity which varies depending on configuration. The graphs of stress and displacement of the manipulators versus time are plotted for each configuration.

(a) Worst Configuration

In the worst configuration, the joint angles of joint 1, 2, 3 and 4 are 0^o, 90^o, 90^o and 90^o respectively. The link twist angle of all the joints is 0^o. The angular velocity of joint1, 2, 3 and 4 are 30 deg/s, 15 deg/s, 15 deg/s and 15 deg/s respectively. The direction of the angular velocity of the joint 2, 3 and 4 is reversed after 3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.11 and Figure 5.12 respectively. The configuration is shown in Figure 5.10.

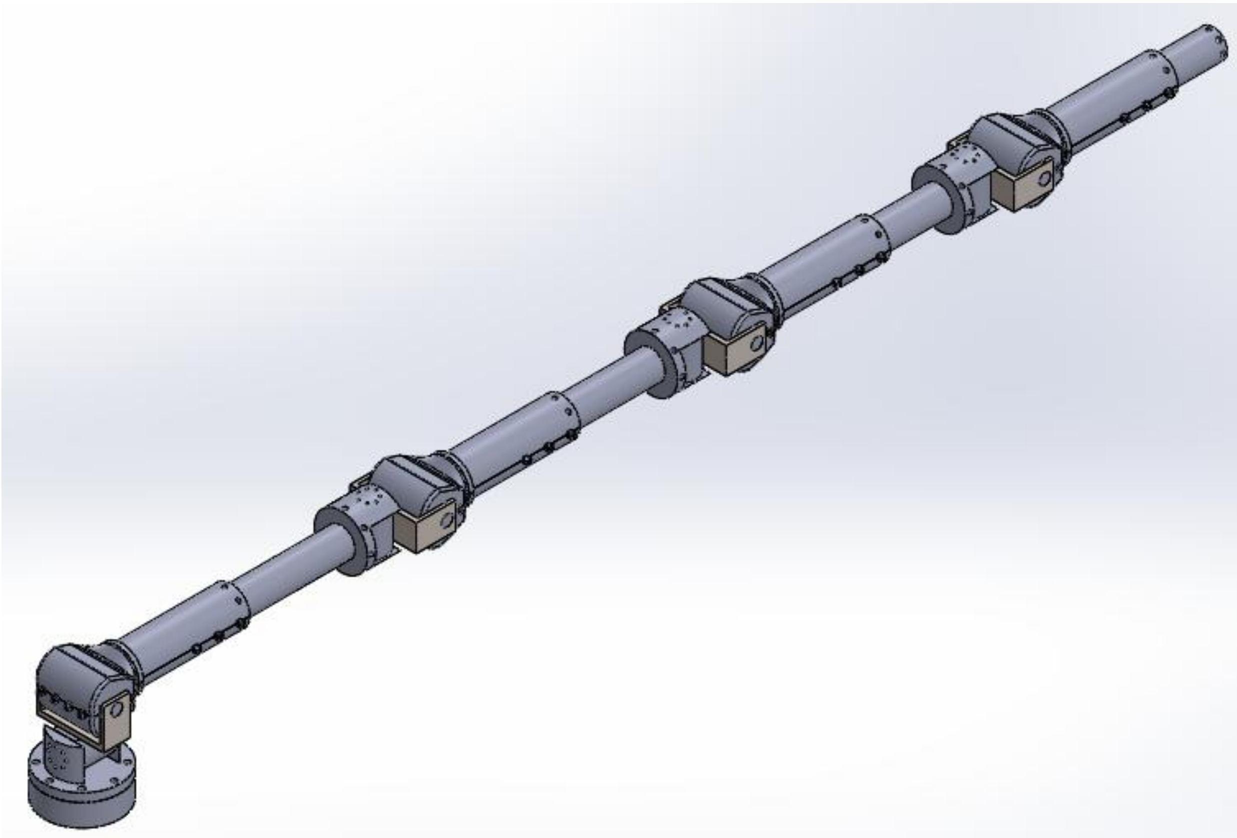


Figure 5.10: Worst configuration of 4-link modular manipulator

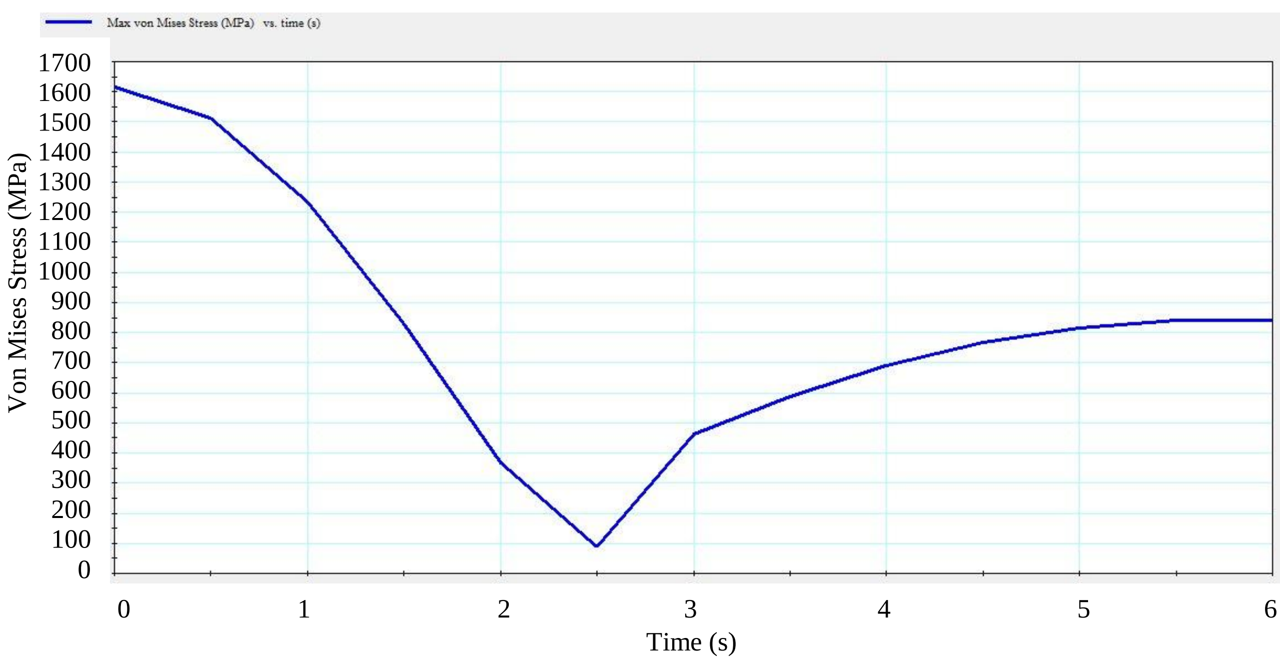


Figure 5.11: Stress versus time plot of manipulator under worst configuration

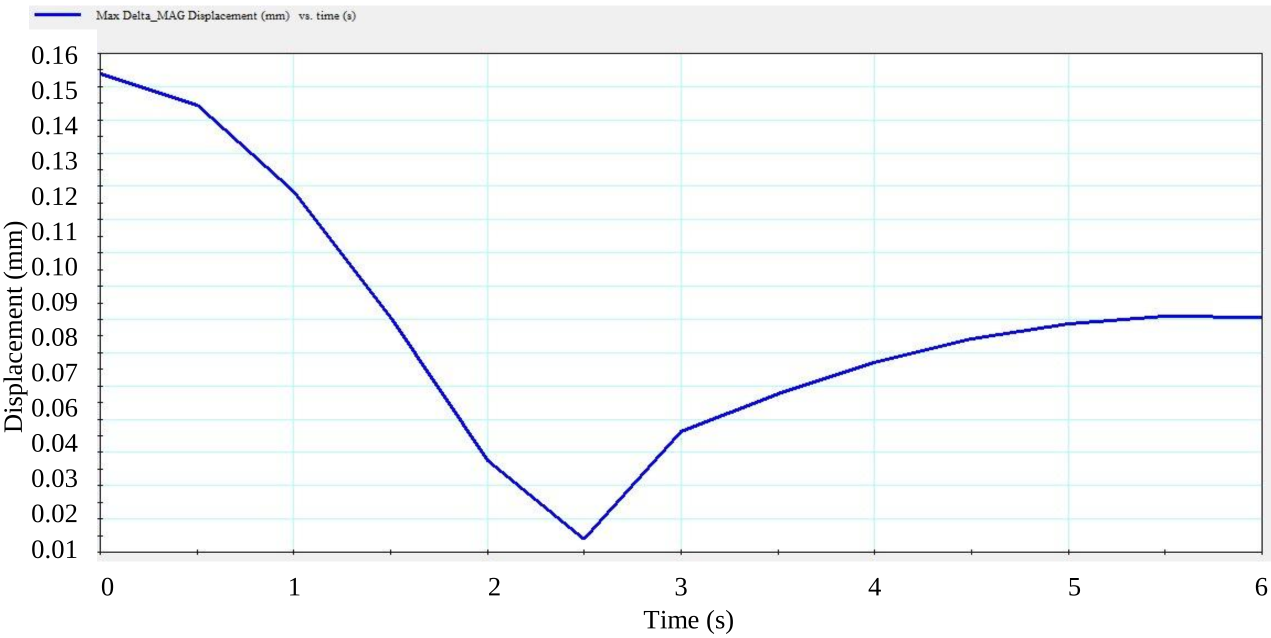


Figure 5.12: Displacement versus time plot of manipulator under worst configuration

(b) Second Configuration

In the second configuration, the joint angle of all joints is 90^o. The link twist angle of the joint 1, 2, 3 and 4 are 45^o, 45^o, 0^o and 45^o respectively. The angular velocity of joint1, 2, 3 and 4 are 7.5 deg/s, 15 deg/s, 15 deg/s and 15 deg/s respectively. The direction of the angular velocity of the joint 2, 3 and 4 is reversed after 3 seconds. The configuration is shown in Figure 5.13. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.14 and Figure 5.15 respectively.

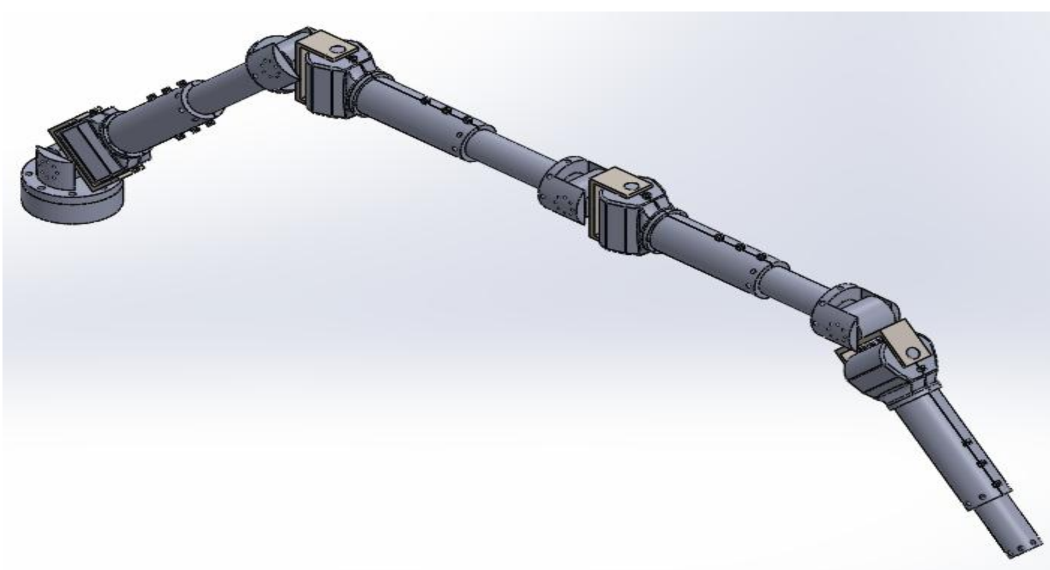


Figure 5.13: Second configuration of 4-link modular manipulator

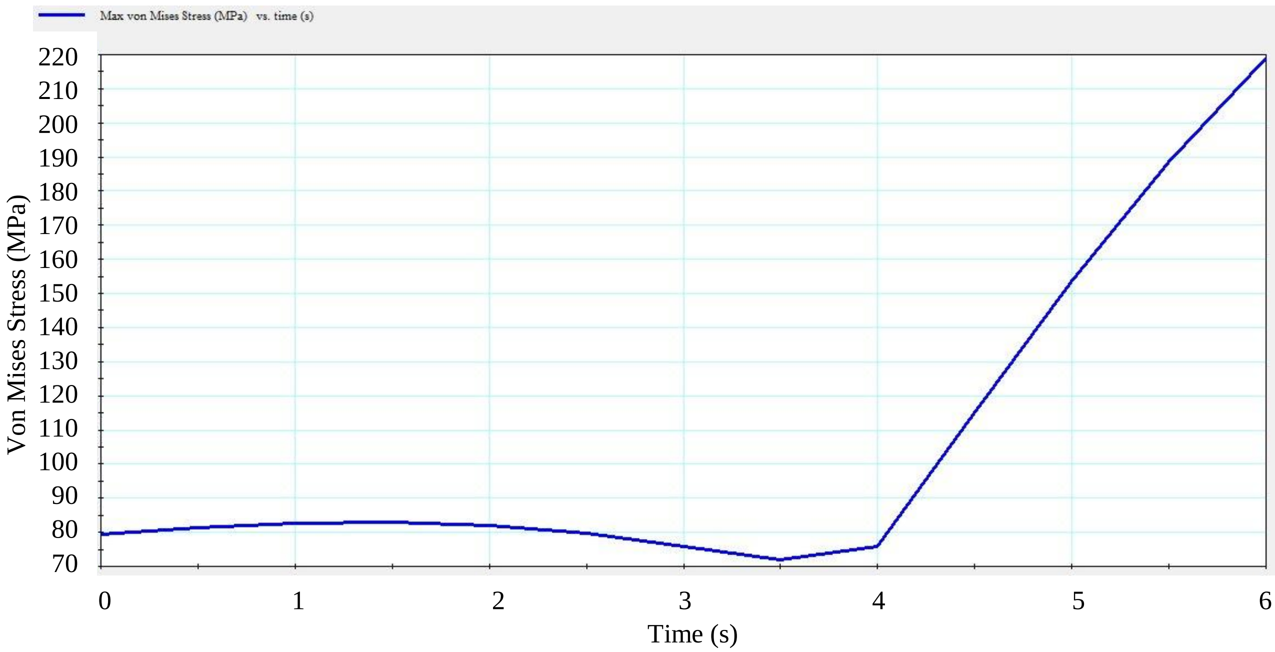


Figure 5.14: Stress versus time plot of manipulator under second configuration

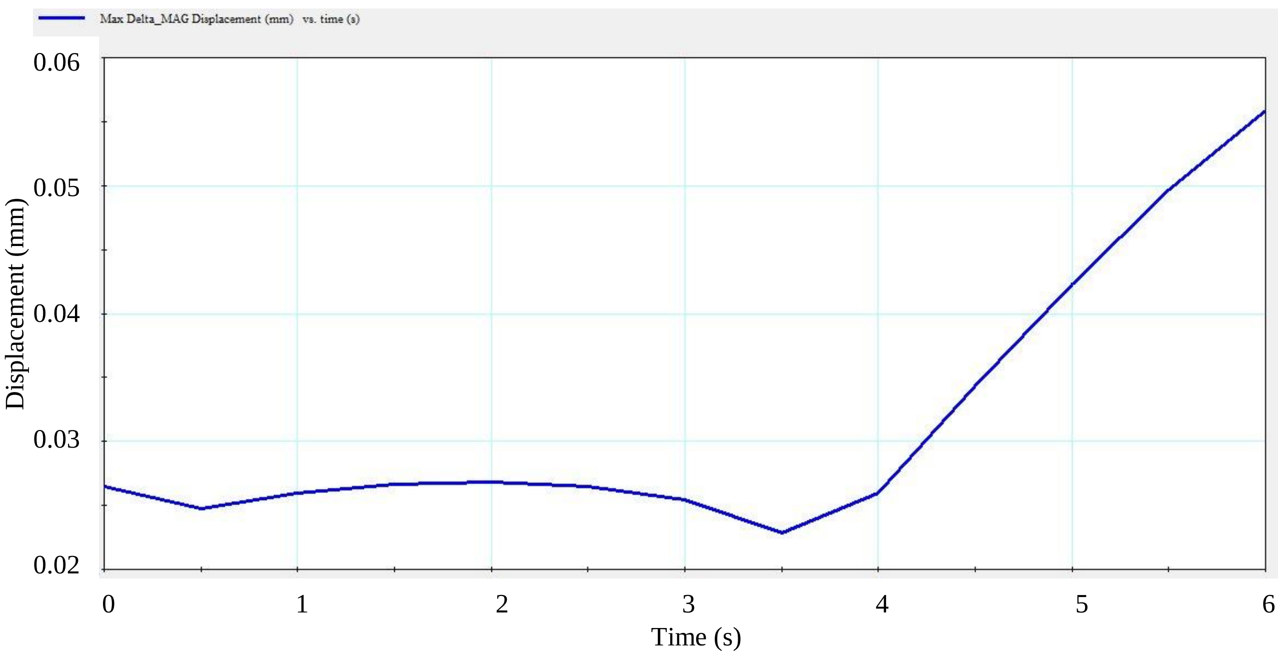


Figure 5.15: Displacement versus time plot of manipulator under second configuration

(c) Third Configuration

In the third configuration as shown in Figure 5.16, the joint angles of joint 1, 2, 3 and 4 are 45^o, 45^o, 90^o and 45^o respectively. The link twist angle of all the joints is 0^o. The angular velocity of joint1, 2, 3 and 4 are 15 deg/s, 15 deg/s, 15 deg/s and 15 deg/s respectively. The direction of the angular velocity of the joint 3 is reversed after 3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.17 and Figure 5.18 respectively.

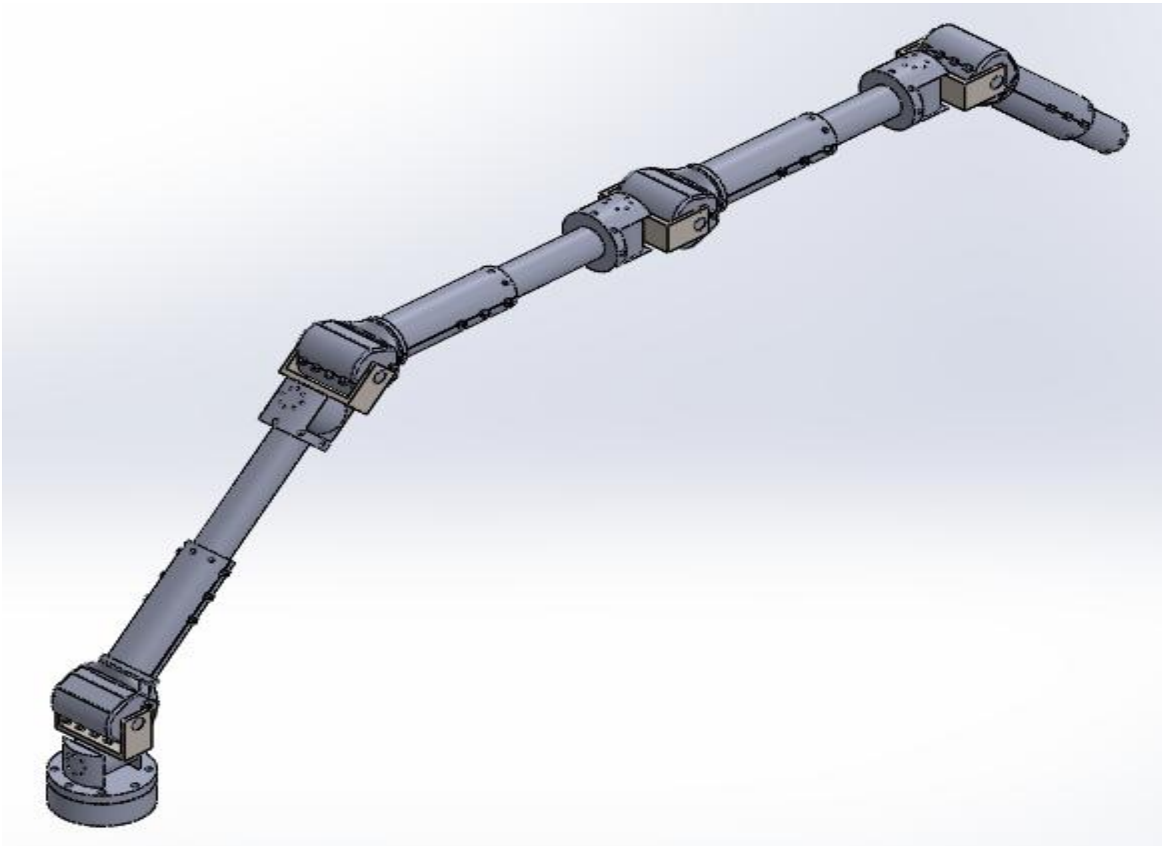


Figure 5.16: Third configuration of 4-link modular manipulator

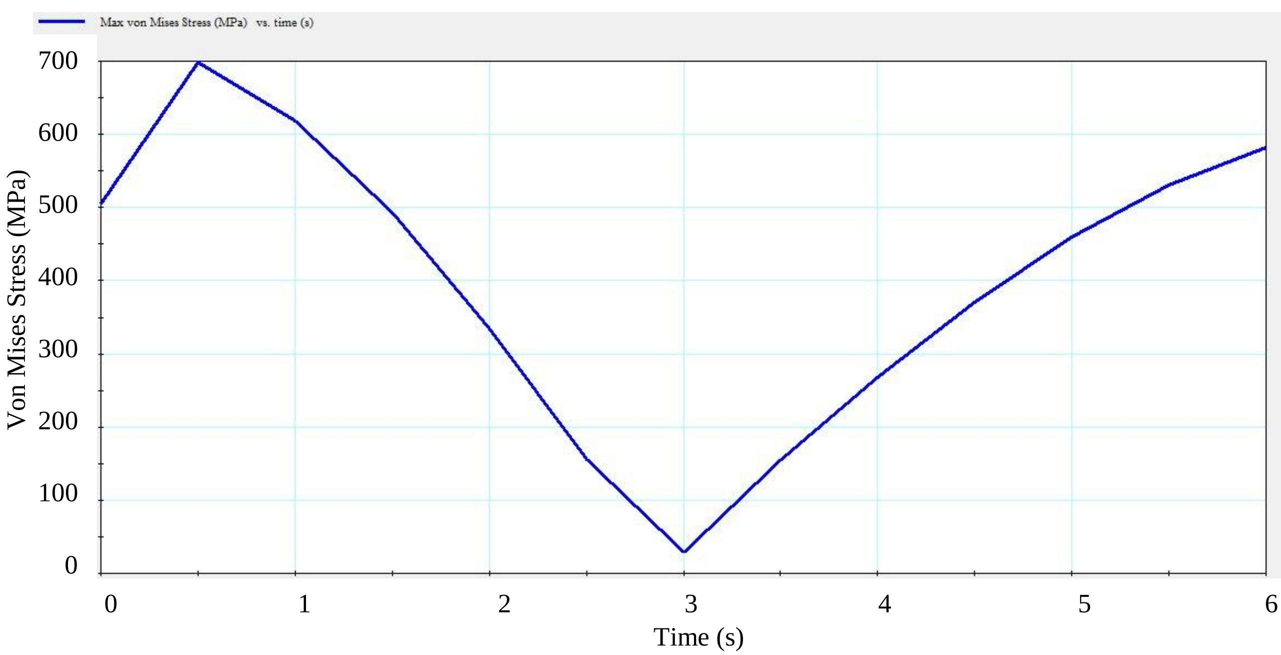


Figure 5.17: Stress versus time plot of manipulator under third configuration

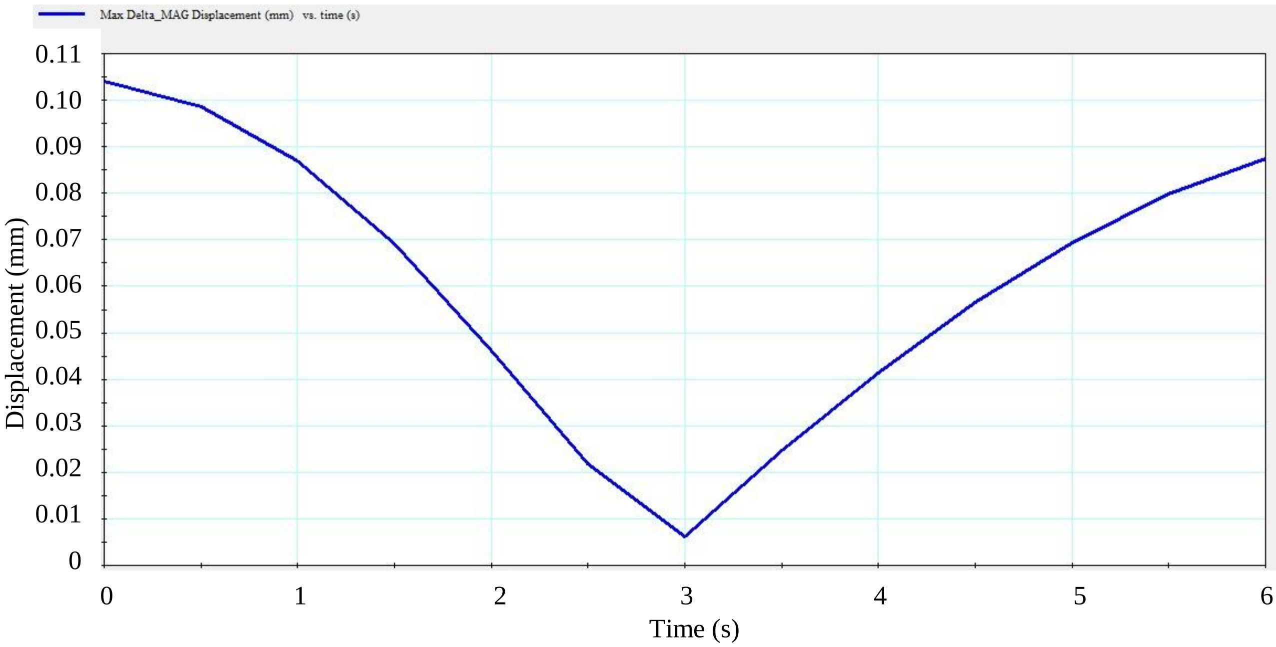


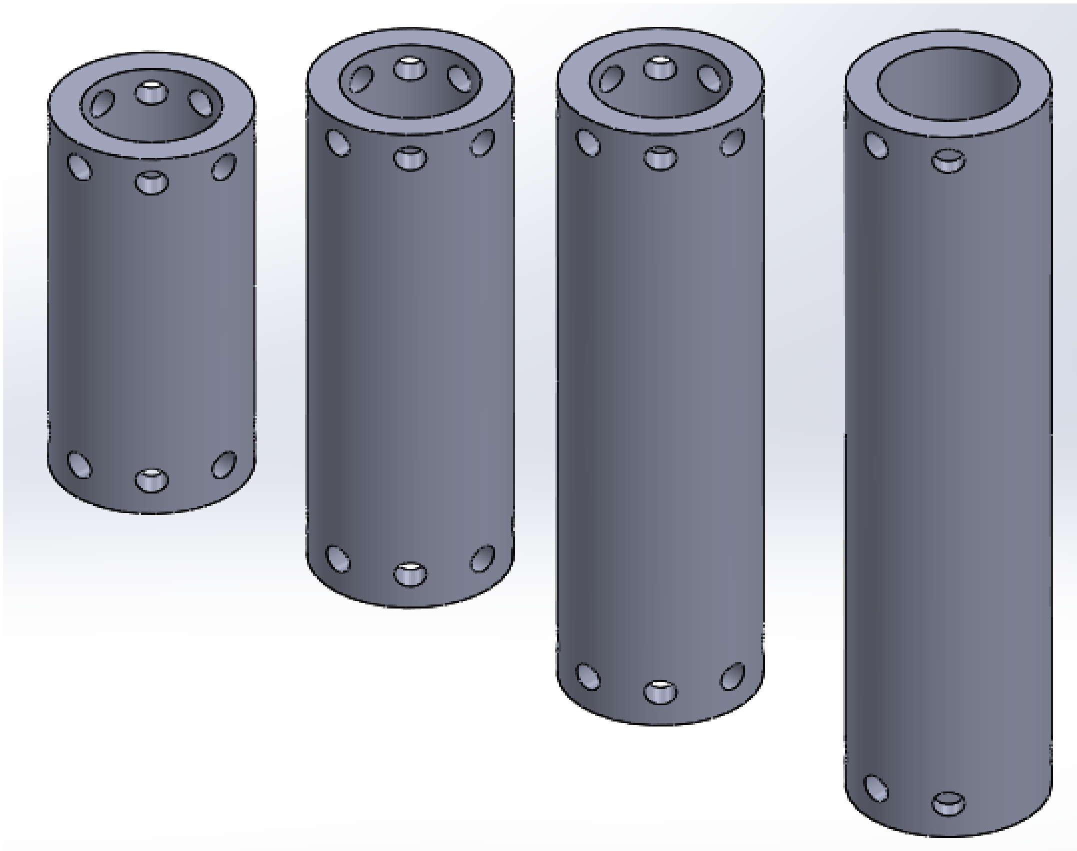
Figure 5.18: Displacement versus time plot of manipulator under third configuration

5.2.3 Modified 2-Link Modular Manipulator

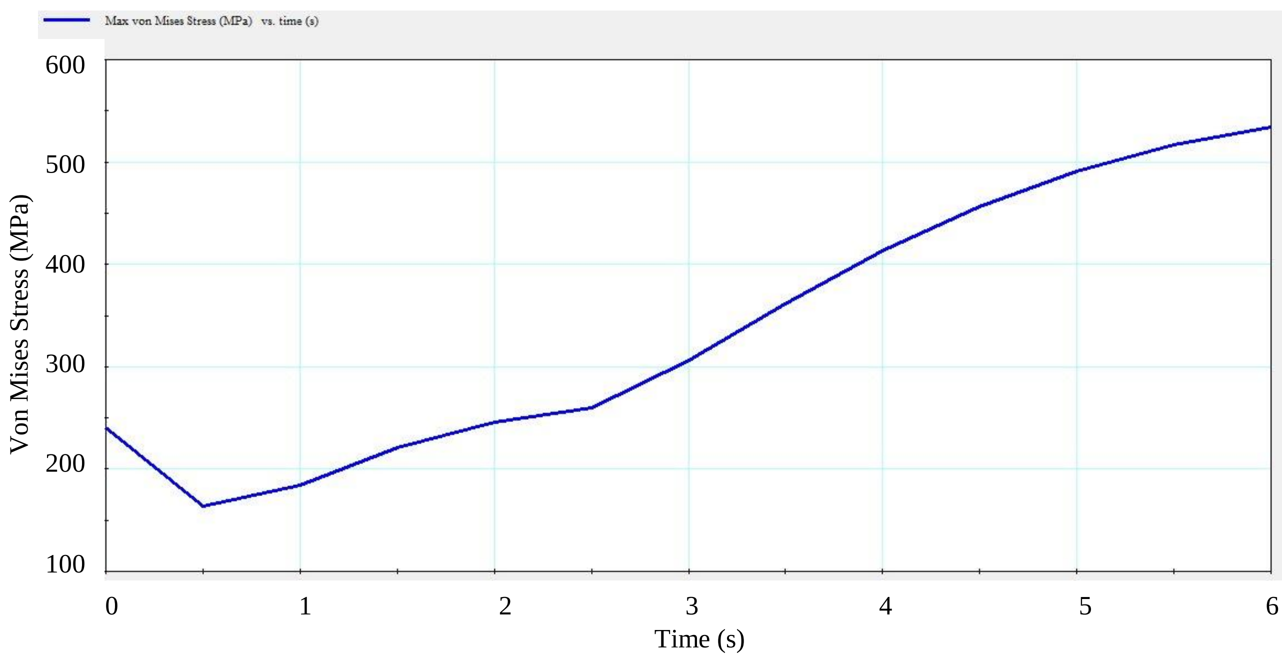
The links of the manipulator are modified. The links are made hollow with a thickness of 10 mm as shown in Figure 5.19(a). These modified links are now used in assembly and a modified 2-link modular manipulator is made. 2-link modular manipulator is assembled by using two joints and two links. The link lengths of link 1 and link 2 are 300mm and 250mm respectively. The manipulator is tested in three different configurations. In every configuration, a load of 50 N in –y direction at last link in addition to gravity is applied. The motors in the joints are made to rotate by giving an angular velocity which varies depending on configuration. The graphs of stress and displacement of the manipulators versus time are plotted for each configuration.

(a) Worst Configuration

In the worst configuration, the joint angles of joint 1 and joint 2 are 0^o and 90^o respectively. The link twist angle of both the joints is 0^o. The angular velocity of joint1 and joint 2 is 30 deg/s. The direction of the angular velocity of the joint 2 is reversed after 3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.19(b) and Figure 5.20 respectively.



(a)



(b)

Figure 5.19: (a) Modified links (b) Stress versus time plot of manipulator under worst configuration

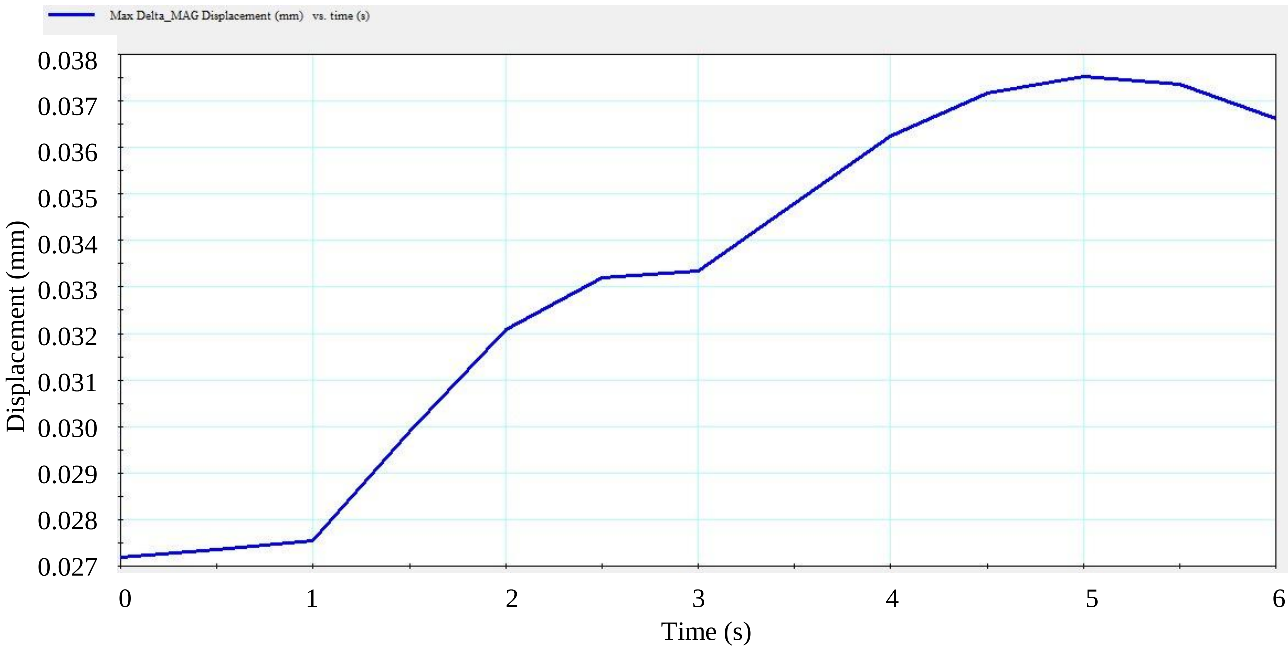


Figure 5.20: Displacement versus time plot of manipulator under worst configuration

(b) Second Configuration

In the second configuration, the joint angles of joint 1 and joint 2 is 45^o. The link twist angle of both the joints is 0^o. The angular velocity of joint1 and joint 2 is 15 deg/s. The direction of the angular velocity of the joint 2 is reversed after 3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.21 and Figure 5.22 respectively.

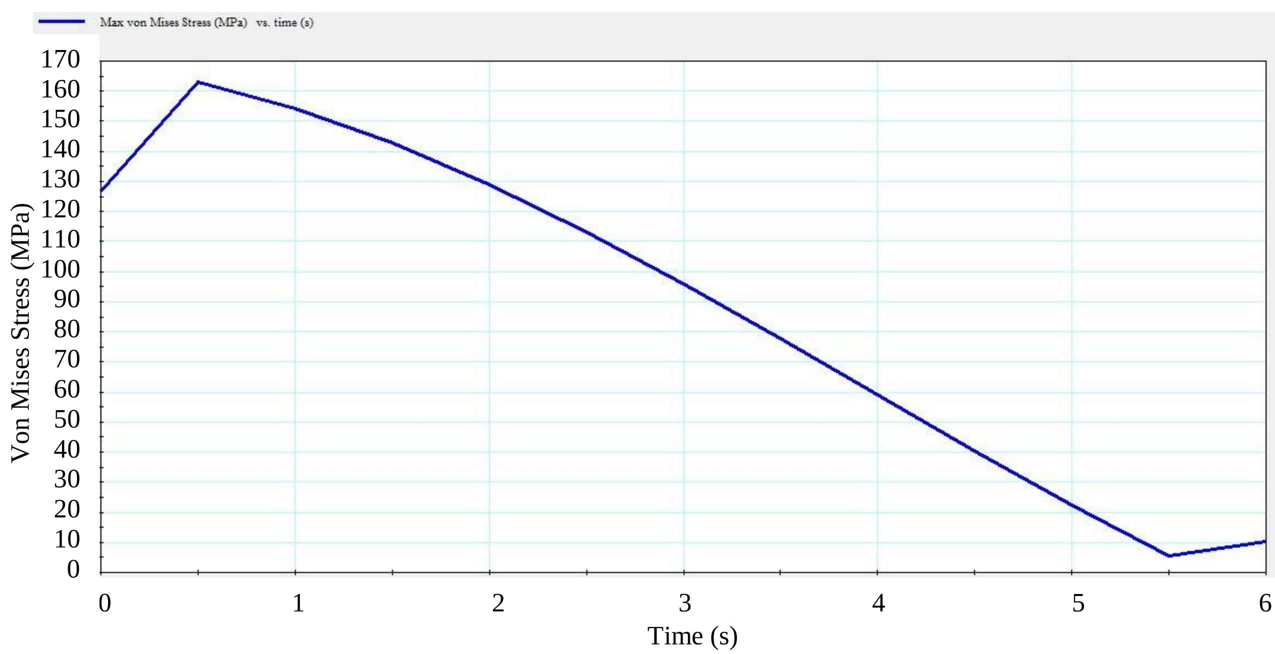


Figure 5.21: Stress versus time plot of manipulator under second configuration

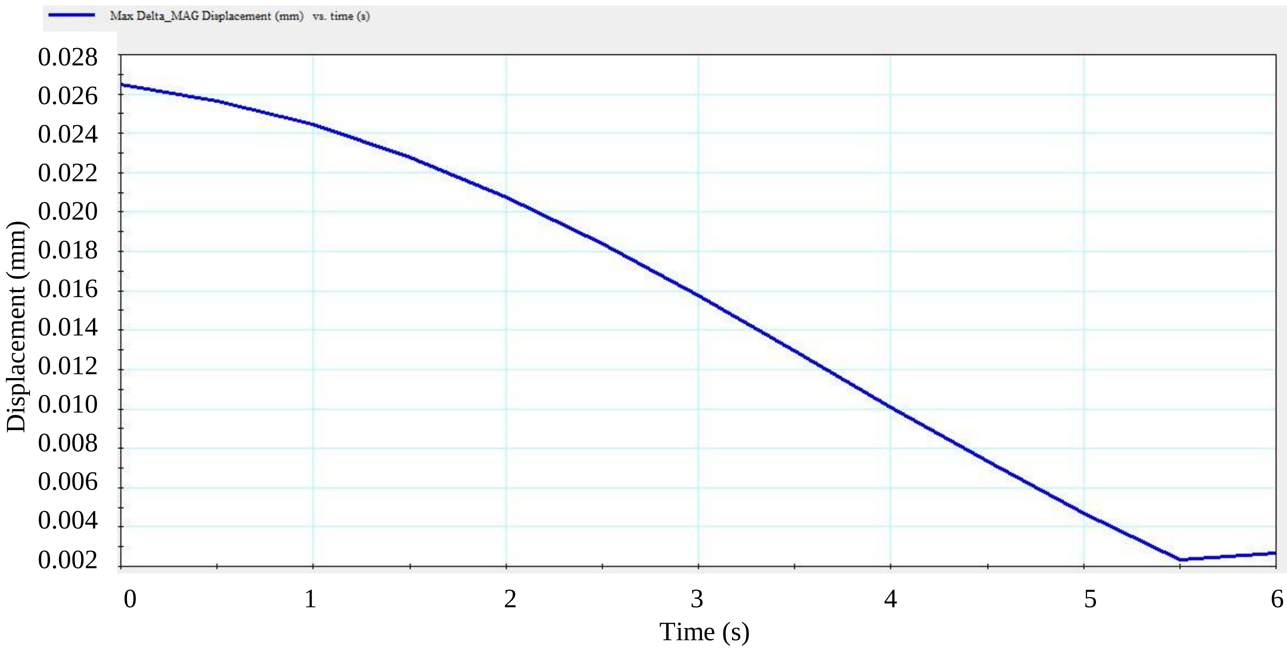


Figure 5.22: Displacement versus time plot of manipulator under second configuration

(c) Third Configuration

In the third configuration, the joint angles of joint 1 and joint 2 is 90^o. The link twist angle of both the joints is 45^o. The angular velocity of joint1 and joint 2 are 15 deg/s and 30 deg/s respectively. The direction of the angular velocity of the joint is reversed after 3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.23 and Figure 5.24 respectively.

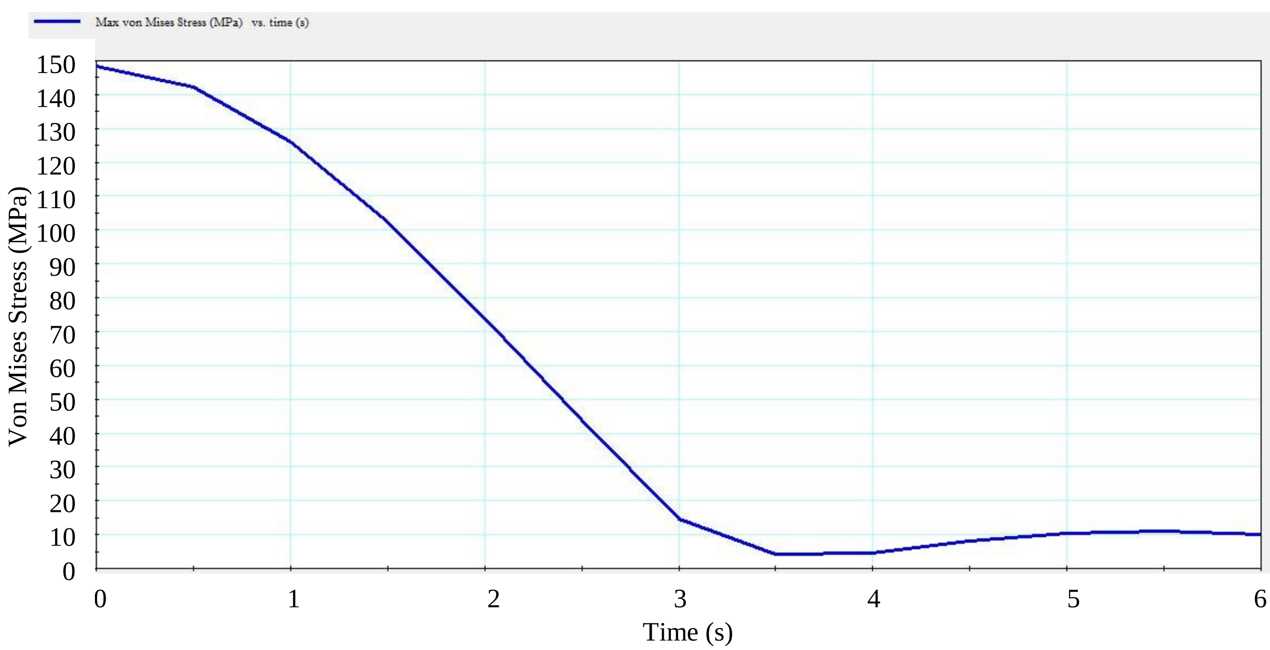


Figure 5.23: Stress versus time plot of manipulator under third configuration

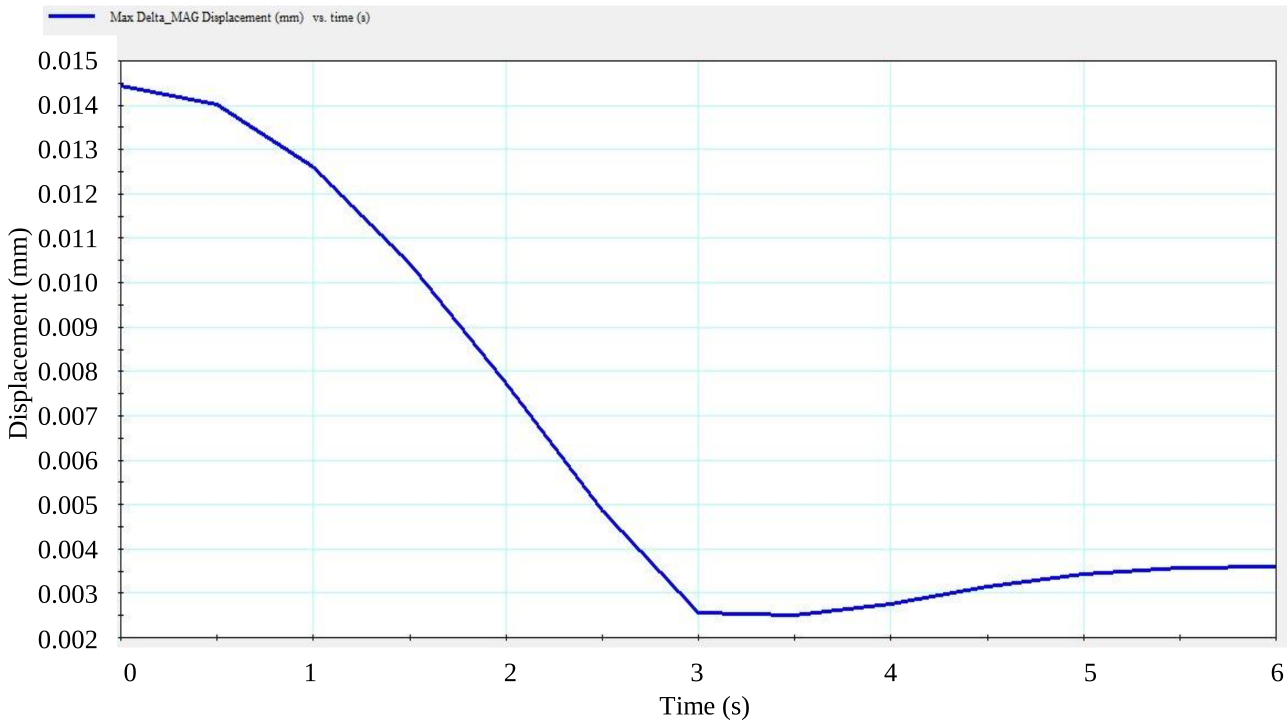


Figure 5.24: Displacement versus time plot of manipulator under third configuration

5.2.4 Modified 4-Link Modular Manipulator

The links of the manipulator are modified. The links are made hollow with a thickness of 10 mm as already discussed. These modified links are now used in assembly and a modified 4-link modular manipulator is made.4-link modular manipulator is assembled by using four joints and four links. The link lengths of link 1, 2, 3 and 4 are 300 mm, 250 mm, 200 mm and 150 mm respectively. The manipulator is tested in three different configurations. In every configuration, a load of 50 N in –y direction at last link in addition to gravity is applied. The motors in the joints are made to rotate by giving an angular velocity which varies depending on configuration. The graphs of stress and displacement of the manipulators versus time are plotted for each configuration.

(a) Worst Configuration

In the worst configuration, the joint angles of joint 1, 2, 3 and 4 are 0^o, 90^o, 90^o and 90^o respectively. The link twist angle of all the joints is 0^o. The angular velocity of joint1, 2, 3 and 4 are 30 deg/s, 15 deg/s, 15 deg/s and 15 deg/s respectively. The direction of the angular velocity of the joint 2, 3 and 4 is reversed after 3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.25 and Figure 5.26 respectively.

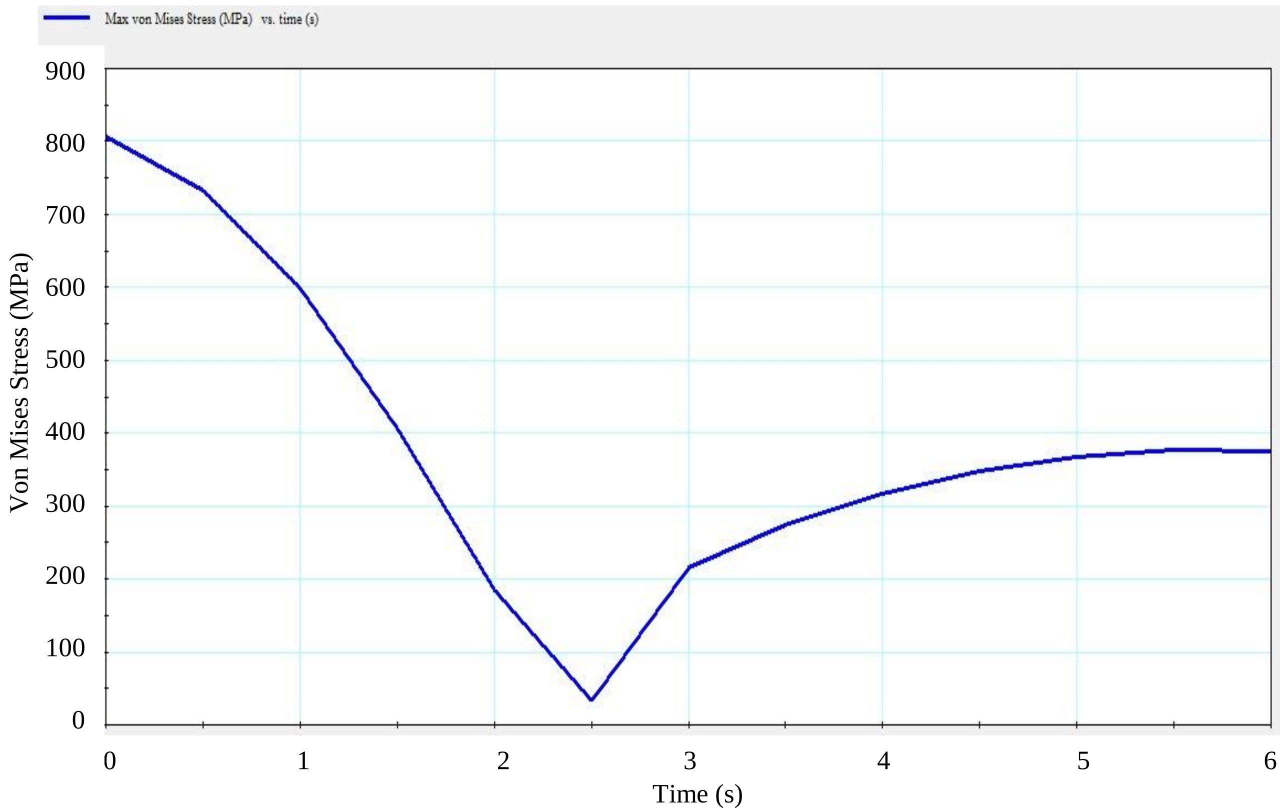


Figure 5.25: Stress versus time plot of manipulator under worst configuration

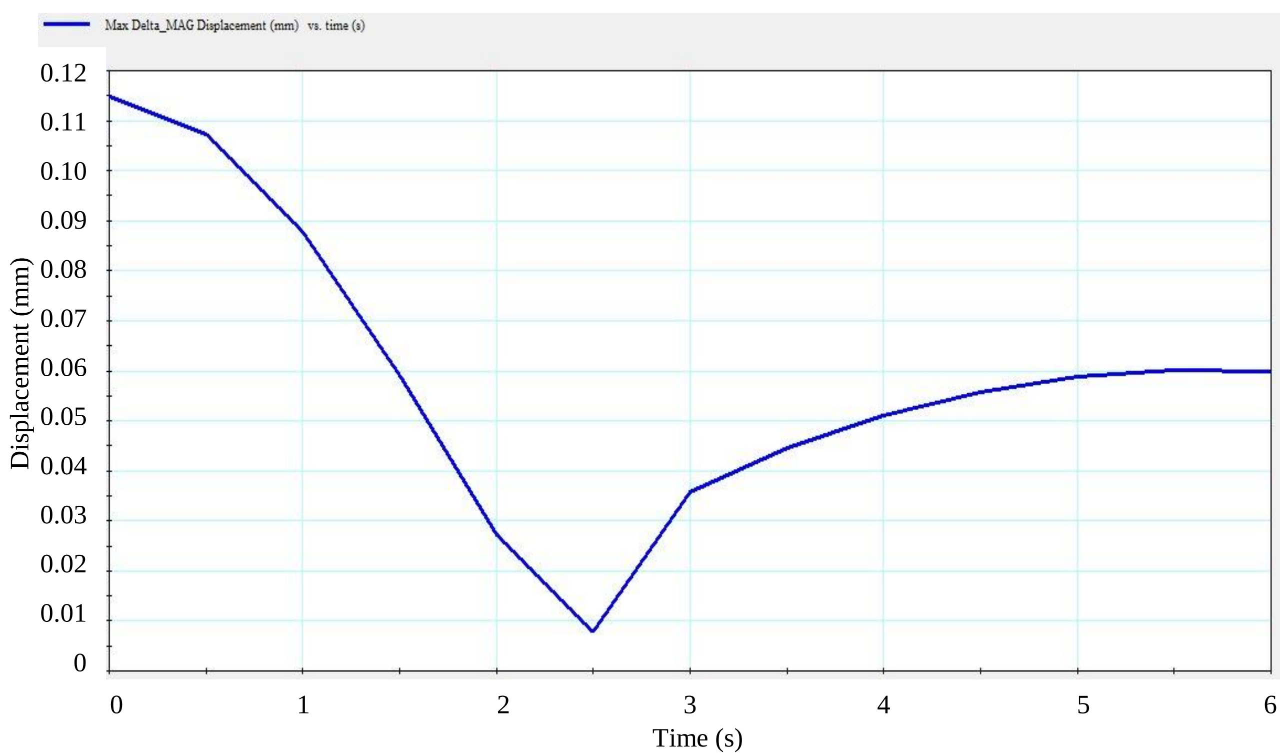


Figure 5.26: Displacement versus time plot of manipulator under worst configuration

(b) Second Configuration

In the second configuration, the joint angle of all joints is 90^o. The link twist angle of the joint 1, 2, 3 and 4 are 45^o, 45^o, 0^o and 45^o respectively. The angular velocity of joint1, 2, 3 and 4 are 7.5 deg/s, 15 deg/s, 15 deg/s and 15 deg/s respectively. The direction of the angular velocity of the joint 2, 3 and 4 is reversed after 3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.27 and Figure 5.28 respectively.

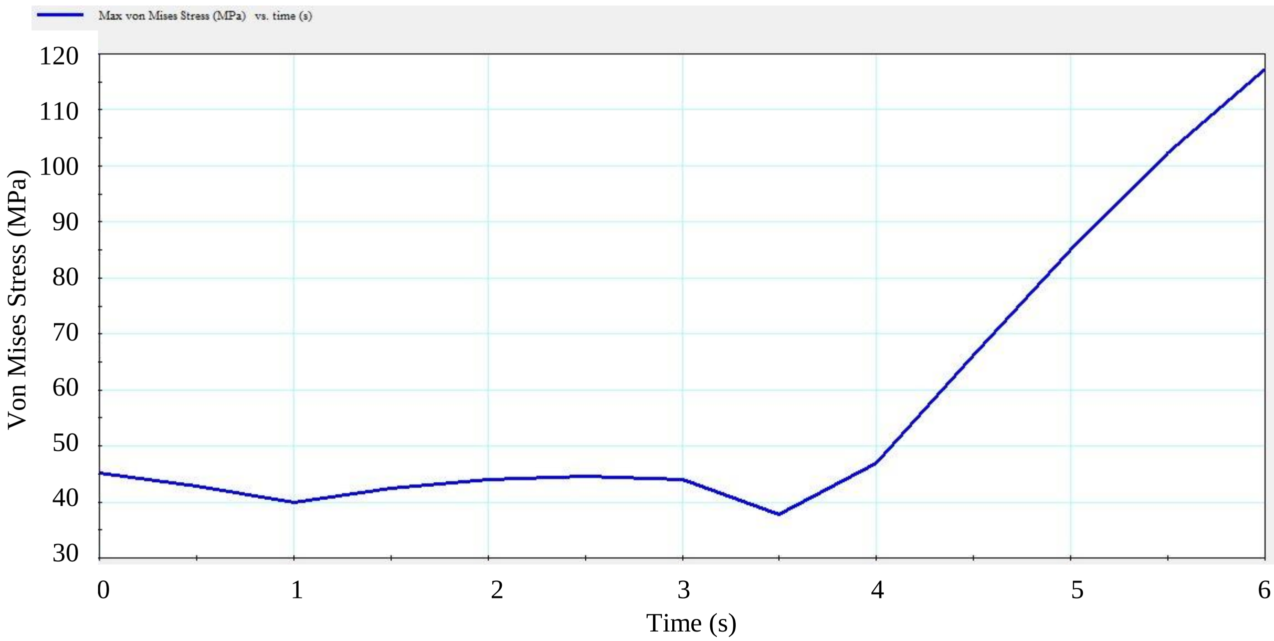


Figure 5.27: Stress versus time plot of manipulator under second configuration

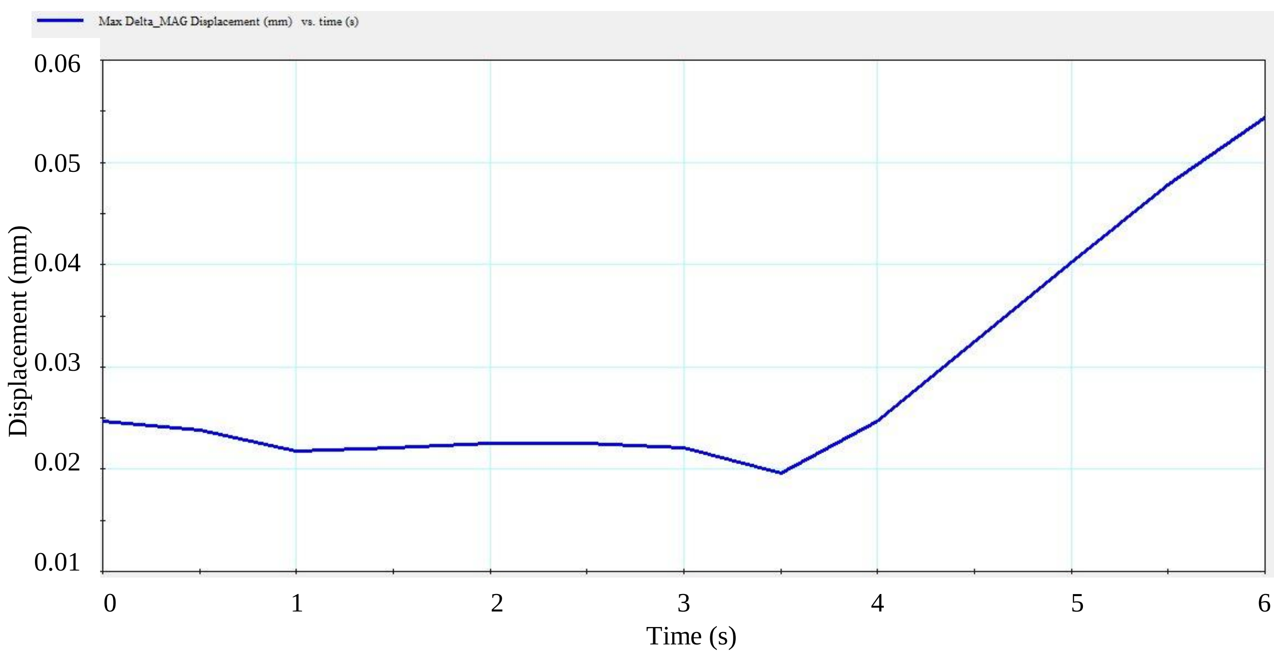


Figure 5.28: Displacement versus time plot of manipulator under second configuration

(c) Third Configuration

In the third configuration, the joint angles of joint 1, 2, 3 and 4 are 45^o, 45^o, 90^o and 45^o respectively. The link twist angle of all the joints is 0^o. The angular velocity of joint1, 2, 3 and 4 are 15 deg/s, 15 deg/s, 15 deg/s and 15 deg/s respectively. The direction of the angular velocity of the joint 3 is reversed after 3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.29 and Figure 5.30 respectively.

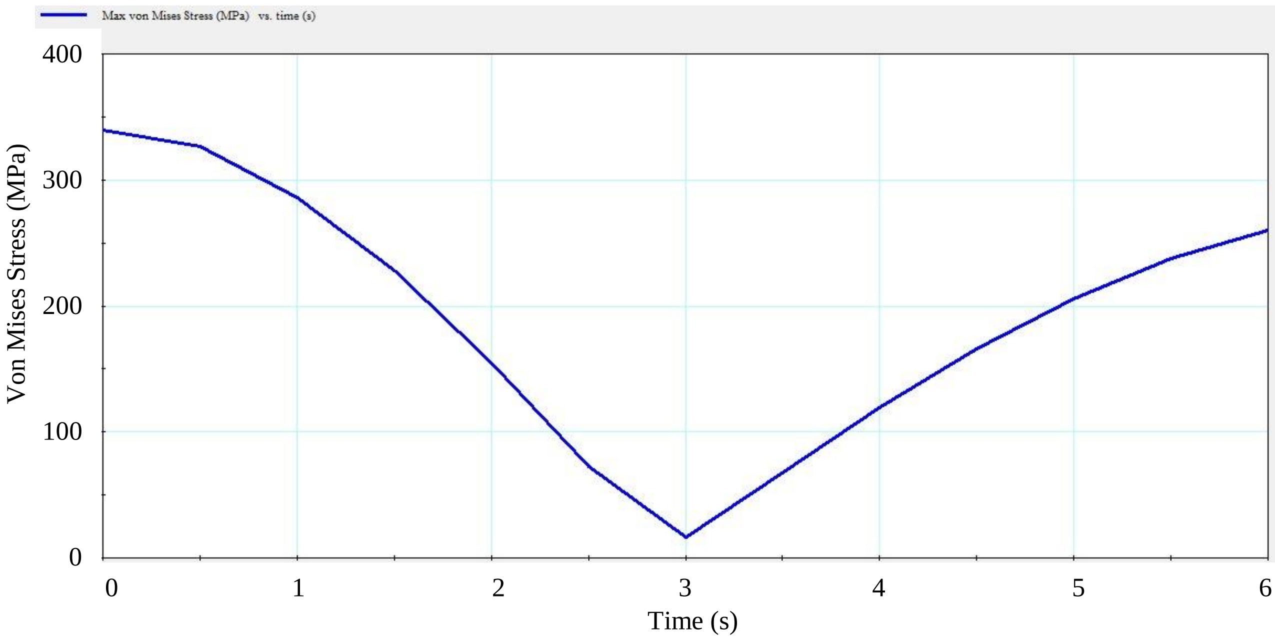


Figure 5.29: Stress versus time plot of manipulator under third configuration

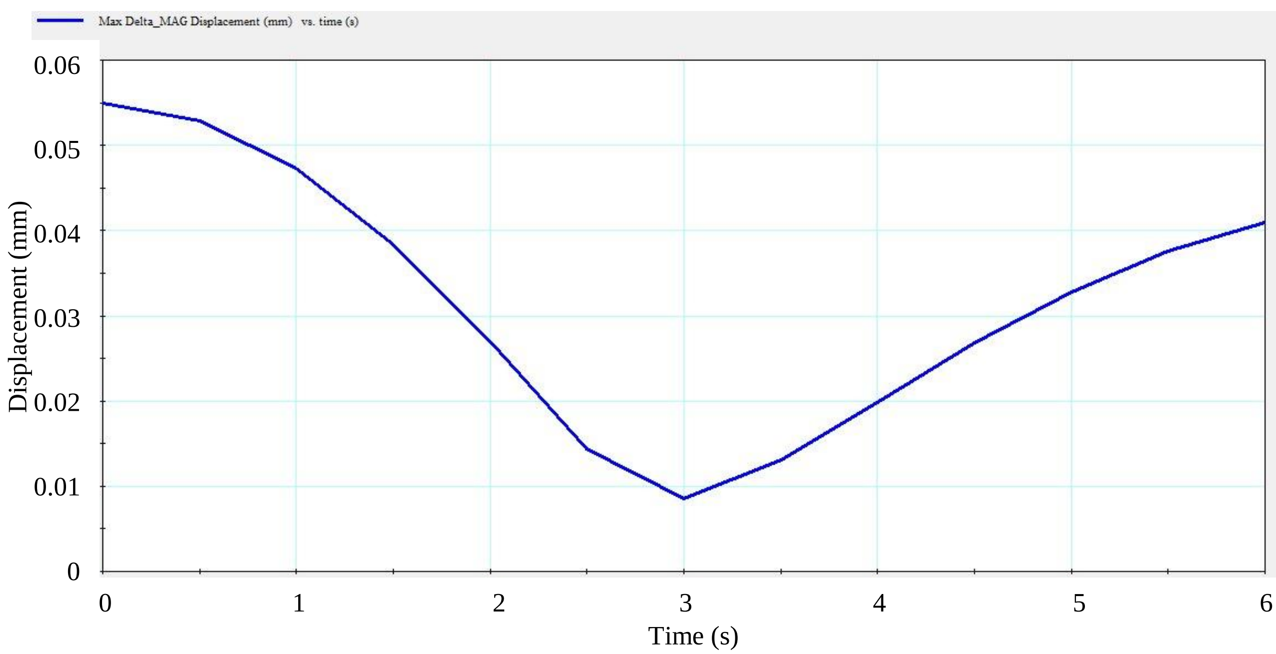


Figure 5.30: Displacement versus time plot of manipulator under third configuration

5.2.5 Comparison of Results

In this section, the results of each configuration in normal case and modified case are compared. The Table 5.1 and 5.2 lists all maximum stress and displacement that occur in each configuration. The results show that stress and displacement is reduced by using hollow links in modified manipulators. When percentage of mass reduced is 10.4 % by using modified approach the percentage of reduction in stress and displacement in worst case of 2-link manipulator are 17.19 % and 30.55 % respectively. While in case of 4-link manipulator the percentage of reduction in stress and displacement in worst case are 50.16 % and 25.9 % respectively.

Table 5.1 Maximum stress and displacement of 2-link modular manipulator

	2-link modular manipulator		Modified 2-link modular manipulator	
Configuration	Stress (MPa)	Displacement (mm)	Stress (MPa)	Displacement (mm)
1	640.2	0.054	530.7	0.037
2	206.6	0.037	163.1	0.026
3	253.3	0.016	148.9	0.014

Table 5.2 Maximum stress and displacement of 4-link modular manipulator

	4-link modular manipulator		Modified 4-link modular manipulator	
Configuration	Stress (MPa)	Displacement (mm)	Stress (MPa)	Displacement (mm)
1	1615	0.154	805	0.114
2	219	0.057	117.5	0.053
3	698	0.104	342	0.055

5.3 Analysis of Helical Gear Approach

In this section, 2-link and 4-link modular manipulators are formulated using helical gear approach. During the relative movement of the structure the manipulators are analyzed. The variation of link twist angle is done to check the strength of the structure. The manipulator is under motion for 6 seconds and plot of stress and displacement are plotted.

5.3.1 2-Link Modular Manipulator

2-link modular manipulator is assembled by using two joints and two links. The link lengths of link 1 and link 2 are 400mm and 350mm respectively. The manipulator is tested in three different configurations. In every configuration, a load of 50 N in –y direction at last link in addition to gravity is applied. The motors in the joints are made to rotate by giving an angular velocity which varies depending on configuration. The graphs of stress and displacement of the manipulators versus time are plotted for each configuration.

(a) Worst Configuration

In the worst configuration, the joint angles of joint 1 and joint 2 are 0^o and 90^o respectively. The link twist angle of both the joints is 0^o. The angular velocity of joint1 and joint 2 is 30 deg/s. The direction of the angular velocity of the joint 2 is reversed after 3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.32 and Figure 5.33 respectively. The configuration is shown in Figure 5.31.

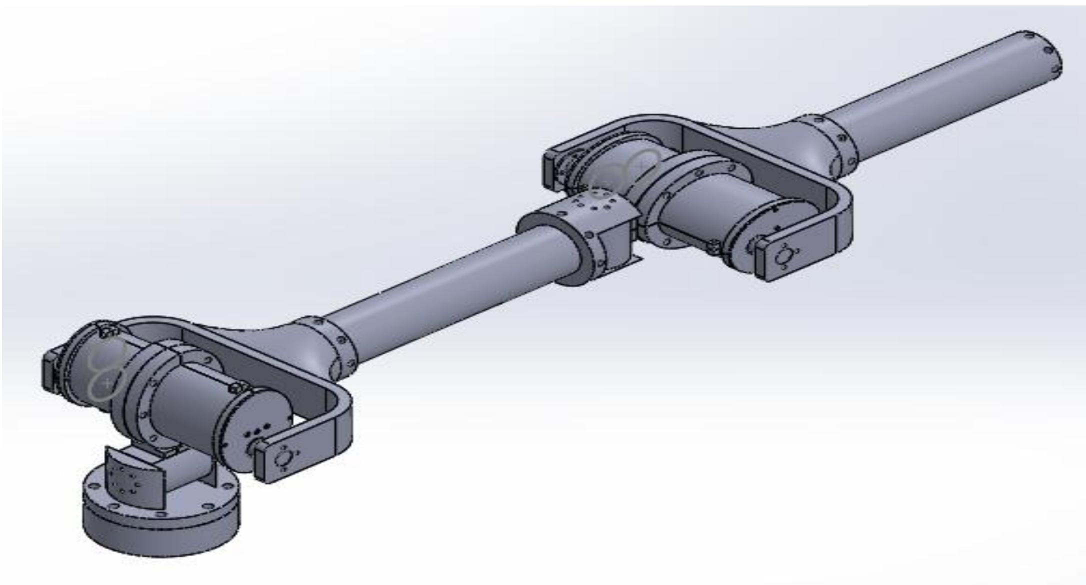


Figure 5.31: Worst configuration of 2-link modular manipulator

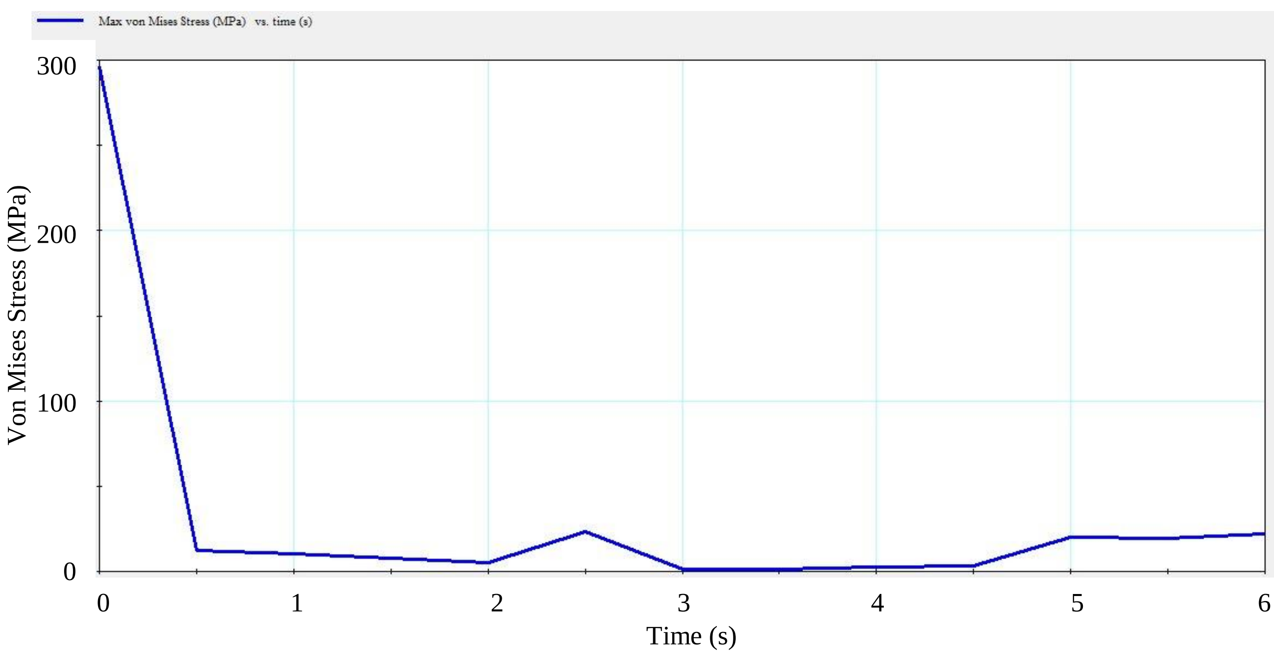


Figure 5.32: Stress versus time plot of manipulator under worst configuration

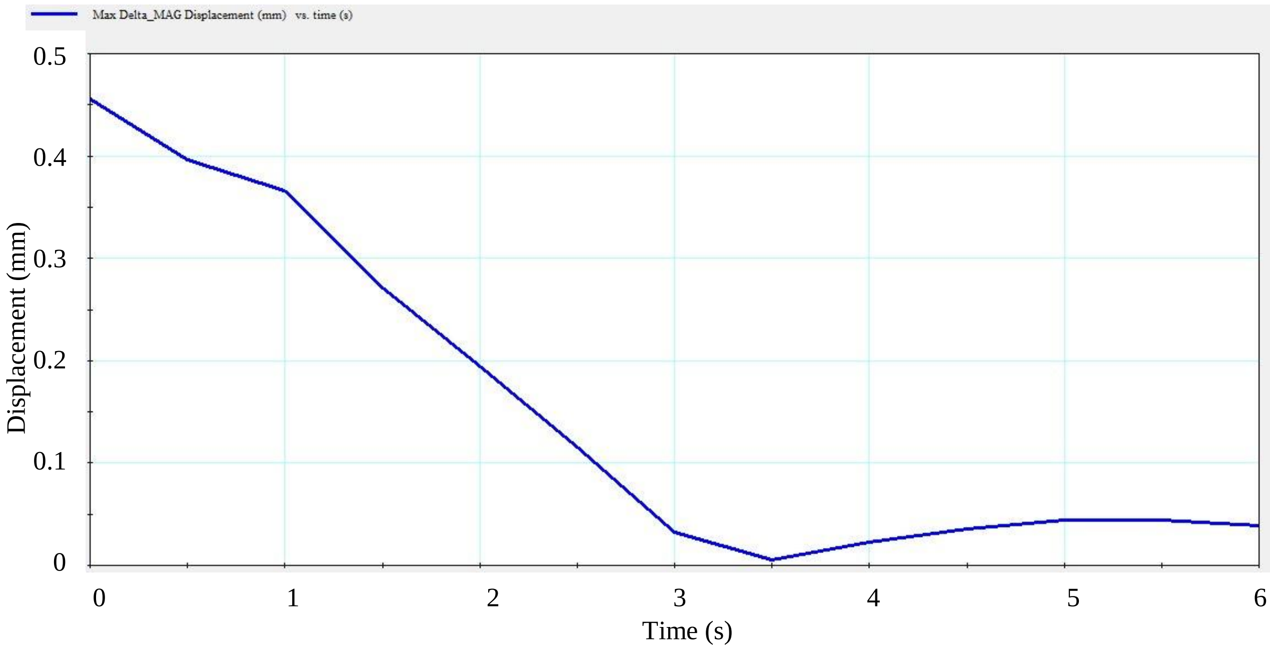


Figure 5.33: Displacement versus time plot of manipulator under worst configuration

(b) Second Configuration

In the second configuration, the joint angles of joint 1 and joint 2 is 45^o. The link twist angle of both the joints is 0^o. The angular velocity of joint1 and joint 2 is 15 deg/s. The direction of the angular velocity of the joint 2 is reversed after 3 seconds. The configuration is shown in Figure 5.34. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.35 and Figure 5.36 respectively.

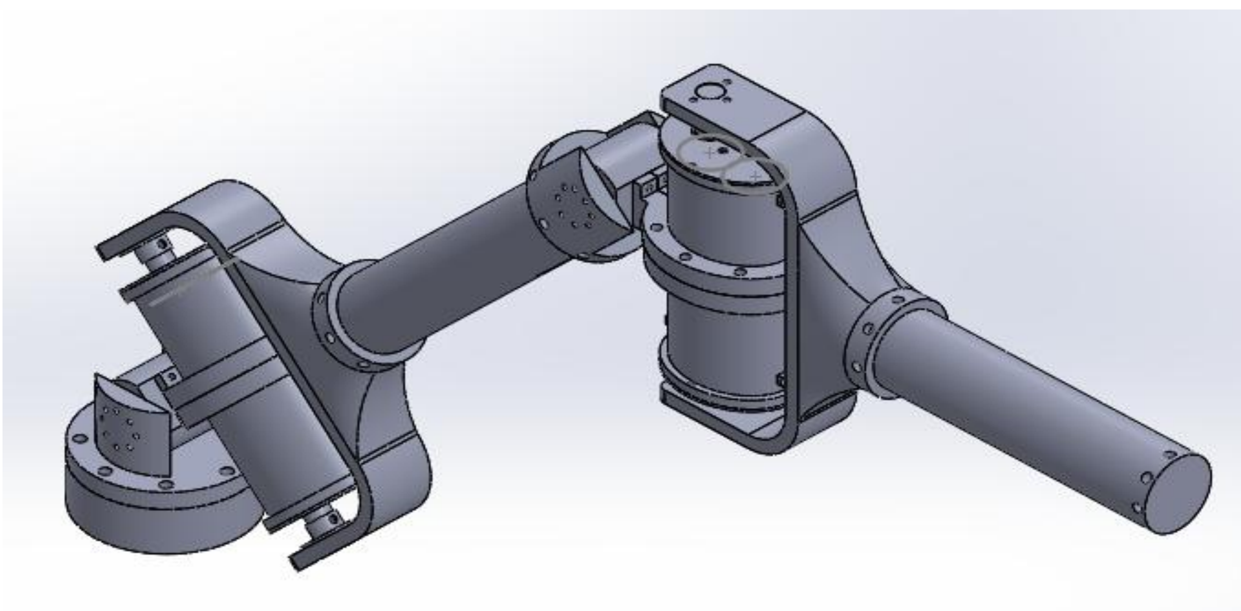


Figure 5.34: Second configuration of 2-link modular manipulator

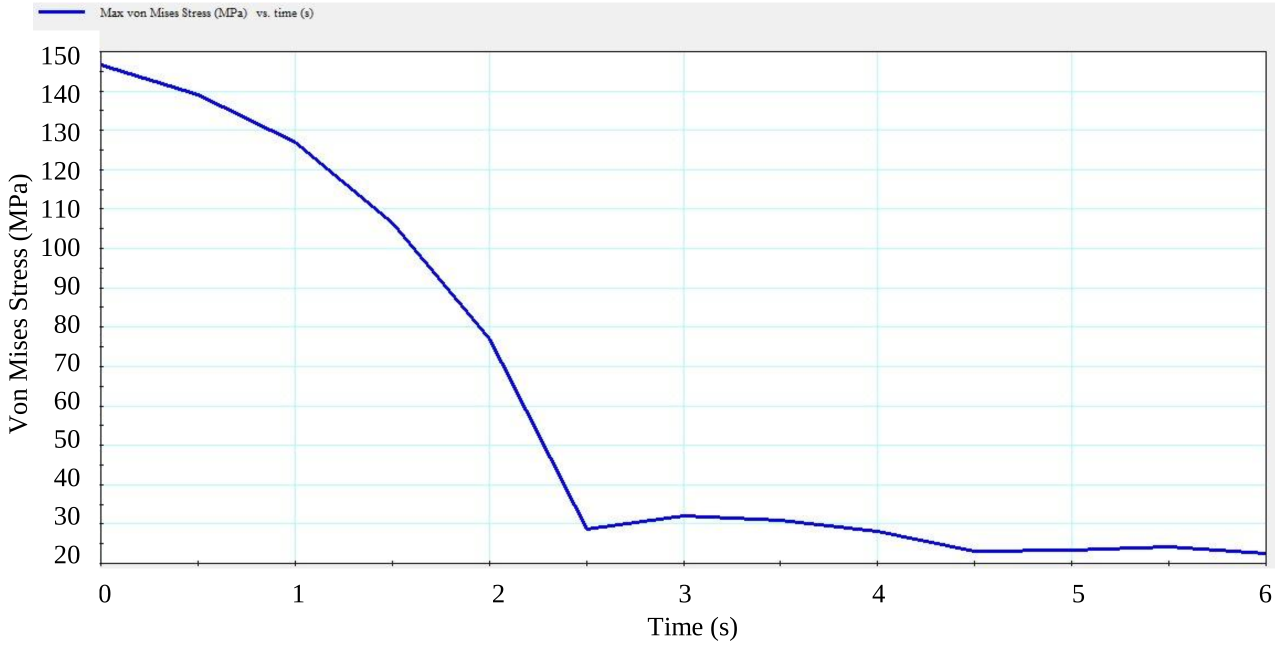


Figure 5.35: Stress versus time plot of manipulator under second configuration

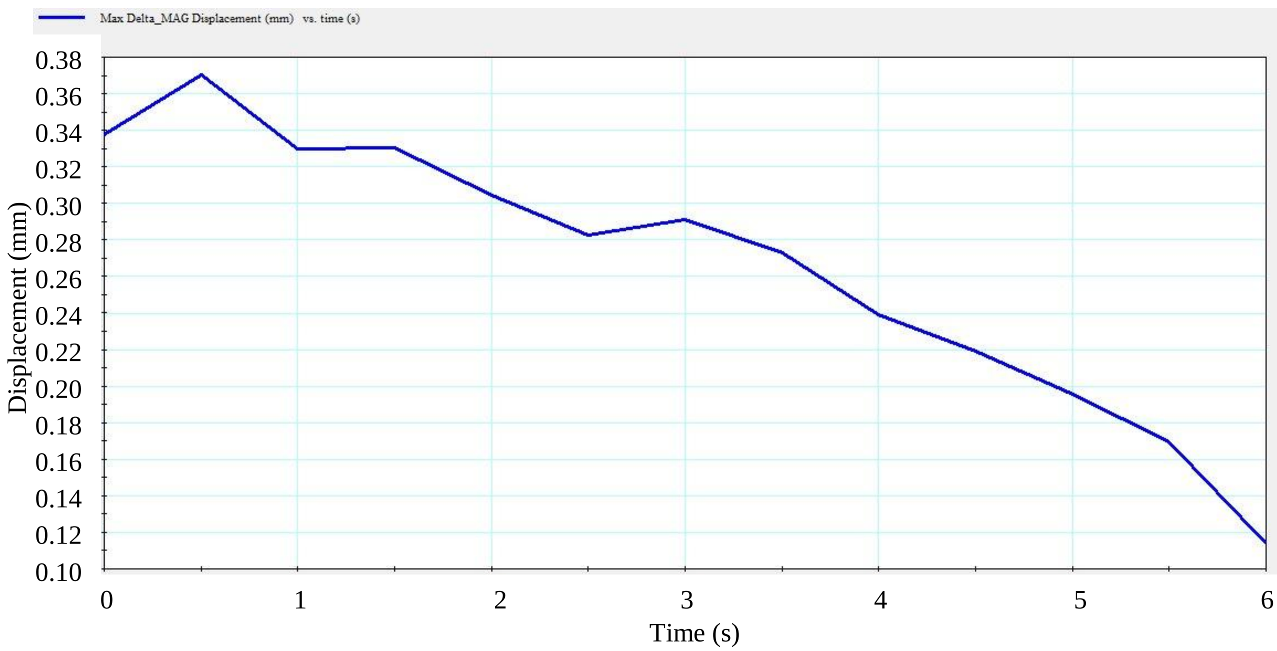


Figure 5.36: Displacement versus time plot of manipulator under second configuration

(c) Third Configuration

In the third configuration as shown in Figure 5.37, the joint angles of joint 1 and joint 2 is 90^o. The link twist angle of both the joints is 45^o. The angular velocity of joint1 and joint 2 are 15 deg/s and 30 deg/s respectively. The direction of the angular velocity of the joint is reversed after

3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.38 and Figure 5.39 respectively.

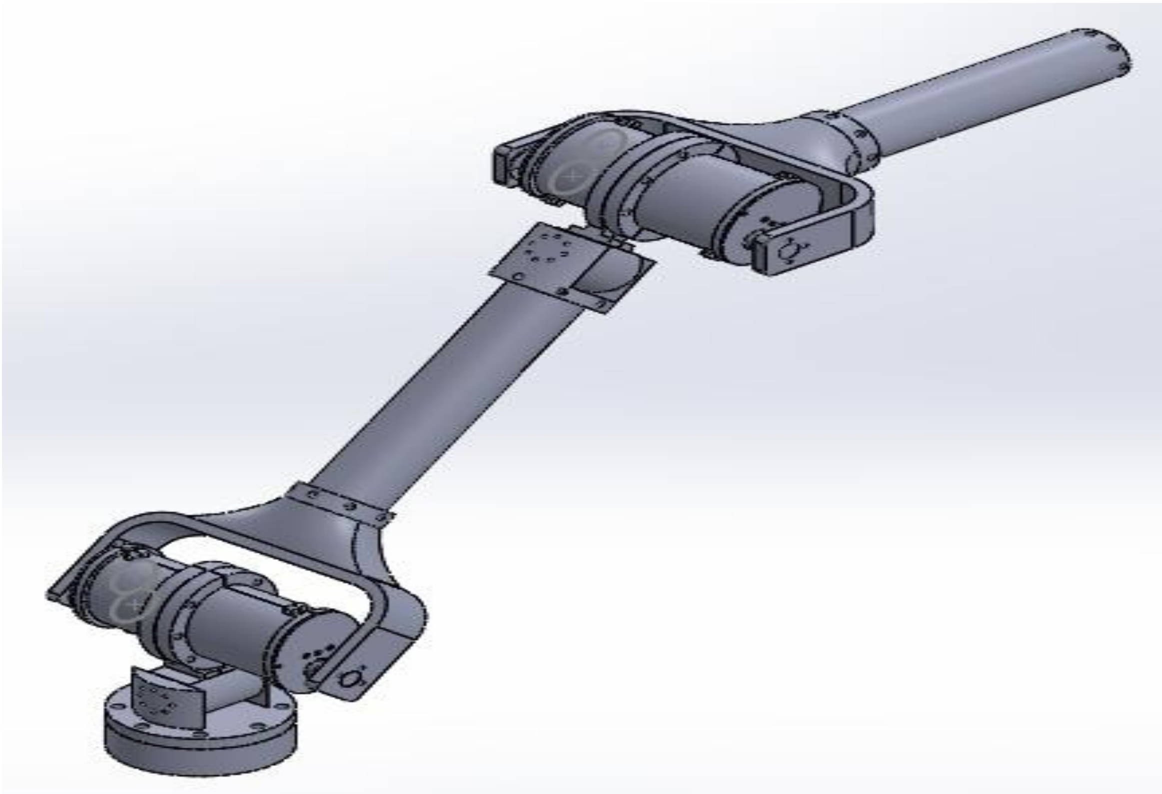


Figure 5.37: Third configuration of 2-link modular manipulator

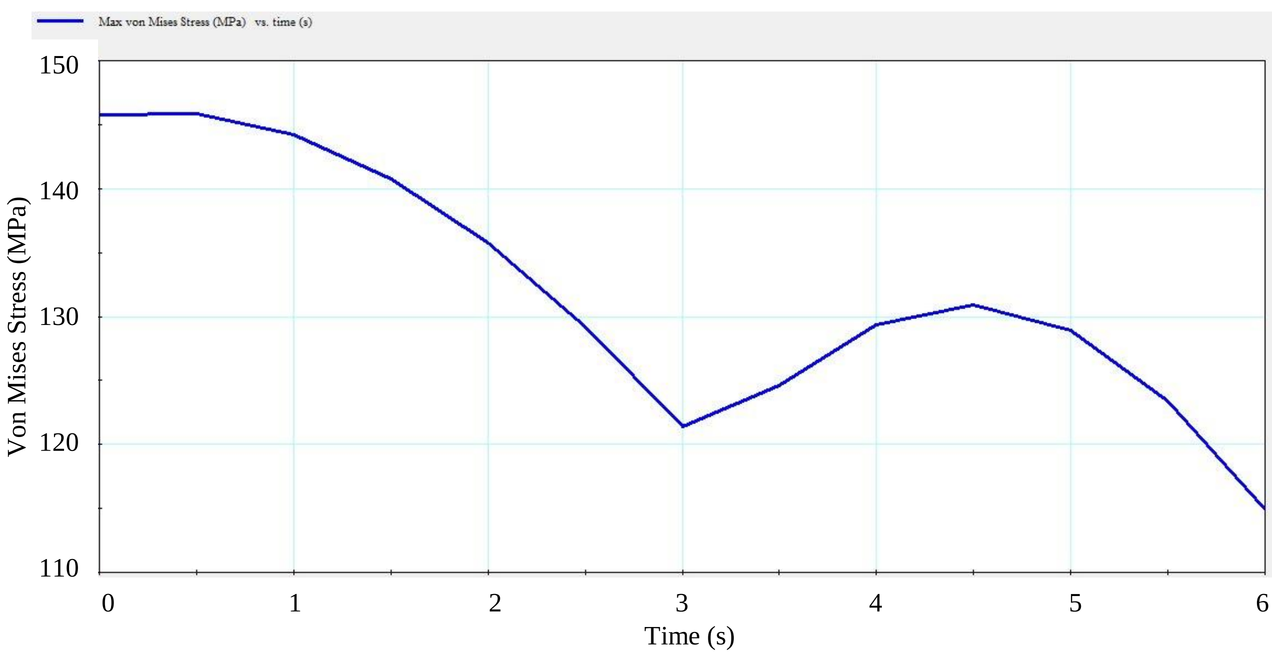


Figure 5.38: Stress versus time plot of manipulator under third configuration

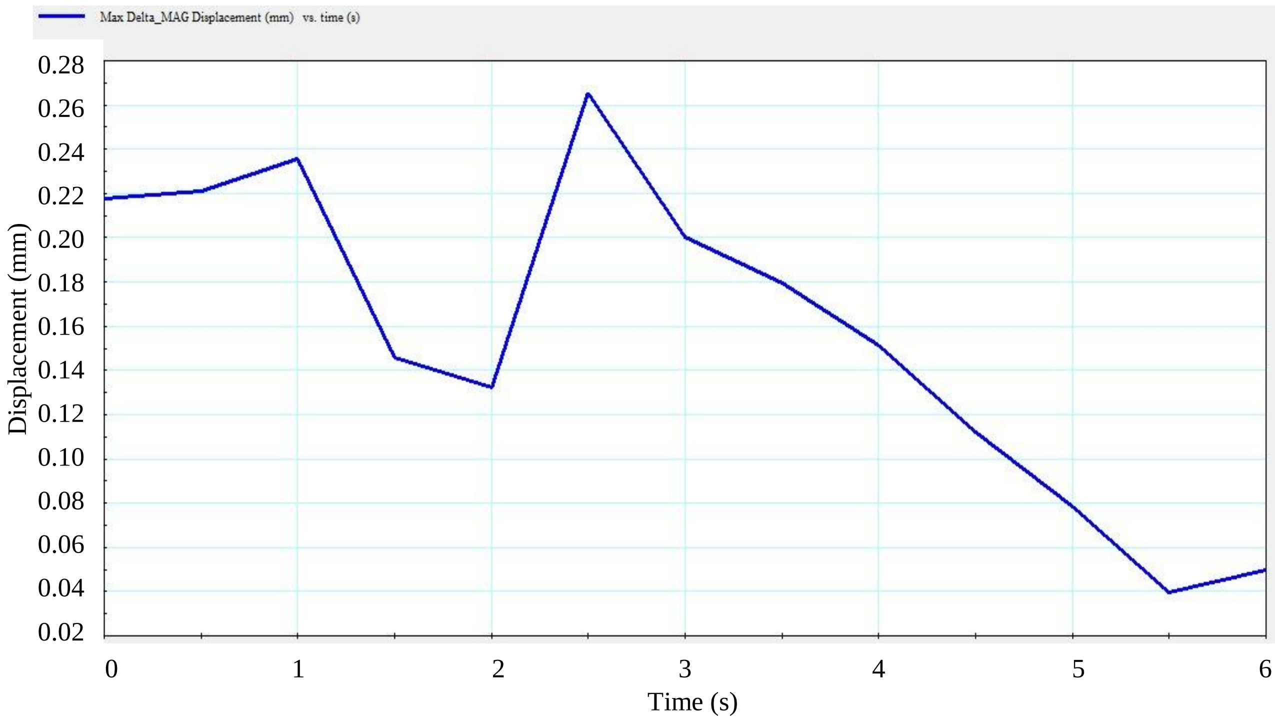


Figure 5.39: Displacement versus time plot of manipulator under third configuration

5.3.2 4-Link Modular Manipulator

4-link modular manipulator is assembled by using four joints and four links. The link lengths of link 1, 2, 3 and 4 are 400 mm, 350 mm, 300 mm and 250 mm respectively. The manipulator is tested in three different configurations. In every configuration, a load of 50 N in –y direction at last link in addition to gravity is applied. The motors in the joints are made to rotate by giving an angular velocity which varies depending on configuration. The graphs of stress and displacement of the manipulators versus time are plotted for each configuration.

(a) Worst Configuration

In the worst configuration, the joint angles of joint 1, 2, 3 and 4 are 0^o, 90^o, 90^o and 90^o respectively. The link twist angle of all the joints is 0^o. The angular velocity of joint1, 2, 3 and 4 are 30 deg/s, 15 deg/s, 15 deg/s and 15 deg/s respectively. The direction of the angular velocity of the joint 2, 3 and 4 is reversed after 3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.41 and Figure 5.42 respectively. The configuration is shown in Figure 5.40.

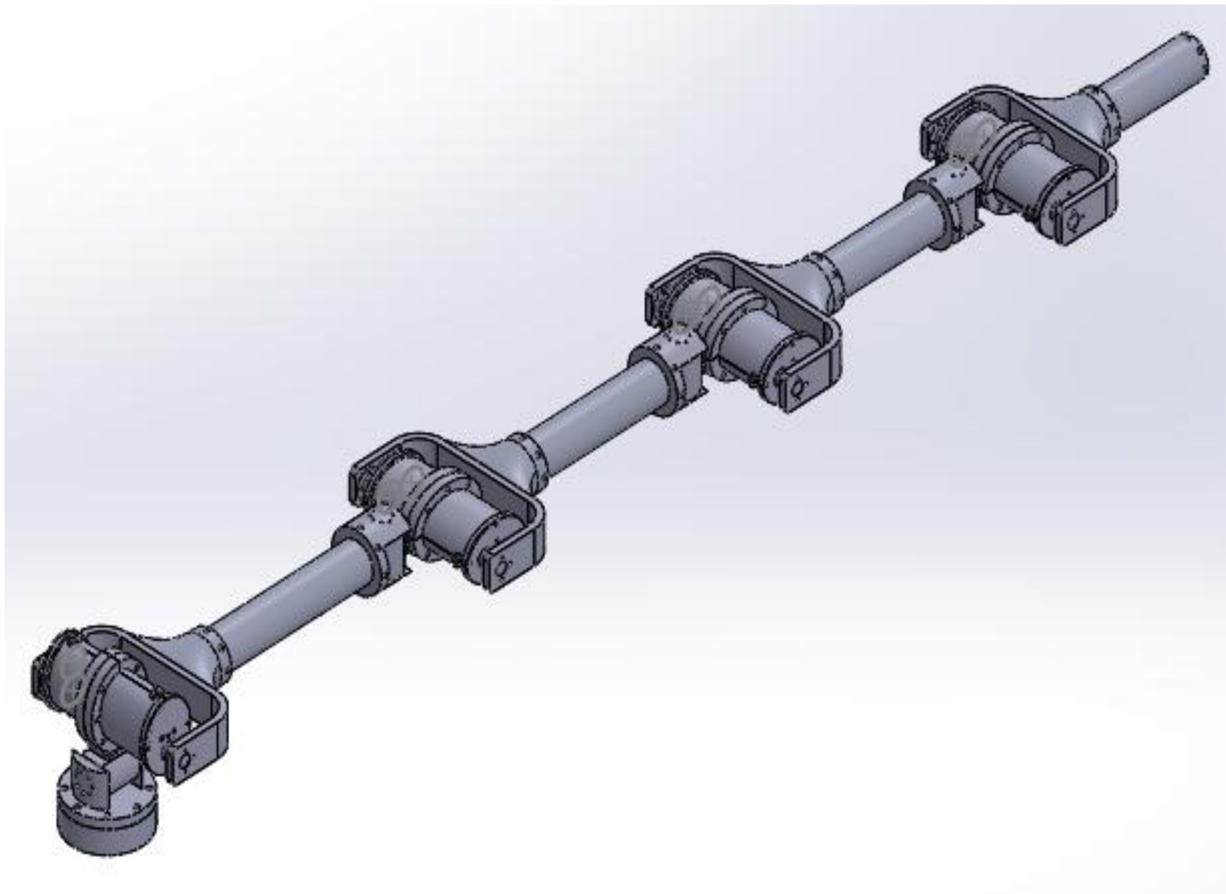


Figure 5.40: Worst configuration of 4-link modular manipulator

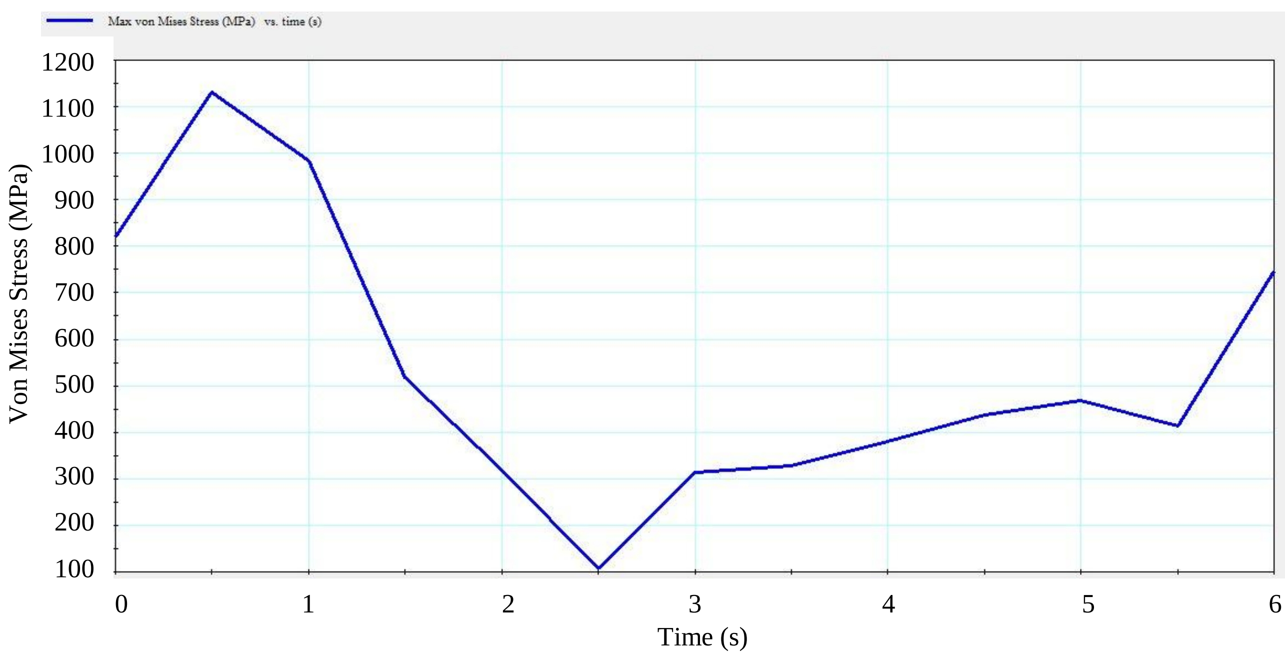


Figure 5.41: Stress versus time plot of manipulator under worst configuration

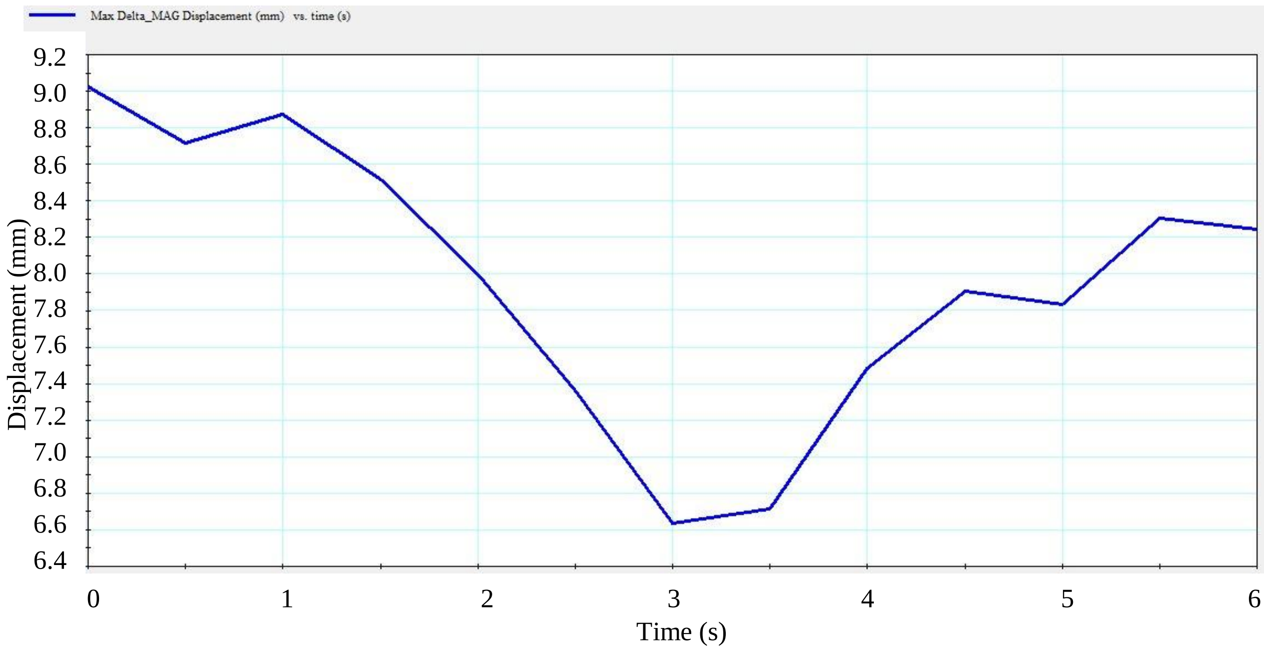


Figure 5.42: Displacement versus time plot of manipulator under worst configuration

(b) Second Configuration

In the second configuration, the joint angle of all joints is 90^o. The link twist angle of the joint 1, 2, 3 and 4 are 45^o, 45^o, 0^o and 45^o respectively. The angular velocity of joint1, 2, 3 and 4 are 7.5 deg/s, 15 deg/s, 15 deg/s and 15 deg/s respectively. The direction of the angular velocity of the joint 2, 3 and 4 is reversed after 3 seconds. The configuration is shown in Figure 5.43. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.44 and Figure 5.45 respectively.

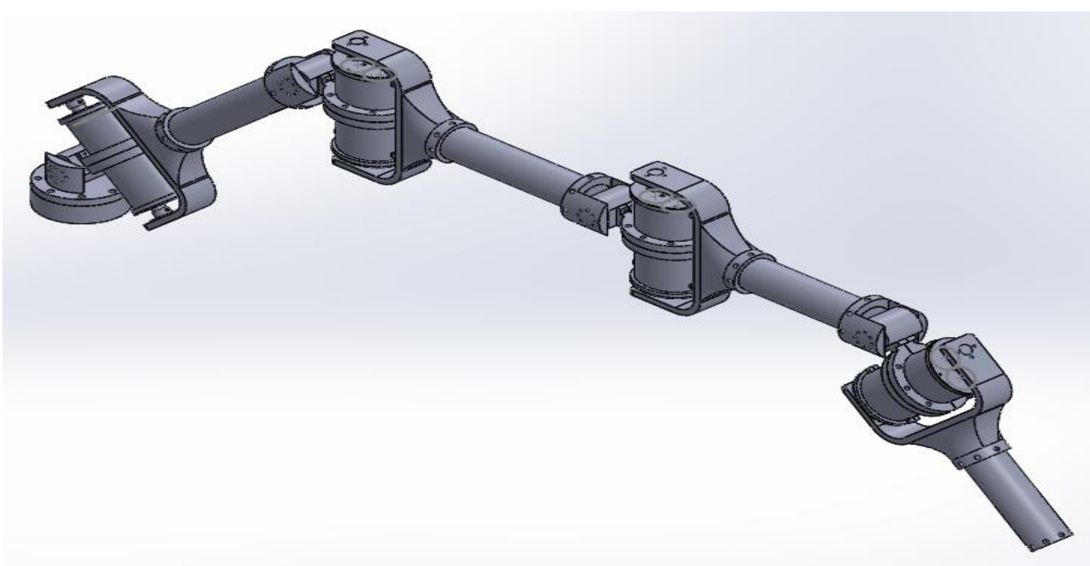


Figure 5.43: Second configuration of 4-link modular manipulator

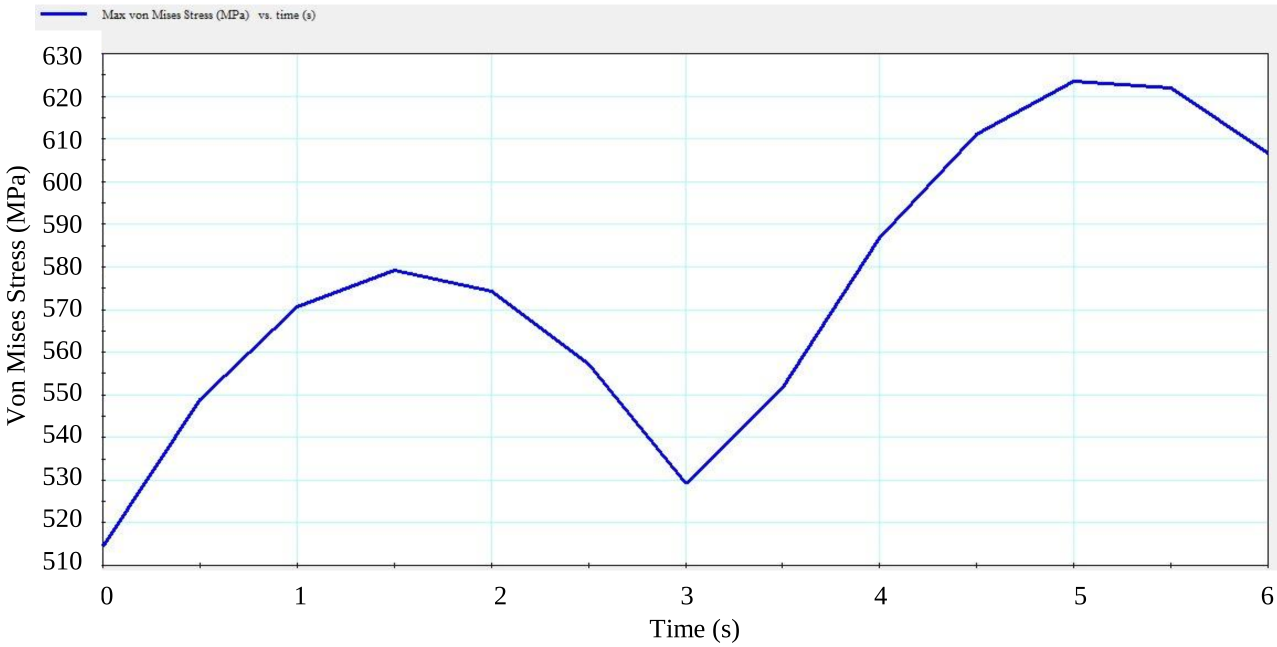


Figure 5.44: Stress versus time plot of manipulator under second configuration

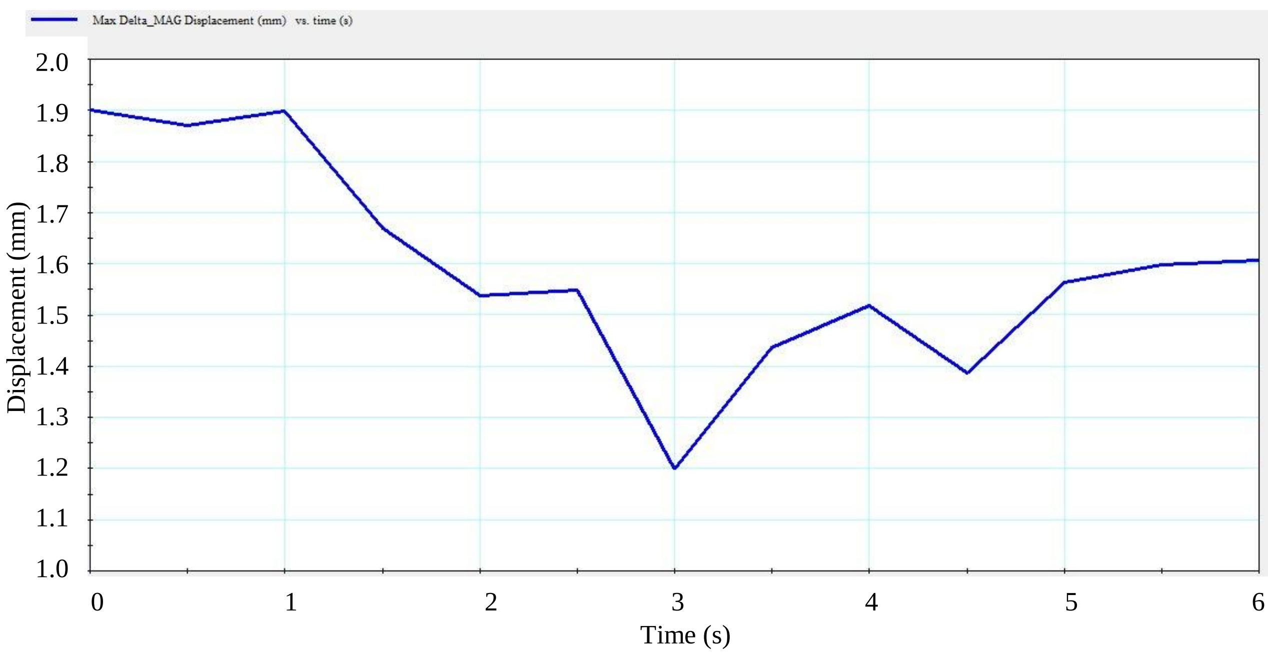


Figure 5.45: Displacement versus time plot of manipulator under second configuration

(c) Third Configuration

In the third configuration as shown in Figure 5.46, the joint angles of joint 1, 2, 3 and 4 are 45^o, 45^o, 90^o and 45^o respectively. The link twist angle of all the joints is 0^o. The angular velocity of joint1, 2, 3 and 4 are 15 deg/s, 15 deg/s, 15 deg/s and 15 deg/s respectively. The direction of the angular velocity of the joint 3 is reversed after 3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.47 and Figure 5.48 respectively.

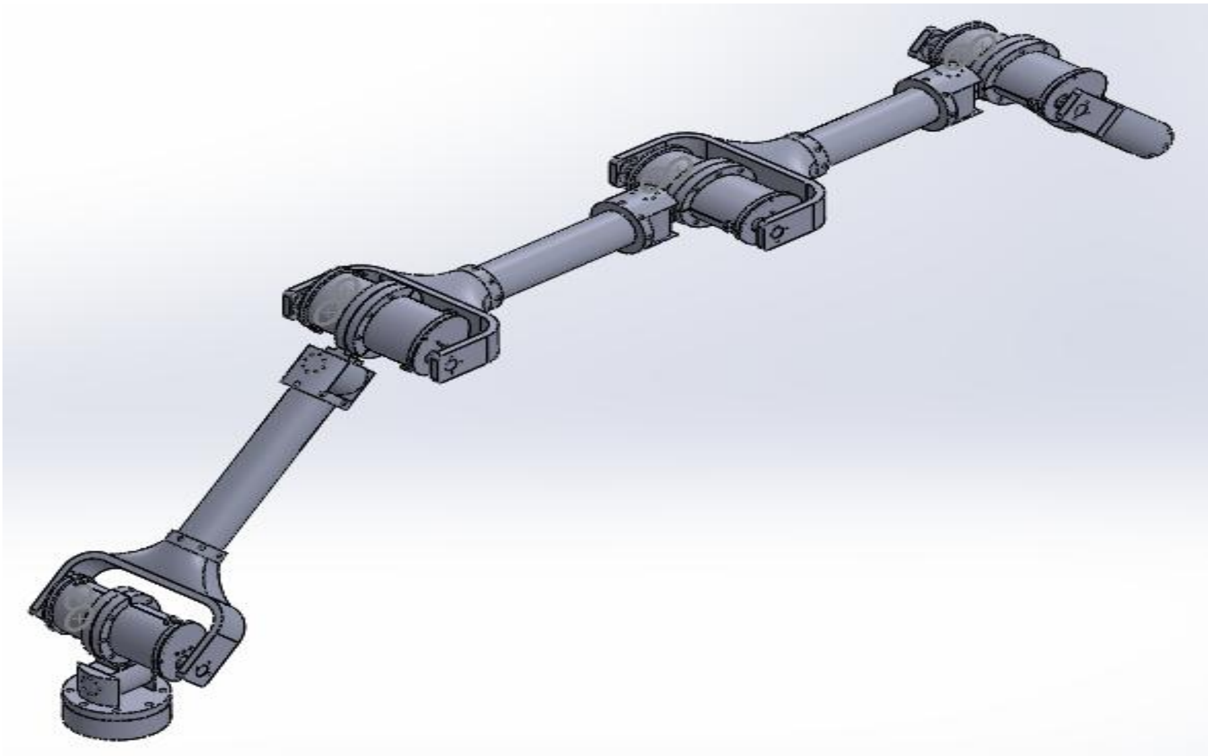


Figure 5.46: Third configuration of 4-link modular manipulator

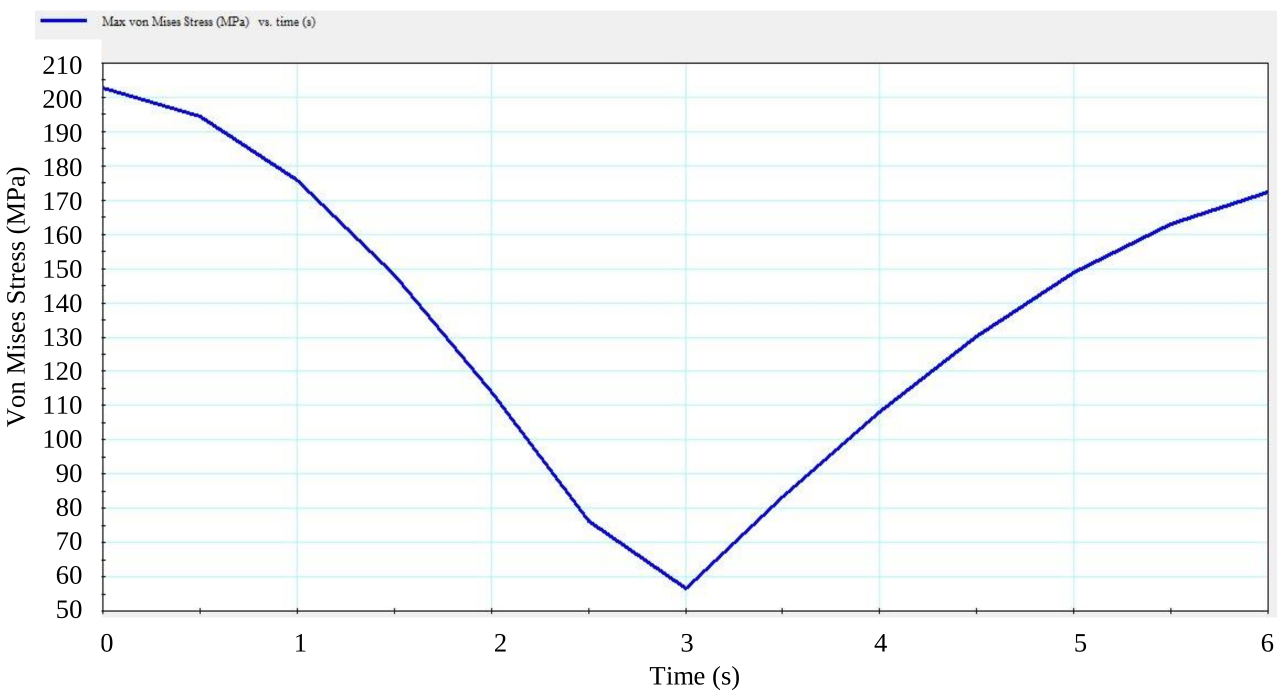


Figure 5.47: Stress versus time plot of manipulator under third configuration

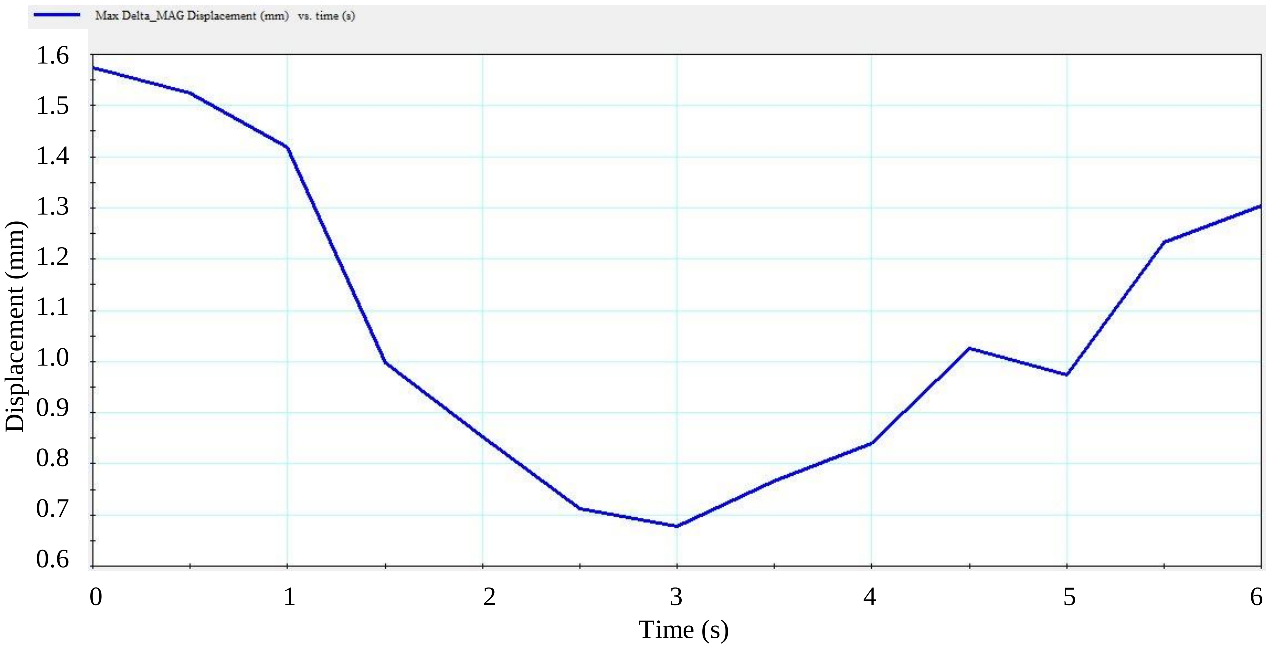


Figure 5.48: Displacement versus time plot of manipulator under third configuration

5.3.3 Modified 2-Link Modular Manipulator

The links of the manipulator are modified. The links are made hollow with a thickness of 10 mm as shown in Figure 5.49. These modified links are now used in assembly and a modified 2-link modular manipulator is made. 2-link modular manipulator is assembled by using two joints and two links. The link lengths of link 1 and link 2 are 400mm and 350mm respectively. The manipulator is tested in three different configurations. In every configuration, a load of 50 N in –y direction at last link in addition to gravity is applied. The motors in the joints are made to rotate by giving an angular velocity which varies depending on configuration. The graphs of stress and displacement of the manipulators versus time are plotted for each configuration.

(a) Worst Configuration

In the worst configuration, the joint angles of joint 1 and joint 2 are 0^o and 90^o respectively. The link twist angle of both the joints is 0^o. The angular velocity of joint1 and joint 2 is 30 deg/s. The direction of the angular velocity of the joint 2 is reversed after 3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.50 and Figure 5.51 respectively.

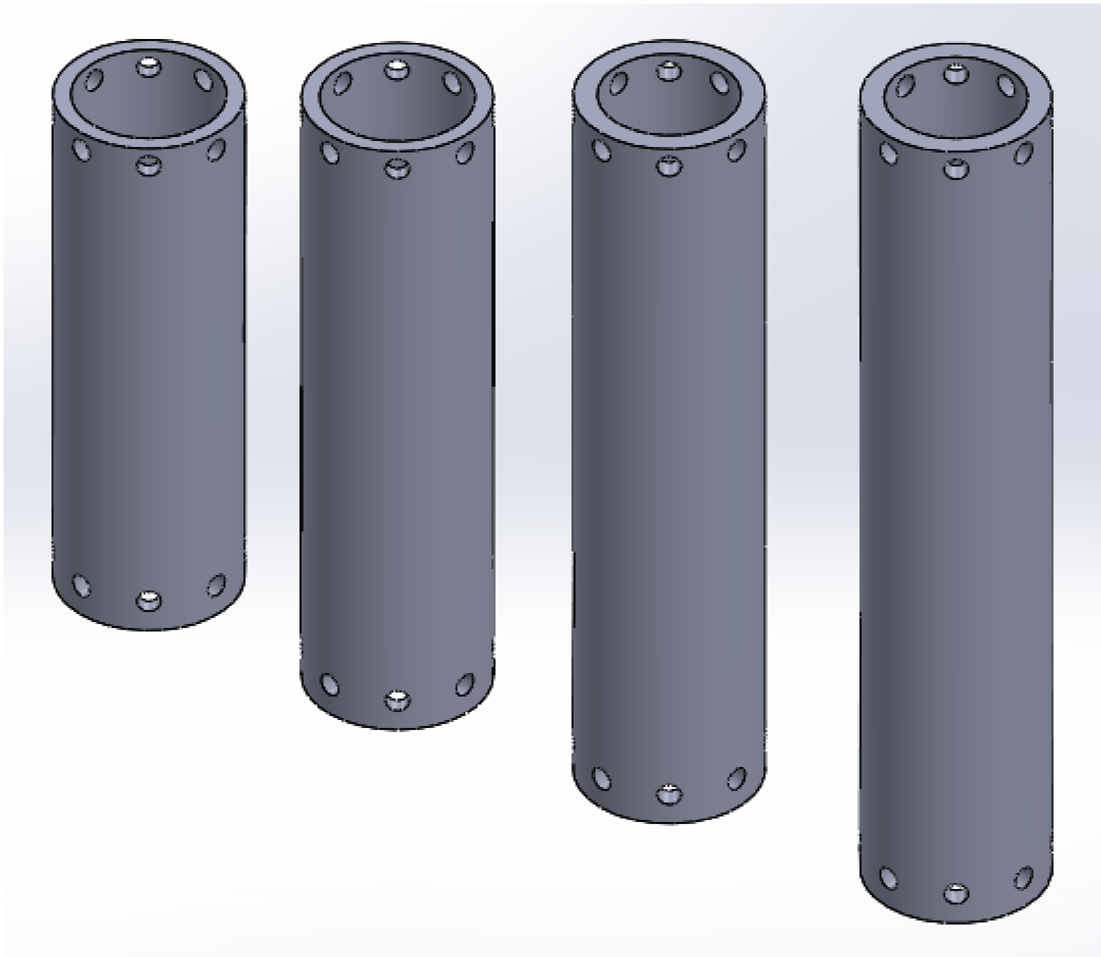


Figure 5.49: Modified links

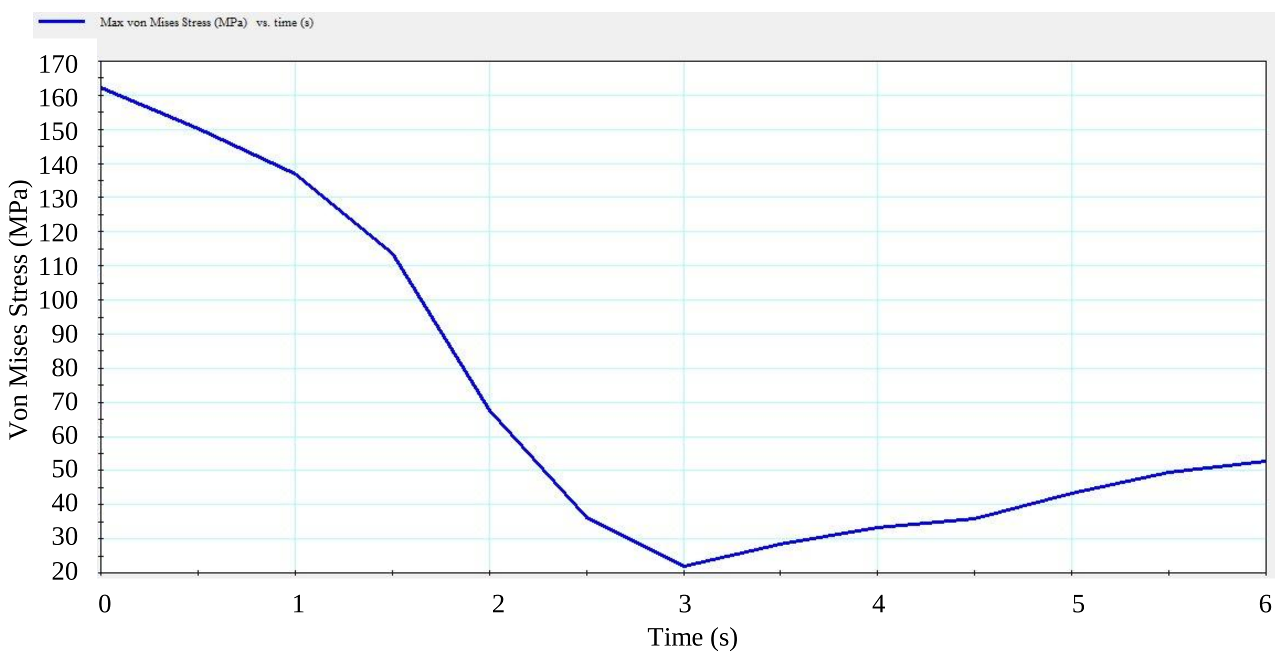


Figure 5.50: Stress versus time plot of manipulator under worst configuration

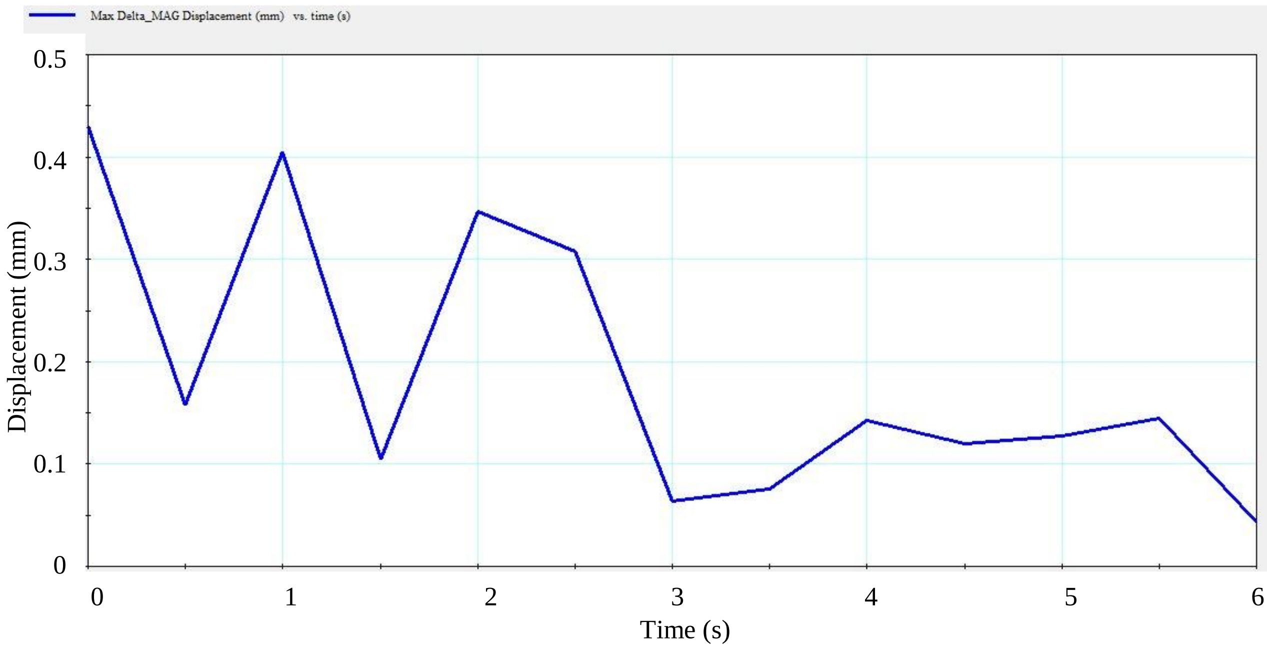


Figure 5.51: Displacement versus time plot of manipulator under worst configuration

(b) Second Configuration

In the second configuration, the joint angles of joint 1 and joint 2 is 45^o. The link twist angle of both the joints is 0^o. The angular velocity of joint1 and joint 2 is 15 deg/s. The direction of the angular velocity of the joint 2 is reversed after 3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.52 and Figure 5.53 respectively.

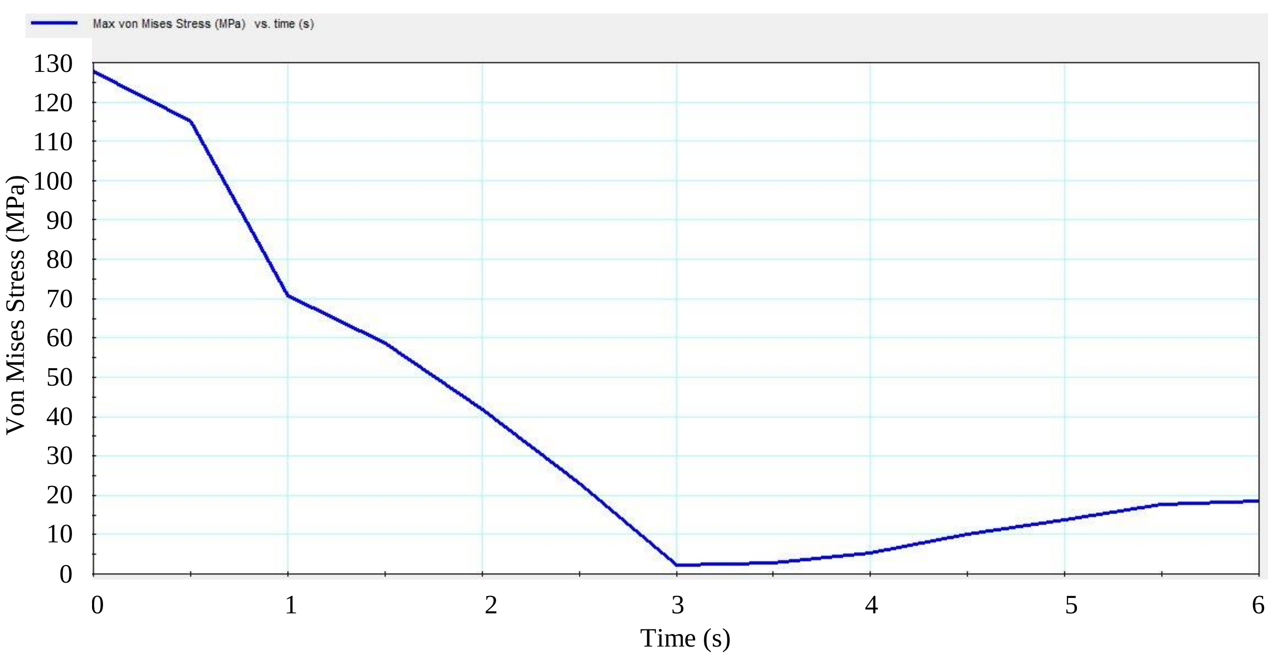


Figure 5.52: Stress versus time plot of manipulator under second configuration

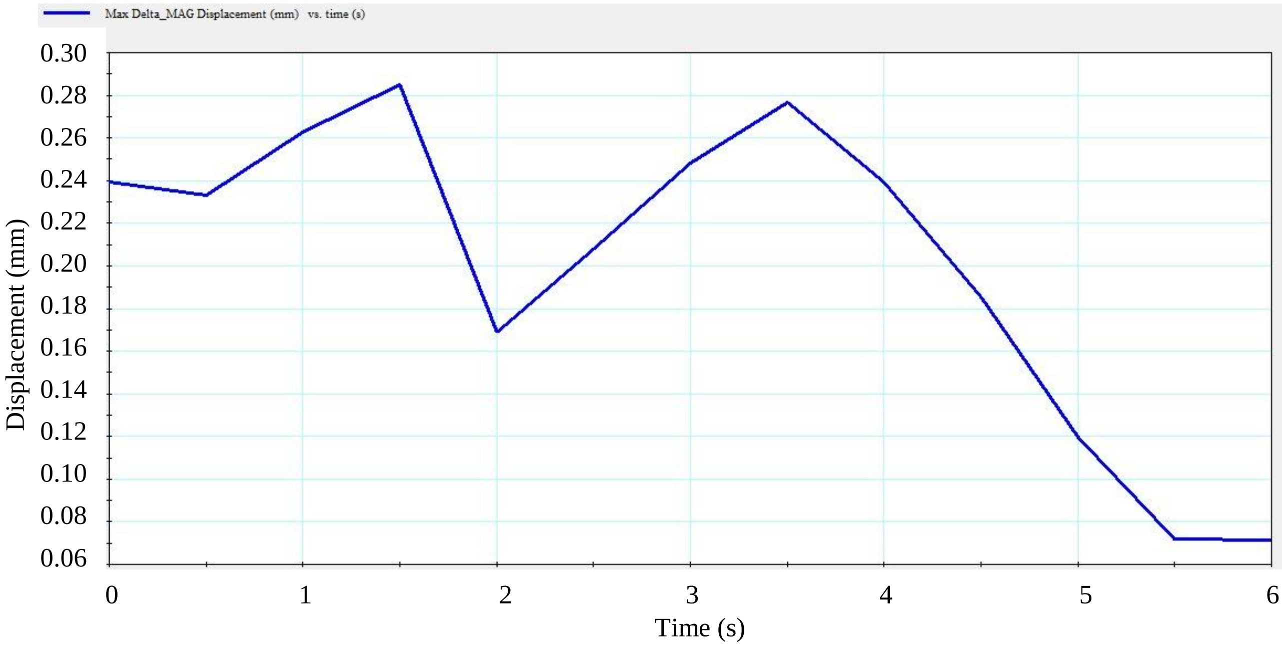


Figure 5.53: Displacement versus time plot of manipulator under second configuration

(c) Third Configuration

In the third configuration, the joint angles of joint 1 and joint 2 is 90^o. The link twist angle of both the joints is 45^o. The angular velocity of joint1 and joint 2 are 15 deg/s and 30 deg/s respectively. The direction of the angular velocity of the joint is reversed after 3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.54 and Figure 5.55 respectively.

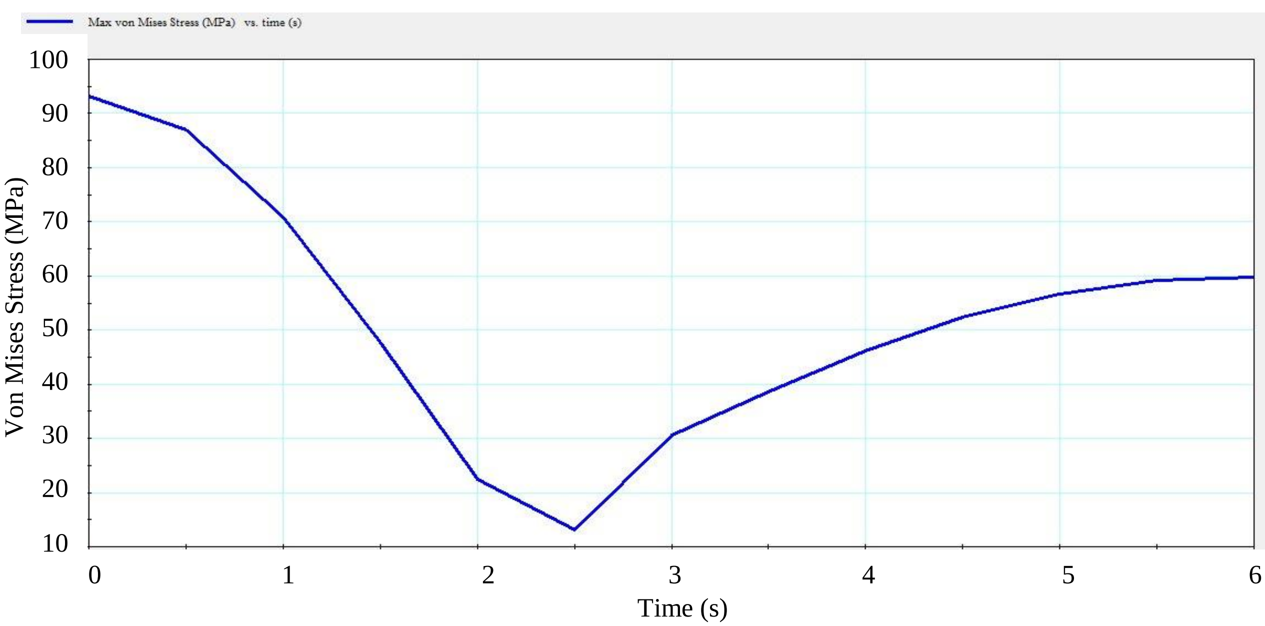


Figure 5.54: Stress versus time plot of manipulator under third configuration

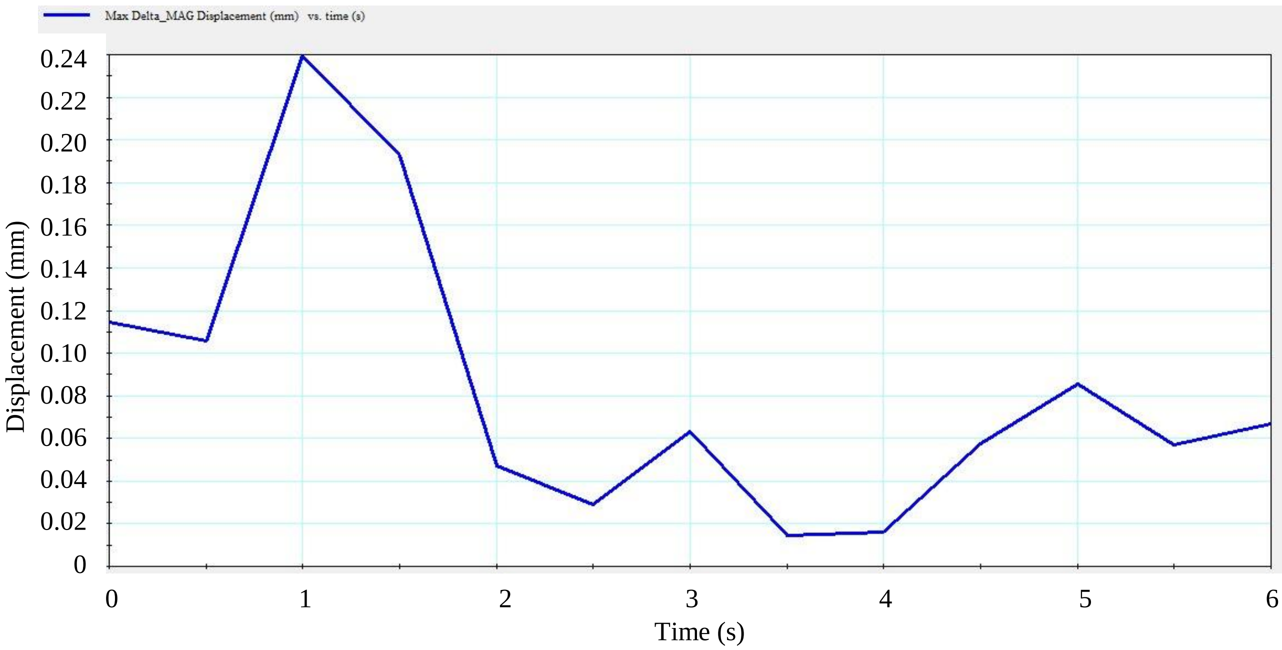


Figure 5.55: Displacement versus time plot of manipulator under third configuration

5.3.4 Modified 4-Link Modular Manipulator

The links of the manipulator are modified. The links are made hollow with a thickness of 10 mm as already discussed. These modified links are now used in assembly and a modified 4-link modular manipulator is made. 4-link modular manipulator is assembled by using four joints and four links. The link lengths of link 1, 2, 3 and 4 are 400 mm, 350 mm, 300 mm and 250 mm respectively. The manipulator is tested in three different configurations. In every configuration, a load of 50 N in –y direction at last link in addition to gravity is applied. The motors in the joints are made to rotate by giving an angular velocity which varies depending on configuration. The graphs of stress and displacement of the manipulators versus time are plotted for each configuration.

(a) Worst Configuration

In the worst configuration, the joint angles of joint 1, 2, 3 and 4 are 0^o, 90^o, 90^o and 90^o respectively. The link twist angle of all the joints is 0^o. The angular velocity of joint1, 2, 3 and 4 are 30 deg/s, 15 deg/s, 15 deg/s and 15 deg/s respectively. The direction of the angular velocity of the joint 2, 3 and 4 is reversed after 3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.56 and Figure 5.57 respectively.

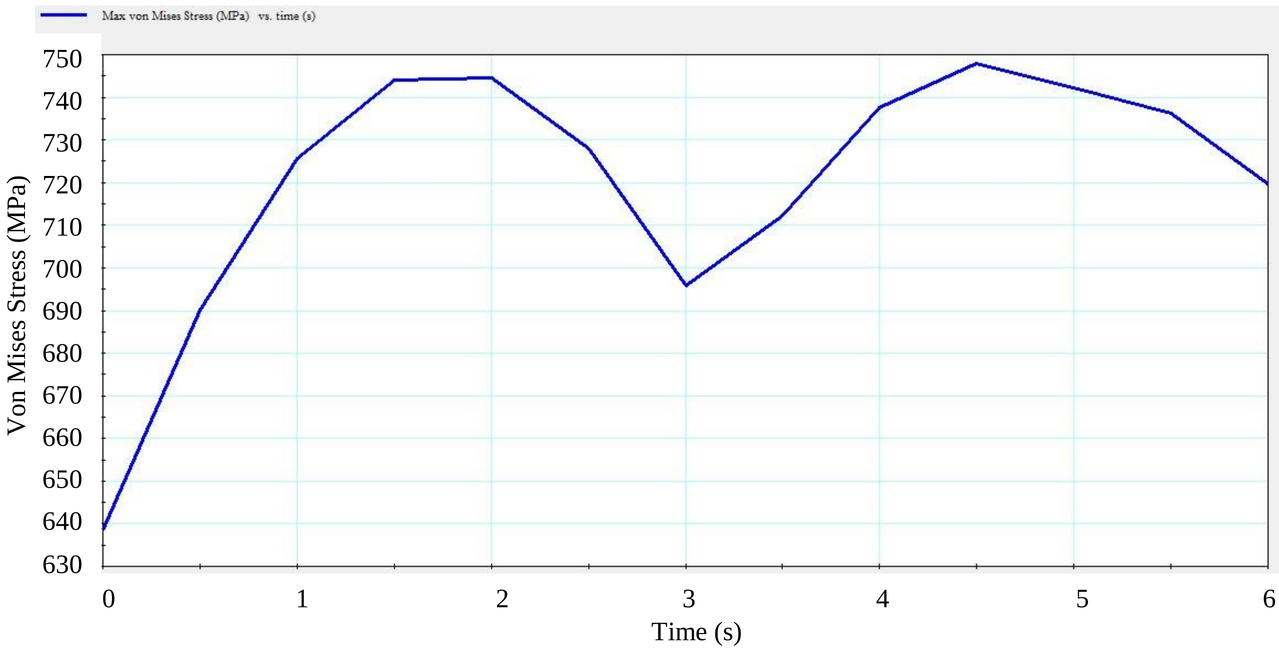


Figure 5.56: Stress versus time plot of manipulator under worst configuration

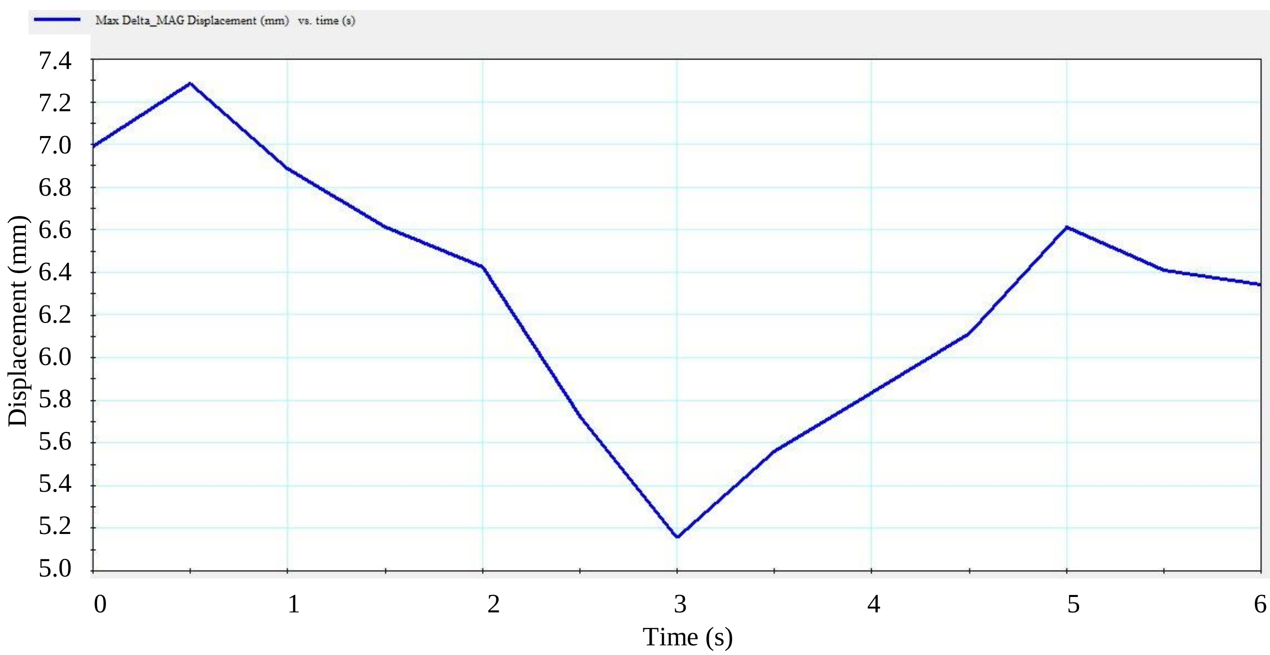


Figure 5.57: Displacement versus time plot of manipulator under worst configuration

(b) Second Configuration

In the second configuration, the joint angle of all joints is 90^o. The link twist angle of the joint 1, 2, 3 and 4 are 45^o, 45^o, 0^o and 45^o respectively. The angular velocity of joint1, 2, 3 and 4 are 7.5 deg/s, 15 deg/s, 15 deg/s and 15 deg/s respectively. The direction of the angular velocity of the joint 2, 3 and 4 is reversed after 3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.58 and Figure 5.59 respectively.

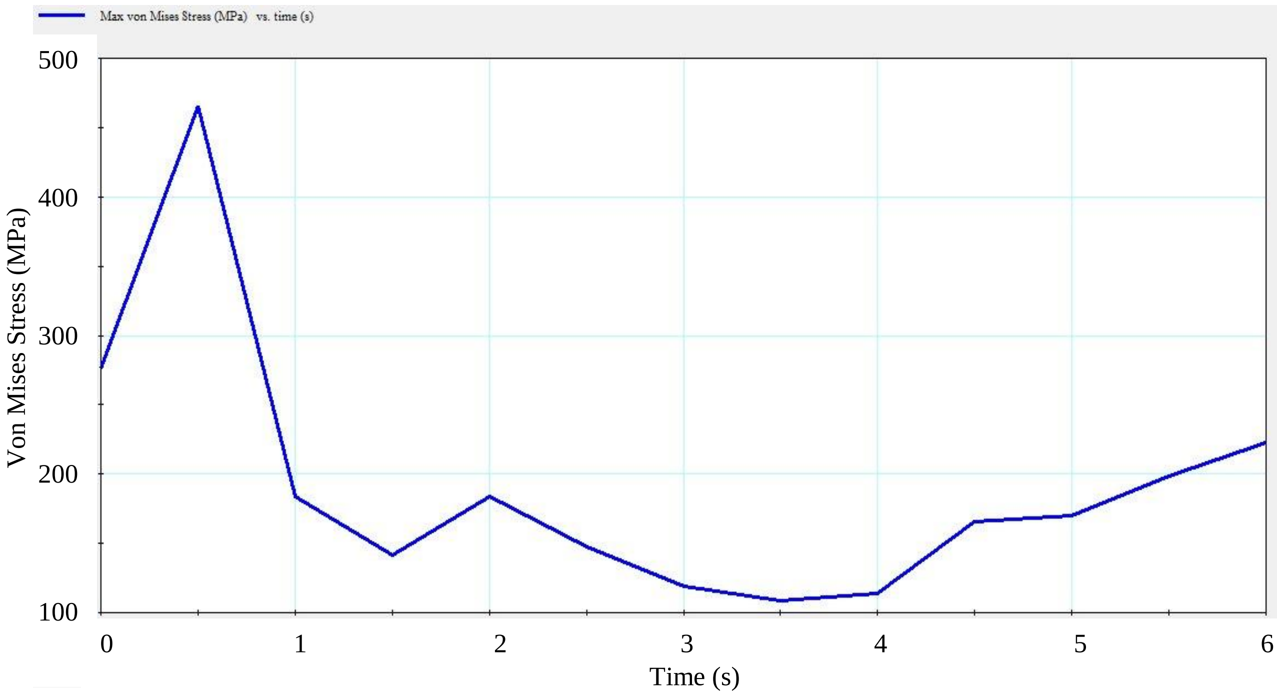


Figure 5.58: Stress versus time plot of manipulator under second configuration

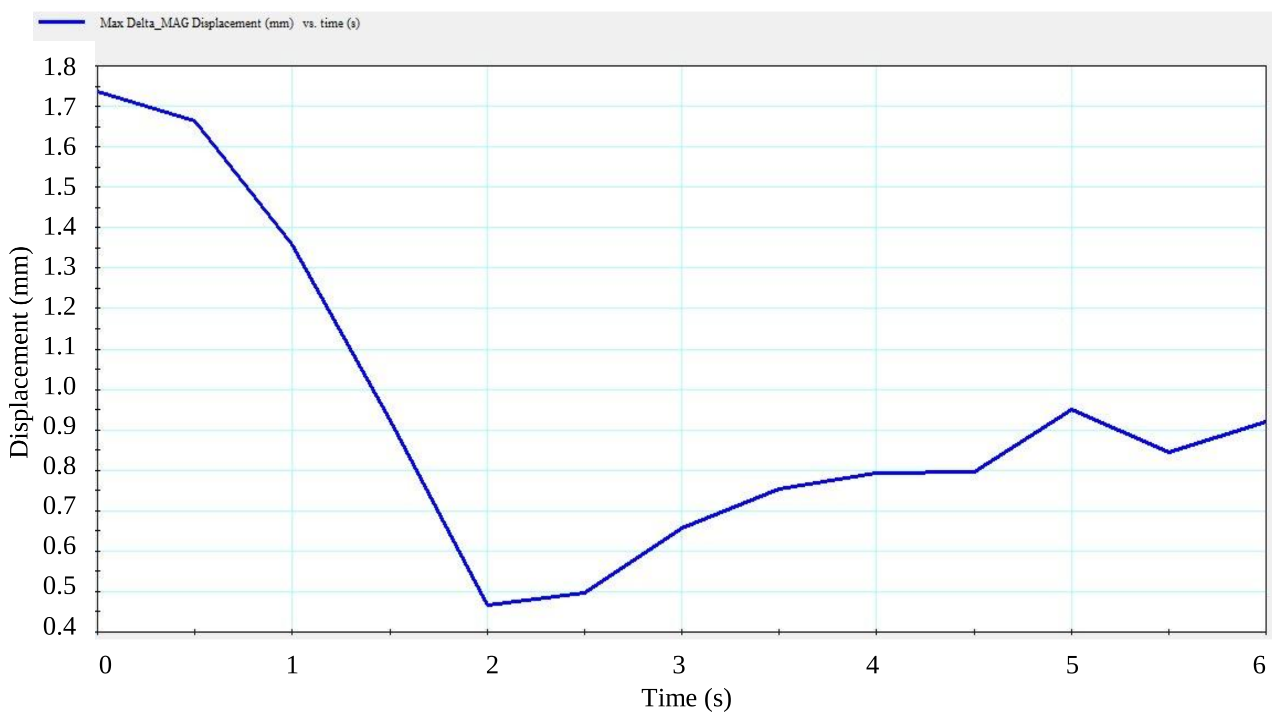


Figure 5.59: Displacement versus time plot of manipulator under second configuration

(c) Third Configuration

In the third configuration, the joint angles of joint 1, 2, 3 and 4 are 45^o, 45^o, 90^o and 45^o respectively. The link twist angle of all the joints is 0^o. The angular velocity of joint1, 2, 3 and 4 are 15 deg/s, 15 deg/s, 15 deg/s and 15 deg/s respectively. The direction of the angular velocity of the joint 3 is reversed after 3 seconds. The plot of stress versus time and displacement versus time are plotted as shown in Figure 5.60 and Figure 5.61 respectively.

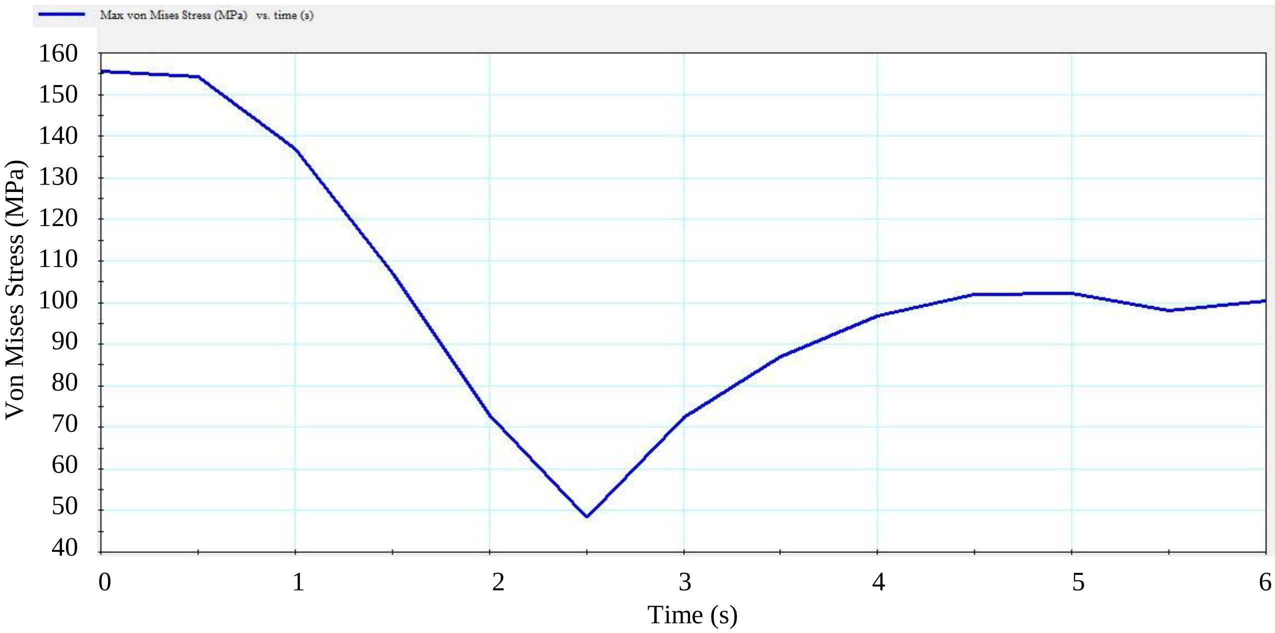


Figure 5.60: Stress versus time plot of manipulator under third configuration

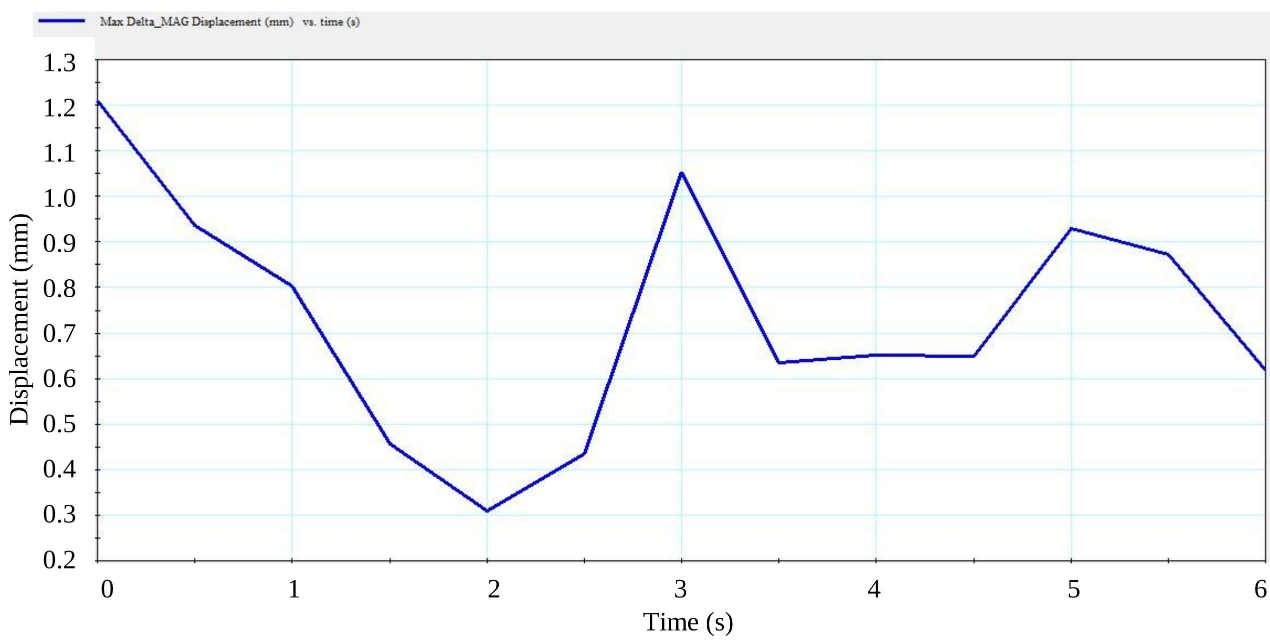


Figure 5.61: Displacement versus time plot of manipulator under third configuration

5.3.5 Comparison of Results

In this section, the results of each configuration in normal case and modified case are compared. The Table 5.3 and 5.4 lists all the maximum stress and displacement that occur in each configuration. The results show that the stress and displacement is reduced by using the hollow links in the modified manipulators. When the percentage of mass reduced is 18.03 % by using modified approach the percentage of reduction in stress and displacement in worst case of 2-link manipulator are 45.27 % and 7.77 % respectively. While in case of 4-link manipulator the percentage of reduction in stress and displacement in worst case are 34.42 % and 19.17 % respectively.

Table 5.3 Maximum stress and displacement of 2-link modular manipulator

	2-link modular manipulator		Modified 2-link modular manipulator	
Configuration	Stress (MPa)	Displacement (mm)	Stress (MPa)	Displacement (mm)
1	296.3	0.45	162.8	0.42
2	146.5	0.37	128.4	0.28
3	145.2	0.26	93.1	0.23

Table 5.4 Maximum stress and displacement of 4-link modular manipulator

	4-link modular manipulator		Modified 4-link modular manipulator	
Configuration	Stress (MPa)	Displacement (mm)	Stress (MPa)	Displacement (mm)
1	1139	9.02	747.9	7.29
2	624.8	1.91	463.1	1.74
3	203.4	1.57	156.3	1.21

5.4 Summary

In this Chapter, 2-link and 4-link modular manipulators have been assembled and presented in different configurations using both bevel and helical gear approach. As the dynamics of the modular manipulators are complex to understand for manipulators having multiple degrees of freedom, the dynamic study of 2-link and 4-link modular manipulators have been performed using SimWise 4D software. The weights of the module links have been reduced by making them hollow and again dynamic study has been carried out for the same configurations. The results showed a significant decrease in maximum stress and deflection compared to solid links.

Chapter 6

Conclusions and Future Directions

6.1 Conclusions

The study on the manipulators is carried out which focuses mainly on the design part of the manipulator. The major findings are concluded below:

- From the literature review, it can be seen that a tremendous efforts have been made by the researchers to design the robots for a specific application in the past, but now a days the application of the robot changes rapidly and therefore there is demand of such a manipulator which can have more flexibility compared to conventional manipulators.
- In the literature review the drive optimization of manipulator has been discussed, this optimization plays a vital role because the performance of the manipulator can be improved and overall mass of robot can be decreased by implementing the optimized drive unit.
- With these observations, the modular manipulators have been designed as it can be used for various applications. Two different approaches have been used for designing the joints. In first, the bevel gears are used to provide rotation which is actuated by motor. In second, the motor give the torque to bevel gear which rotates joint.
- The design of the joints is designed in such a way that assembly of the base and shaft are capable of varying the link twist angle. This variation in link twist angle doubles the degree of freedom for the manipulator.
- A library of four links has been developed. Each link has different link length. Therefore the link lengths of the manipulators have been varied using different links. Due to this variation the manipulator can function in different environments and for different applications.
- The joints and links have been assembled to form 2-link and 4-link modular manipulator. The static and dynamic analyses of these manipulators having different configurations have been performed using ANSYS and SimWise 4D respectively.

- At last the design of the links has been modified by making them hollow. The dynamic analyses of the modular manipulators assembled using these links have been performed and the result showed a significant improvement in the results.

6.2 Future Directions

The work presented in thesis can be extended in some directions as

- The work can be extended for full-scale prototype development of the modular manipulator. One of the link and joint pares is already under development at IIT Ropar.
- The work can be extended for trajectory planning where it can be shown that the conventional serial manipulator may not be able to perform a variety of tasks, where the modular manipulator with same number of links is able to do the same task.
- The work is limited to the mechanical structure only therefore the control for this manipulator is one field in which the work can be extended. The control needs the program which can be coded as per the application.
- The drive motors which are used in the joints are to be finalized which is another direction for extension of work.
- As the manipulator can be assembled in many configurations it becomes necessity to include sensor so that the accidental collisions can be avoided. This is one future direction which is also important for this type of manipulator.

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