

## Mathematical Modeling and Kinematic analysis of 3-RRR Planar Parallel Manipulator

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### Abstract

Parallel mechanisms are found as positioning platforms in several robot manipulator applications tool manufacturing applications. Today, various types of these mechanisms are classified based on the structure, type of joints, and degree of freedom. An important and basic planar mechanism providing three degrees of freedom at the end-effector (movable platform) is a 3-RRR linkage. The forward kinematics in parallel mechanisms is a multi-solution problem and involves cumbersome calculations compared to inverse kinematics. With forward kinematics, the input kinematic parameters for any manipulator are known, and the end effector coordinate must be determined. The kinematic equations are generated with mechanics principles, and Jacobian matrices are formulated, With the Jacobian matrix, the regular workspace and dexterous workspace analysis calculated. The main objective is to fabricate a model of this planar manipulation mechanism with calculated dimensions and observe the practical workspace and dexterous workspace available at the end effector. The practical workspace and calculated workspace is presented in this paper. This final output data is useful for manipulator designers to design manipulators for different applications. In addition to this, the stress analysis is performed with Ansys software's help to estimate the moving platform's failure zone.

**Keywords:** 3RRR Parallel Planar Manipulator, Workspace analysis, Regular Dexterous Workspace, fabrication of 3RRR PPM Model, Performance analysis, Stress analysis, load-carrying capacity, precise and accurate position.

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### 1. Introduction

As the demand for various products and flexible services rapidly increasing day by day, new technologies are developing to meet the estimated target [1]. In service and manufacturing applications, robots play a crucial role in better and more accurate production than a special-purpose machine-like NC CNC and DNC machines; robots have more advantages than manual intervened machines [2]. This rapid demand has led to the research and development of different new types of mechanisms in robots. Parallel and serial manipulators have high medical equipment applications, service robots, industrial manufacturing sector line in assembly robots, assembly

operations, and remote healthcare space explorations. [3] Robotics branch is a multi-disciplinary area. Robots are made of multi-discipline parts that need mechanical (design and mechanism) and electrical components and sensor application, computer systems, and data science, artificial intelligence, etc. [4] there are two sections in a parallel manipulator that are mechanical, responsible for mechanical part manufacturing and actuation of parts, kinematics, and robot dynamics. The electronic section responsible for the sensors and actuators of the robot controlling the robot is fully dependent on the selection of electronic accessories. The software technology is useful to robot programming and path planning [5]. The 3RRR Planar Parallel Manipulator is a mechatronic system with two platforms: a moving and a fixed platform. The fixed

platform is the base. It is connected to a moving platform with different linkages. Each link consists of an actuated joint. In this analysis, all links are connected with revolute joints.

The industrial robotic Manipulator is useful to decrease the human intervention and effort in the repetitive works as well as un hygiene works, as we know that the manipulator system consists of kinematic links, pairs, and joints like revolute prismatic and spherical with these joint the desires Degrees of freedom is achieved which is presented in mechanism theories of Theory of machines like Grubler criteria [6]. This paper deals with parallel manipulators' kinematics, characterized by the possibility of one or more kinematic loops. In parallel manipulators, the moving platform is connected to a fixed platform with several kinematic links [7]. In a closed-loop mechanism and parallel manipulators, the un-actuated or passive joints need not be a single degree of freedom joint. We have spherical, cylindrical, and hooked or other multi DOF joints [8] that have presented a tracking control of PKMs (Parallel Kinematic Machines), which is useful to avoid singularity[9], as singularity avoidance is a major problem in the parallel and serial manipulators. [10] The functional workspace of a PKM is often limited because of interference in mechanical components; RRR PKM workspace can be obtained with different motors' help. [11] the idea of a configurable stage was presented in equal controllers as a possibility for the advancement of holding robots with unique high execution clarifying points like streamlining, manipulability records, and getting a handle on worried about the equal controller with a configurable stage [12].

The manipulability index measure was proposed by [13]. This is to measure the manipulating ability of the robotic mechanism in positioning and orienting the end effectors. [14] Serial robots have machine learning [15] approach algorithms, to optimize the workspace [16] inspected the strategies for settling kinematic redundancies of controllers by the impact on joint forces [17]. The comparison concluded that the serial Manipulator has less load carrying capacity, and parallel manipulators can properly position high load carry capacity [18]. 3 RRR Model is fabricated and tested for lower limb rehabilitation [19], [47]. By nature, the singular value is a major problem in parallel kinematic machines[20]. The end effector loses its input in this condition, and the Manipulator is not functioning as per the program that may lead to accidents in the workspace zone [21], [48]. Any Mechatronic device works on the program of instructions [22], [49].

## 2. Architecture of 3RRR planar parallel Robot

PKMs are closed-loop systems that can be outfitted with prismatic or revolute actuators [50]-[52]. Such machines include separate sequential chains in which a fixed base is associated with a moving platform [28]. PKMs can be arranged into different types in the literature [29], and the structure of such PKMs can be developed dependent on 3-RRR and 3-RPR planar parallel robots. The condensing of "P" indicates prismatic, and "R" indicates revolute [30]. The new component of parallel manipulators can execute accurate and flexible moments to quire various arrangements dependent on calculations involved in the inverse kinematic position problem. Moreover, the singularity issues of PKMs with revolute joint was solved [31].

3RRR parallel planar Manipulator has 3DOF; Degrees of Freedom (DOF) is the arrangement of autonomous removals and revolutions that determine the body's dislodged or distorted position and direction or framework [32]-[37]. In simple words, the DOF is that the number of possible motions possible for a mechanic. The DOF for planar configuration, as shown in the figure. One is computed using Gruebler's equation as  $L$  represents several kinematic links,  $J$  indicates the number of binary pairs, and  $h$  represents higher pairs associated with the mechanism [38]-[41]. The mechanism considered is 3RRR planar parallel Manipulator, which consists of one moving platform and one fixed base platform with links connected with revolute joints; this mechanism consists of 8 links, 9 joints, there are no point or line contacts; thus, higher pairs are zero [41]-[46]. The degree of freedom of 3-RRR planar parallel Manipulator is calculated shown below:

$$\text{Degrees of freedom} = 3(L-1) - 2*J - H$$

$$\text{Degrees of freedom} = 3(8-1) - 2(9) - 0 = 3$$

The most observable fascinating highlights of parallel manipulators are these mechanisms have High payload capacity, High throughput developments (high increasing velocities), High mechanical unbending nature, Low moving mass, Simple mechanical development, Actuators can be situated on the base. However, the most perceptible detriments are. They have more modest workspaces than chronic controllers of comparable size, Singularities inside the working volume, High coupling between the moving kinematic chains.

In this Manipulator, one fixed platform of AAA and CCC is the movable platform is considered.  $L_1$ ,  $L_2$ ,  $L_3$  are the links connected to fixed platform  $r_1$ ,  $r_2$ ,  $r_3$  is connected to the moving platform. The orientation angle  $\alpha$  explains the orientation and position of the moving platform, and all three links also making an angle of  $\theta$  with the fixed base  $\phi$  is the angle between the two links. In this article, the 3RRR indicates the three revolute

joints in each pair three links like that three pairs of links are there; all links are connected with the simple bolt and nut joint to reduce the joint's frictional effects. R indicates the actuated joint that the motor is placed at that joint location like 3RRR indicates that the first revolute joint which connects the base and link is actuated, or in other words, the motor is placed at the first joint location for easier prototype if the motor is at second joint then the robotic Manipulator is represented as 3RRR.

Three servo motors are used at three joints. The servomotors are actuated with Arduino Uno programming. The motors are actuated with a certain degree of freedom to reduce collision among the links that may lead to a singularity in the robot configuration. Three motors are actuated one by one with an angle of rotation of 50-80 degrees at every joint, and the end effector workspace is drawn with the help of the program. The Matlab theoretical solution is nearly matching the end effort output.

During the design stage, the triangular platform and link lengths are designed and assembled with mechanical software (Adams). Further, the link lengths are optimized in such a way that the link adjacent to the platform is taken as 1.15 times to the other link, which is connected to base with the help of revolute joint after assembly in the file is uploaded to ansys for analysis the finite element analysis is done on the Manipulator to calculate stress variation in the moving platform.

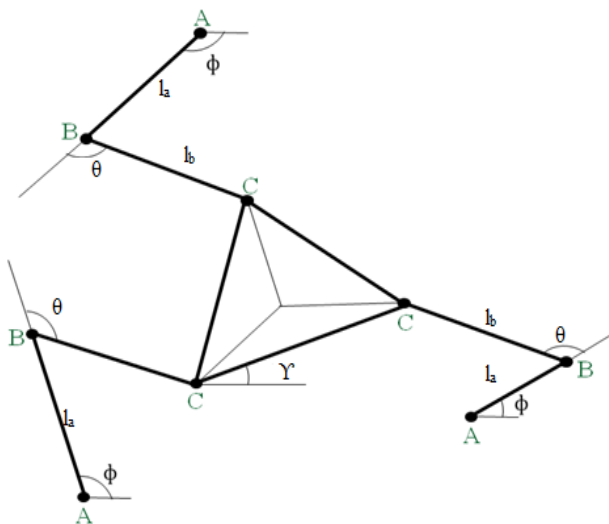


Figure 1. The 3RRR planar parallel Manipulator

### 3. Mathematical modeling of Manipulator

The Manipulator is modeled with the help of a simple resolution technique. The Jacobean matrix, which is a

relation between link lengths and angles, is derived from calculating performance indices from the figure 1.

$$\text{loop closure equation is } AB + BC + CD = AD \dots\dots(1)$$

$$X_p = l_a \cos(\phi_i) + l_b \cos(\theta_i) + l_c \cos(\phi_i + \gamma_i) + x \dots\dots\dots(2)$$

$$Y_p = l_a \sin(\phi_i) + l_b \sin(\theta_i) + l_c \sin(\phi_i + \gamma_i) + y \dots\dots\dots(3)$$

Rewriting the above equations

$$l_b \cos \theta_i = X_p - l_a \cos \phi_i - l_c \cos(\phi_i + \gamma_i) - x \dots\dots\dots(4)$$

$$l_b \sin \theta_i = Y_p - l_a \sin \phi_i - l_c \sin(\phi_i + \gamma_i) - y \dots\dots\dots(5)$$

Squaring and adding the above equations, we get

$$l_b^2 = X_p^2 + y_p^2 + l_a^2 + l_c^2 + x^2 + y^2 - 2x_p l_a \cos \phi_i - 2x_p l_c \cos(\phi_i + \gamma_i) - 2X_p \cdot x + 2l_a l_c \cos \phi_i \cdot \cos(\phi_i + \gamma_i) + 2l_a \cdot x \cos(\phi_i) + 2l_c \cdot x \cos(\phi_i + \gamma_i) - 2Y_p l_c \sin(\phi_i + \gamma_i) - 2Y_p \cdot y + 2l_a l_c \sin \phi_i \cdot \sin(\phi_i + \gamma_i) + 2l_a \cdot Y \sin \phi_i + 2l_c \cdot y \sin(\phi_i + \gamma_i) \dots\dots\dots(6)$$

By rearranging cosφ and sinφ of equation 6 in the format of the below equation

$$K \sin \phi + M \cos \phi = N \dots\dots\dots(7)$$

$$\text{Whereas } N = X_p^2 + y_p^2 + l_a^2 + l_c^2 + x^2 + y^2 - 2x_p l_c \cos(\phi_i + \gamma_i) - 2X_p \cdot x + 2l_c \cdot x \cos(\phi_i + \gamma_i) - 2Y_p l_c \sin(\phi_i + \gamma_i) - 2Y_p \cdot y + 2l_c \cdot y \sin(\phi_i + \gamma_i)$$

$$M = -2x_p l_a + 2l_a l_c \cos(\phi_i + \gamma_i) + 2l_a \cdot x$$

$$K = -2l_a Y_p + 2l_a l_c \sin(\phi_i + \gamma_i) + 2l_a \cdot y$$

$$\phi = \text{Atan } 2(K, M) + \text{Atan } 2(\sqrt{(K^2 + M^2 - N^2)}, N) \dots\dots\dots(8)$$

$$\dot{x} = -l_a \sin \phi_i (\dot{\phi}_i) - l_b \sin \theta_i (\dot{\theta}_i) - l_c \sin(\phi_i + \gamma_i) (\dot{\phi}_i + \dot{\gamma}_i) \dots\dots\dots(9)$$

$$\dot{y} = l_a \cos \phi_i (\dot{\phi}_i) + l_b \cos \theta_i (\dot{\theta}_i) + l_c \cos(\phi_i + \gamma_i) (\dot{\phi}_i + \dot{\gamma}_i) \dots\dots\dots(10)$$

By solving the above equations by removing the passive variable and rewriting the above equations in the desired form of:

$$J_{\theta} \dot{\theta}_i = J_x \dot{X}$$

$$\begin{aligned}
 l_a \sin(\phi_i - \theta_i) (\dot{\phi}_i) &= \cos(\theta_i) \dot{x} + \sin(\theta_i) \dot{y} \\
 &- l_c \sin(\theta_i - (\phi_i + Y_i)) \dot{\phi}_i \\
 &\dots\dots\dots(11)
 \end{aligned}$$

$$\begin{aligned}
 J_x = & \begin{bmatrix} \cos(\theta_1) & \sin(\theta_1) & -l_c \sin(\theta_1 - (\phi_1 + Y_1)) \\ \cos(\theta_2) & \sin(\theta_2) & -l_c \sin(\theta_2 - (\phi_2 + Y_2)) \\ \cos(\theta_3) & \sin(\theta_3) & -l_c \sin(\theta_3 - (\phi_3 + Y_3)) \end{bmatrix} \\
 & \dots\dots\dots(12)
 \end{aligned}$$

And

$$\begin{aligned}
 J_{\theta_i} = & \begin{bmatrix} l_a \sin(\phi_1 - \theta_1) & 0 & 0 \\ 0 & l_a \sin(\phi_2 - \theta_2) & 0 \\ 0 & 0 & l_a \sin(\phi_3 - \theta_3) \end{bmatrix} \\
 & \dots\dots\dots(13)
 \end{aligned}$$

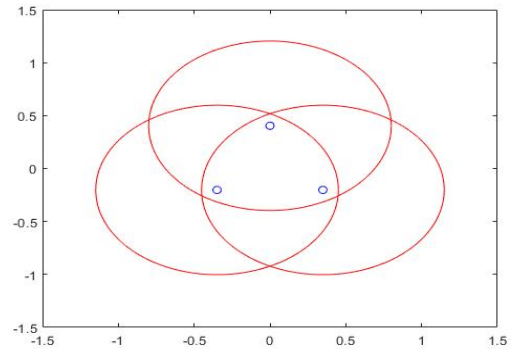
With  $J_{\theta}^{-1} J_x$

$$\begin{aligned}
 J = & \begin{bmatrix} \frac{\cos(\theta_1)}{l_a \sin(\phi_1 - \theta_1)} & \frac{\sin(\theta_1)}{l_a \sin(\phi_1 - \theta_1)} & \frac{-l_c \sin(\theta_1 - (\phi_1 + Y_1))}{l_a \sin(\phi_1 - \theta_1)} \\ \frac{\cos(\theta_2)}{l_a \sin(\phi_2 - \theta_2)} & \frac{\sin(\theta_2)}{l_a \sin(\phi_2 - \theta_2)} & \frac{-l_c \sin(\theta_2 - (\phi_2 + Y_2))}{l_a \sin(\phi_2 - \theta_2)} \\ \frac{\cos(\theta_3)}{l_a \sin(\phi_3 - \theta_3)} & \frac{\sin(\theta_3)}{l_a \sin(\phi_3 - \theta_3)} & \frac{-l_c \sin(\theta_3 - (\phi_3 + Y_3))}{l_a \sin(\phi_3 - \theta_3)} \end{bmatrix} \dots\dots\dots \\
 & \dots\dots\dots(14)
 \end{aligned}$$

### 4. Workspace of manipulators

The workspace of any manipulator is defined as the volume of the space in which the end effector can locate the objects, same can be specified by nonexistence or existence of inverse kinematic solution the space reached by the end effector with at least one orientation is called the reachable workspace, and space can be reached with more than one orientation within the workspace called dexterous workspace, it is evident that the dexterous workspace is a subset (smaller) or same to the reachable workspace, for three degrees of freedom 3RRR planar parallel Manipulator the workspace is calculated by drawing three circles of the radius of maximum link length, the area of intersection of three circles indicates the dexterous workspace of the Manipulator [23], i.e., the robot can have more than one orientation to reach the end

effector. Different workspace manipulators defined by [24] are reachable position workspace; Dexterous workspace is also called full orientation angle workspace. The following indices measure the performance of the parallel Manipulator, as shown in figure 2.



**Figure 2.** The Matlab solution of the workspace of 3RRR planar Parallel Manipulator

### 4.1 Dexterity Indices

It is proposed by [25] they defined that the workspace in which the end effector can reach any point with more than one orientation also defined as the measure of a manipulator to achieve varying positions at the selected point [26], the dexterity index is a value which is ranges from 0 to 1. It depends on the manipulator structure. In a serial Manipulator, the small last link size will decide the possible orientation and position of the robot's end-effector and Dexterity index.

### 4.2 Yoshikawa proposes manipulability index

It is a measure of the kinematic performance of the robot [27] This index is a widely accepted term to measure the kinematic manipulability the Manipulability index is defined as the square root of the determinate of the product of the Jacobean matrix and its transpose by using singular value decomposition theorem we solve this index also ranges from 0 to 1, the higher value of indices means better performance of Manipulator and vice versa. The Yoshikawa manipulability indices have the limitations like scale dependency means based on link length, the manipulability indices will change it is an unbounded index it serves the relative measure of the degree of condition, it depends on the order of Eigenvalues to overcome limitations some authors are proposed different indices like relative manipulability index and normalized manipulability index and global manipulability index.

### 4.3 Mechanical Assembly

## Mathematical Modeling and Kinematic analysis of 3-RRR Planar Parallel Manipulator

The Manipulator is fabricated from 3D printed parts and assembled on a wooden sheet. The gaps and profiles are sliced unpredictably to decrease the heaviness of the moving parts. Standard latches are utilized, and all help joints are uniquely crafted utilizing fast prototyping. The sequential arm is associated with an equal base through a three-sided stage that underpins the sequential arm and bears a significant mechanical loading aspect, as shown in figures 3 to 5.

### 4.4 The Prototype

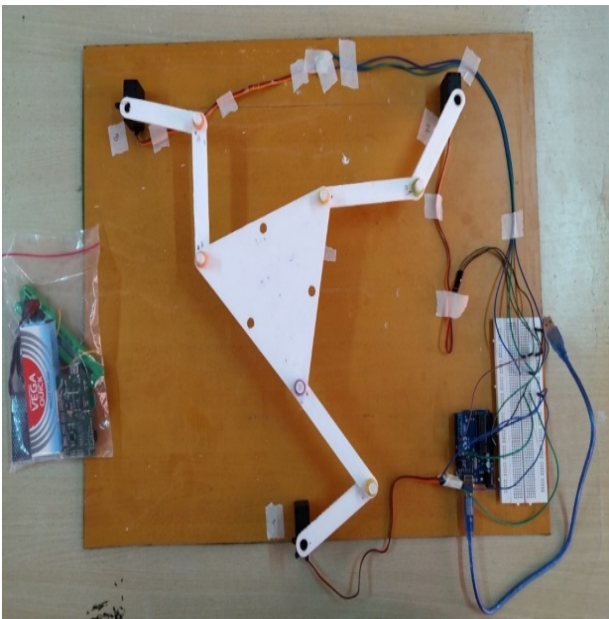


Figure 3. A top view of the Prototype

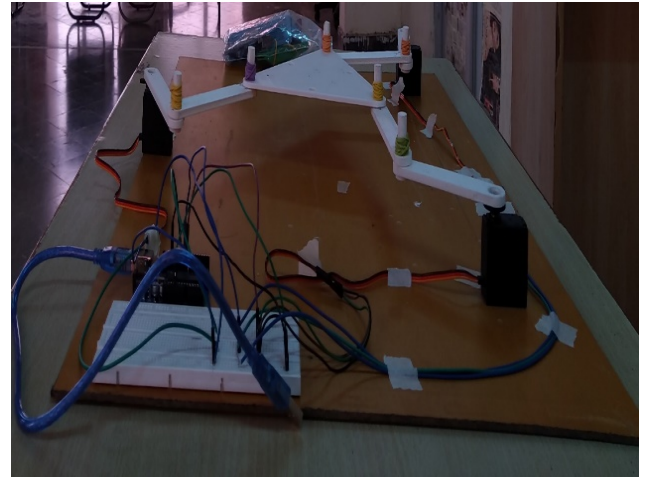
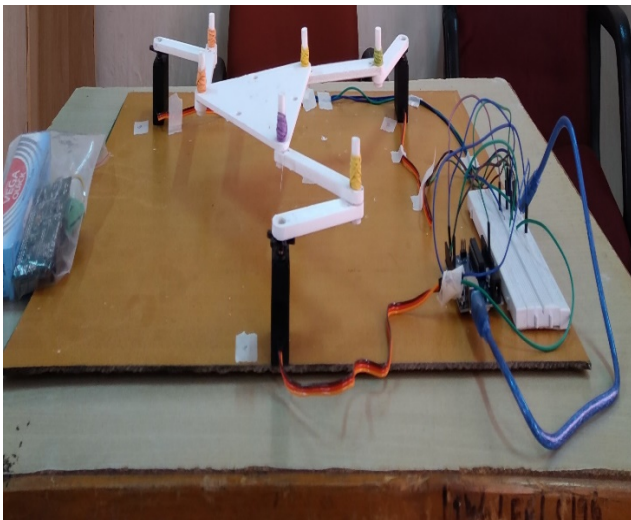


Figure 4 & 5. An Isometric view of the prototypes

### 4.5 Stress analysis

The planar parallel Manipulator is developed using the above described above. All links are designed with the help of Creo2.0 and printed on a rapid prototyping machine for less weight and high strength, durability. Kinematic analysis and the analysis related to forces and velocity is carried out in software (MATLAB). Further, the Manipulator's calculated workspace is tested successfully in a fabricated model (prototype) with the help of Arduino, as well as to test the failure points of the Manipulator the prototype is uploaded to Ansys workbench and did finite element analysis. Von-mises stresses are calculated for this mechanism, as shown in figures 6 to 9.

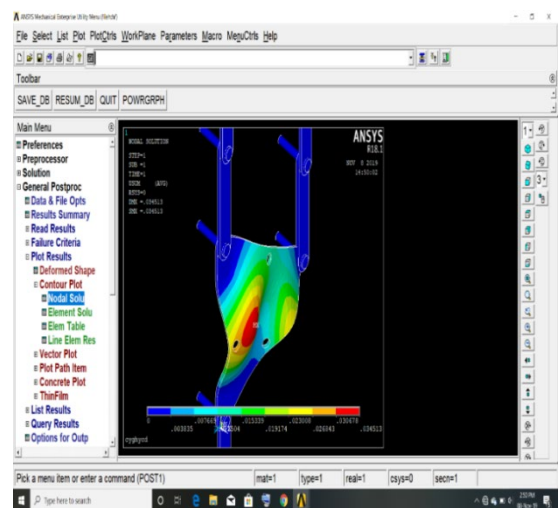


Figure 6. Vector Nodal Solution in Ansys

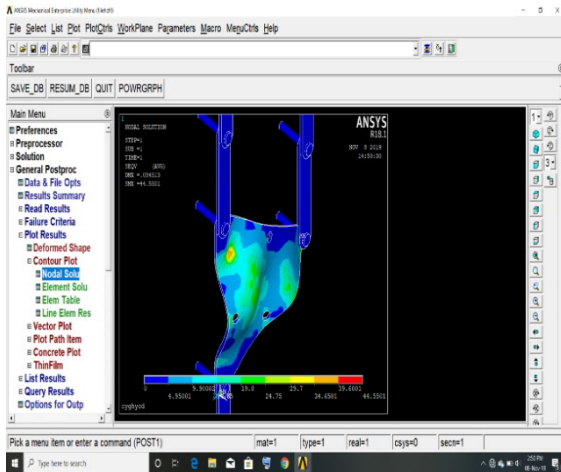


Figure 7. Von Mises Criteria Nodal Solution

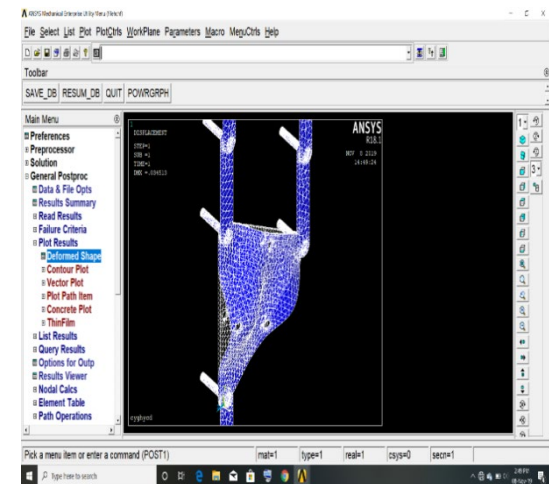


Figure 8. The stress analysis of 3RRR planar parallel manipulator

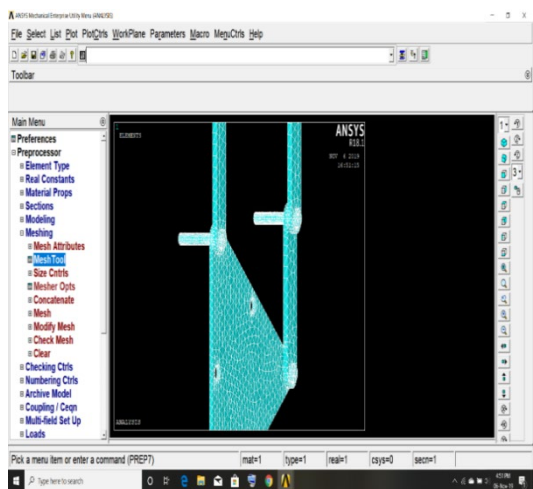


Figure 9. The stress analysis of 3RRR planar parallel Manipulator

## 5. Experimental Results and Discussions

The Parallel manipulator base kinematics was actualized through the Arduino Uno Interface program. For inverse kinematics and forward kinematics, the actuators are given specific angles, and the final platform position is recorded. Different combinations of actuator positions are tried to assess the reachable workspace and minimum singularity limits. The outcomes were tried against the workspace examination done in basically. The practical workspace (prototype) was not the same, i.e., less than the estimated reachable workspace, because of the joint angle problems, i.e., joint constraints given in the Arduino program, the effect of minimum singularity position, different physical constraints of links, and moving platform.

In Inverse Kinematics of a parallel planar manipulator, the robot position, i.e., the x and y directions of the stage, is taken as input values in the written code. The inverse kinematic problem is processed to locate the joint angles. Position and orientation of the moving platform at a point for the experiment; the position and orientation can be changed easily while editing the program code. The possible workspace is calculated, and the moving platform is moved to the old pose (position and orientation). The trajectory shows the position arrays to test the Manipulator's inverse kinematics that results showed the correct result. The non-feasible non-reachable points in the workspace are displayed as error values on the output screen.

The planar parallel robot's reachable workspace comprises all points that the end effector can reach without any error. There are many kinds of workspaces, specifically reachable workspace, dexterous workspace, and constant orientation. The constant orientation-workspace comprises all dexterous points that the Manipulator can reach by the end effector at a fixed stage position and orientation. The reachable workspace comprises all points reachable by the Manipulator's end effector by at least (minimum) single orientation. The dexterous - workspace comprises the area covered by the Manipulator's end-effector with any directional pose of the working mechanism in a point of the workspace is becoming unstable.

Singularity is the position where the Manipulator will lock up or loses the input instructions. Some minimum singular points are assembled around the workspace ends like the hinged link positions. If the robotic Manipulator works near and around singular point regions, then the accuracy, precision, rigidness, and other robot performance indices will be more awful. To estimate or

compute the manipulator workspace, a numeric discretization measure can be adopted.

## 6. Conclusion

This work concludes that the inverse kinematic solutions of the 3-RRR parallel planar mechanism are derived. With the Jacobian matrix's kinematic relations formulated using the regular process, the Jacobian matrix correlates between the joint angles and displacements. The objective of this analysis is to find the dexterous workspace and regular workspace of the Manipulator. The parallel planar Manipulator is fabricated with additive manufacturing techniques. The model is tested with servo motors and programming with Arduino and the kinematic analysis was carried out in computational software (MATLAB). With Arduino programming, the controlling motions are applied to all actuated joints. The dexterous workspace, the Regular reachable workspace, was easy compared with the computation workspace. The workspace calculated using the mathematical relations, and the fabricated model workspace have differences like the fabricated model has less workspace compared to the computational workspace. Further, the fabricated manipulator performance can be improved by adding advanced PID controllers and artificial intelligence methods for training the robot architecture and the précised mechanical components.

### 6.1. Future scope

A prototype with high accuracy and precision to be developed to estimate the performance of the robotic Manipulator. The analysis of the control system is implemented for robotic Manipulator needs to develop. A multi-objective problem to be formulated includes different performance indices of robot-like dexterity manipulability and stiffness to be set up. The dynamic analysis of the proposed mechanism and sensitivity, stiffness other indices to be calculated for the better design inputs for placing the end-effector position.

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