



## **A NOVEL DESIGN OF DELTA ROBOT**

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### **Abstract:**

*This paper represents an ideal pick and place robot should carry out the operations in minimum time and should also be cost efficient. One of the fastest configurations of industrial robot used is the Delta configuration. It is three degrees of freedom parallel configuration used for very high speed pick and place operations capable of achieving high cycle rates up to 200 cycles per minute. The objectives of this paper are designing a Delta robot capable of carrying 1kg payload, achieving a cycle rate of 120 cycles per minute covering a work volume of 400x300x200 mm<sup>3</sup>. The project involves kinematic and dynamic modeling of the robot for the above specifications. The kinematic parameters, involving the lengths of the bicep and forearm, are calculated based on the work volume requirements and the dynamic parameters, involving the motor torque and speed, are calculated based on the maximum acceleration requirements and the inertia of the system. The project further involves the structural analysis of the robot which deals with the proper sizing of the mechanical structure which should be capable of withstanding the high torque and acceleration required for smooth and fast motion. Thus the delta robot is designed to achieve very high cycle rates on par with the commercial industrial delta robots and at the same time cost efficient. The future work involves integrating the mechanical system with the control system and programming the system for a particular application.*

**Key Words:** Delta Robot, Kinematic Modeling, Work Volume Analysis, Dynamic Modeling&Stress Analysis

### **1. Introduction:**

An industrial robot is defined by ISO 8373 as an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axis. Industrial robots have been used for a wide range of applications including pick and place, painting, assembly, product inspection, quality control and testing. The earliest known industrial robot, conforming to the ISO definition was completed by Griffith P. Taylor in 1937 and published in Meccano Magazine, March 1938. The first company to produce a robot was Animation, founded by Devol and Joseph F. Engelberger in 1956. In 1969 Victor Scheinman at Stanford University invented the Stanford arm, an all-electric, 6-axis articulated robot designed to permit an arm solution. In 1981, Sankyo Seiki, Pentel and NEC presented the SCARA robot, a completely new concept for assembly robots. The delta robot was invented in the early 1980s by a research team led by Professor Reymond Clavel for manipulation of light and small objects at a very high speed. The delta robot has undergone various transformations in the past few decades and it is one of the most efficient solutions for industrial pick and place applications.

US 20110259138 A1 [7] is the patent for the special type of ball joint used in the delta robot. It provides a method for friction less motion between the arms and about the type of material used for the socket. R. Clavel [1] discusses about the basic structure and working of the delta robot. André Olsson [2] has framed the forward and inverse geometric kinematic model for the delta robot, the velocity and acceleration kinematic

model and the dynamic model of the delta robot using the conventional approach for solving the dynamics of the parallel manipulators. Alain Codourey[3] has framed the velocity and acceleration kinematic model for the delta robot. M Lopez, E Castillo, G Garcia, and A Bashir[4] have formulated the inverse, direct, and intermediate Jacobians for the Delta robot.

A.Codourey, E. Burdet [5] have framed the body-oriented method for finding a linear form of the dynamic equation of fully parallel robots, which helps in arriving at a closed form solution of the dynamics of the delta robot and narrowing down to the required motor torque. Pradya Prempraneerach [6] has laid out the concept behind the work space generation of the delta robot. Excel Ultralite Carbon Fiber Tubes Datasheet [8] provides the material properties about the carbon fiber tubes used for the robot arms. Fag Data book[9] was referred for the selection of the various mechanical components in the system which involves the angular contact ball bearings, lock nuts and lock washer. Misumi Data book [10] was referred for the selection of the spring that holds the forearms together.

In order to compare and benchmark the delta robot being developed a number of delta robots available in the market were studied. The manuals or datasheet of the robots compared are listed below Fancu M-1iA Series\_171 [11] provides the specifications and information about the kinematic parameters of the Fancu M-1iA series of Delta robots. AsyriL ROBOT-POC-01\_Datasheet\_E[12] provides the specification of the Pocket Delta Robot, a miniature delta robot made by AsyriL. It provides wide range of information about how a miniature delta robot can be designed. DeltaRobot-R6Y3+InstallManual[13] provides assembly guide for the Omron Delta robot and also the lengths of arms of the robot which was very helpful in benchmarking the delta robot as the ratio plays an important role.

## 2. Delta Robot:

Delta robot is a parallel 3 DOF robot designed by Professor Raymond Clavel for realizing very high speed pick and place operations. The basic advantages of the delta robot conform to that of the parallel robot. The basic structure of the delta robot is explained with the help of Figure 1.

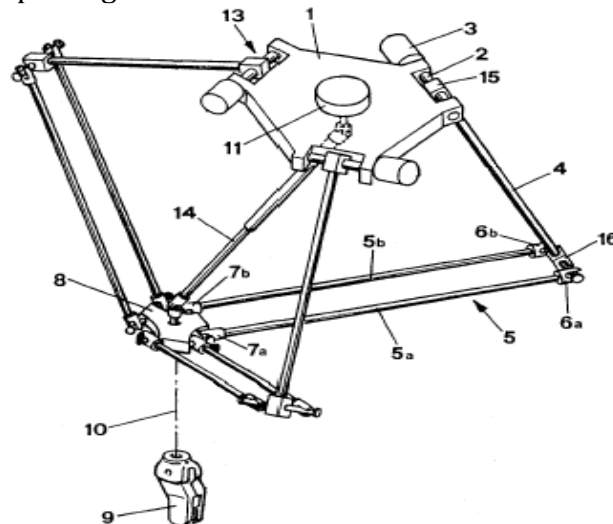


Figure 1: Delta Robot Structure

The delta robot consists of two platforms: the upper one (1) with three motors (3) mounted on it, and smaller one (8) with an end effectors (9). The platforms are connected through three arms with parallelograms; the parallelograms restrain the

orientation of the lower platform to be parallel to the working surface (table, conveyor belt and so on). The motors (3) set the position of the arms (4) and, thereby, the XYZ position of the end effectors, while the fourth motor (11) is used for rotation of the end effectors.

### **3. Kinematic Modeling of Delta Robot:**

Robot kinematics involves analyzing the movement of structures with multiple degrees of freedom. Robot structures usually consist of rigid bodies called links and joints which are usually revolute or translational. This basically involves the relationship between the kinematic chains and the position, velocity, and acceleration of the links. Kinematics involves only the study of motion of the robot system without considering the forces that cause it. Robot Kinematics can be divided into two parts, the forward kinematics part and the inverse kinematics part. Robot kinematics is used to generate the work volume of the robot.

#### **3.1 Forward Kinematics:**

Forward kinematics involves the computational method to identify the configuration of the robot in Cartesian space while specifying the joint space parameters. Robot parameters can be divided into two types, one being the Joint space parameters and the other, the Cartesian space parameters. The joint space parameters consists of the angle of rotation or translational movement of the joints and the Cartesian space parameters involve the positions of the links and joints in the three dimensional space rendered by a fixed reference frame. Forward kinematics gives you the end effectors position for a given set of joint parameters.

#### **3.2 Inverse Kinematics:**

Inverse kinematics involves the computational method to compute the joint space parameters when specifying the Cartesian space parameters. Here, the endeffectors position is known and the joint parameters are the unknown. The inverse kinematics procedure will result in the values for joint parameters, which is usually the angle of rotation or the translational movement required to achieve the specified endeffectors position.

#### **3.3 Kinematic Constraints for a Delta Robot:**

The physical setup of a delta robot includes several ball joints and revolute joints. The ball joints are usually limited within their maximum pivot angle range and there volute joints are not allowed to rotate completely through the entire 360 degrees range of motion because of the mechanical constraints that are present in the structure of the robot.

##### **3.3.1 Revolute Joint Constraint:**

The revolute joints are limited in their negative direction of rotation and the angle to which the rotation is limited varies from robot to robot depending on the physical setup of the robots base. In this design, the revolute joints are restricted in the negative direction to a maximum of sixty degrees in each arm of the delta robot.

##### **3.3.2 Ball Joint Constraint:**

Delta robots are usually equipped with twelve ball joints and each ball joint is limited within its maximum pivot angle range, this in turn limits the maximum extent of movement of the robot arms and also the maximum reach of the robot system as a whole. Each ball joint is restricted to move freely only within its specified maximum pivot angle range. Thus whenever the forearms are to swing sideways, the maximum distance the end point of the forearm can reach is restricted which in turn restricts the work volume of the robot. Here, the maximum pivot angle range is limited to (+/- 60)degrees.

### 3.4 Work Volume Analysis:

The work volume of the robot was generated using MATLAB coding by assigning the kinematic parameters for the robot, on an iterative procedure the desired work volume was generated and the final kinematic parameters were fixed. The major kinematic parameters influencing the work volume were the lengths of the forearm and bicep and the length of the sides of the base and end effectors triangle. The other factors that affect the work volumes were the ball joint pivot angles and the mechanical constraint implied on the revolute joints of the motor axis. Here, the work volume was generated using the inverse kinematic procedure.

The desired work volume is usually described in terms of maximum reach diameter of the delta robot which was decided to be 600 mm. Optimized Input kinematic parameters for the desired work volume:

- ✓ Bicep length = 175 mm
- ✓ Forearm length = 400 mm
- ✓ Base triangle side length = 500 mm
- ✓ End effector triangle side length = 100 mm
- ✓ Ball joint pivot angle range = +/- 60 degrees
- ✓ Motor axis revolute joint restriction = - 60 to +130 degrees

Work volume for the delta robot is shown in Figure2

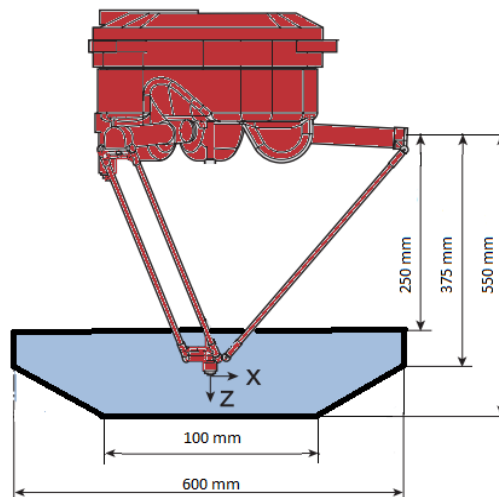


Figure 2: Volume of Delta robot

The screenshots of the work volume generated using MATLAB are shown below:

Front view is shown is Figure3

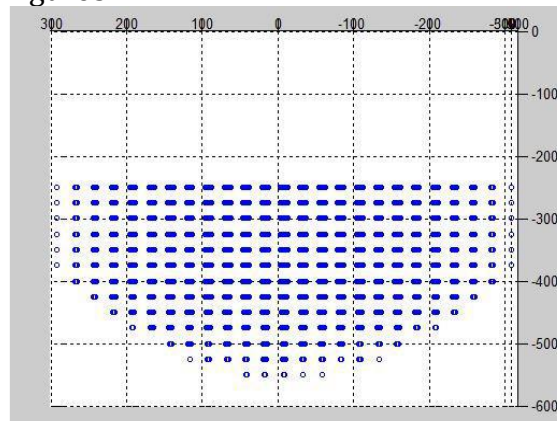


Figure 3: Front view of the work volume

Top view is shown in Figure 4.

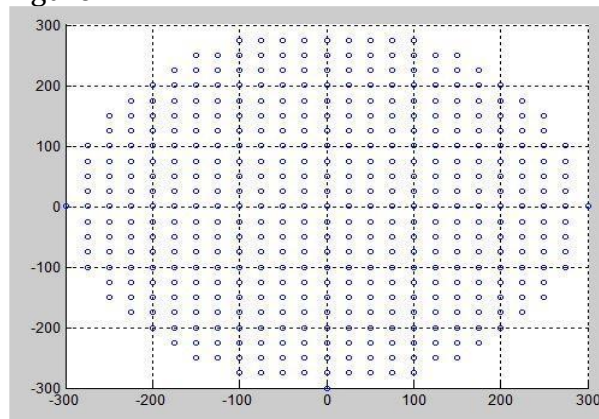


Figure4: Top view of the work volume

Isometric view is shown in Figure 5

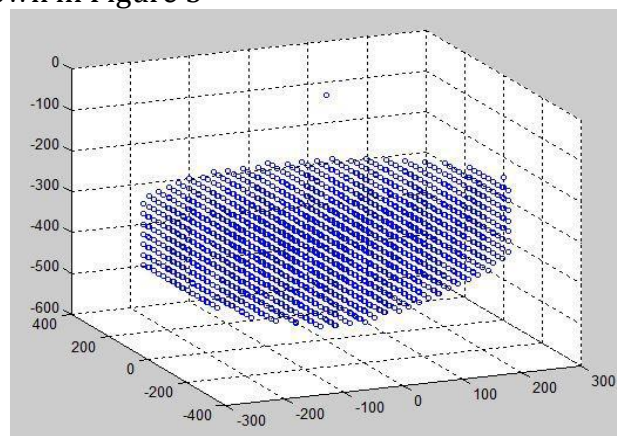


Figure 5: Isometric view of the Work

The work volume screenshots shown above consists of a discrete set of points where the robot end effectors can reach within the work volume. The work volume is generated using the following algorithm. A cube of some arbitrary size is taken and the inverse kinematic values are calculated for each and every point in the cube. All the points having the proper inverse kinematic values are considered to be a valid point in the work volume and are plotted.

#### **4. Dynamic Modelling of the Robot:**

The dynamic model of the delta robot is used to size the servo motors to be used in the delta robot. The dynamic model consists of the forward and inverse dynamic models. The forward dynamic model is used to arrive at the end effectors motion parameters from the motor torque provided, whereas the inverse dynamic model is used to arrive at the motor torque requirements from the end effector's Cartesian velocity, Cartesian acceleration and the motion profile considered for system. We use the inverse dynamic model to arrive at the motor specification for the delta robot. The motion profile considered for the dynamic modeling is the triangular velocity profile. In order to arrive at the dynamic model, the velocity and acceleration kinematic model have to be developed.

#### **5.1 Velocity and Acceleration Kinematics:**

The velocity kinematics of the delta robot involves the development of a Jacobian matrix which maps the Cartesian velocities in the end effectors frame to the joint velocities in the joint frame. The maximum Cartesian velocity calculated above can be converted into the maximum angular velocity required by the motor.



$$J = \begin{bmatrix} S_1^T \\ S_2^T \\ S_3^T \end{bmatrix}^{-1} \begin{bmatrix} S_1^T b_1 & 0 & 0 \\ 0 & S_2^T b_2 & 0 \\ 0 & 0 & S_3^T b_3 \end{bmatrix} \tag{1}$$

Where  $S_i$  is given by the following equation,

$$S_i = \begin{bmatrix} x_n \\ y_n \\ z_n \end{bmatrix} - {}^R_iR_z \left[ \begin{bmatrix} R \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} l_A \cos(\theta_i) \\ 0 \\ l_A \sin(\theta_i) \end{bmatrix} \right] \quad i = 1, 2, 3. \tag{2}$$

Where  $\begin{bmatrix} x_n \\ y_n \\ z_n \end{bmatrix}$  - is the end effector position,

${}^R_iR_z$  - is the Rotation matrix for each bicep from the origin,

$R$  - Displacement between the origin and a side of end effector plate,

$l_A$  - Length of the bicep,

$\theta_i$  - Angular motion of each bicep

And  $b_i$  is given by

$$b_i = {}^R_iR_z \begin{bmatrix} l_A \cos(\theta_i) \\ 0 \\ l_A \sin(\theta_i) \end{bmatrix} \tag{3}$$

The Jacobian matrix maps the Cartesian and joint velocities by the equation

$$\dot{X}_n = J * \dot{\Theta}$$

The acceleration kinematics involves the mapping of the Cartesian acceleration to the joint acceleration by the relation given below, (4)

$$\ddot{X}_n = \dot{J}\dot{\Theta} + J\ddot{\Theta}$$

Thus from the Cartesian velocity and acceleration, the corresponding joint velocity and acceleration can be found by using this model. Hence these values can be used for the motor torque calculation. (5)

Once the values of these parameters are known, the dynamic model can be framed using the closed loop equation given by the following equation

$$\tau = (I_b + m_{nt} + J^T J)\ddot{\Theta} + (J^T m_{nt} \dot{J})\dot{\Theta} - (\tau_{Gn} + \tau_{Gb}) \tag{6}$$

Where

$$\tau_{Gb} = r_{Gb} G_b [\cos \theta_1 \quad \cos \theta_2 \quad \cos \theta_3]^T \quad \text{Gives the torque due to gravity acting on the actuated joint}$$

$$\tau_{Gn} = J^T m_{nt} [0 \quad 0 \quad -g]^T \quad \text{Torque due to gravity acting on the travelling plate}$$

$$I_b = \begin{bmatrix} I_{b1} & 0 & 0 \\ 0 & I_{b2} & 0 \\ 0 & 0 & I_{b3} \end{bmatrix} \quad \text{Inertia matrix}$$

Where  $I_{bi} = I_m k_r^2 + I_{brake} k_r^2 + I_{bc}$

$I_m$  - motor inertia

$I_{brake}$  - brake inertia

Total inertia of the system where

$$I_{bc} = \frac{m_b}{3} l_A^2 + l_A^2 (m_c + r m_{fb})$$

$$m_{nt} = m_n + m_{payload} + 3(1 - r)m_{fb} \quad \text{Net mass of one of the bicep to forearm assembly}$$

Now with this closed form equation for torque, the various torque values can be generated by iterating the end effectors position and the maximum torque can thus be calculated.

**5.3.1 Speed Calculation:**

The maximum speed required is calculated by taking arbitrary points within the 25-305-25 path that the robot has to travel and the inverse kinematic solutions are found for the various points. This gives joint position of the three motors for the various Cartesian positions of the end effectors. The path considered is plotted in fig 6.

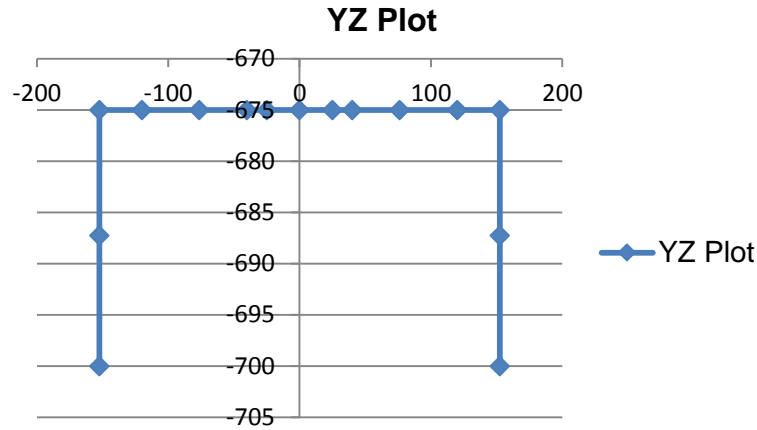


Figure 6: YZ Plot showing the path of motion.

The inverse kinematic solutions for the various points considered are listed in Table 1.

Table 1: Inverse Kinematics Values

X	Y	Z	$\theta_1$	$\theta_2$	$\theta_3$
0	-152.5	-700	15.418	43.668	43.668
0	-152.5	-687.25	12.134	40.763	40.763
0	-152.5	-675	8.973	38.019	38.019
0	-120	-675	17.83	39.982	39.982
0	-76.25	-675	21.683	35.688	35.688
0	-40	-675	35.058	27.849	27.849
0	-25	-675	33.091	28.572	28.572
0	0	-675	24.053	24.053	24.053
0	25	-675	27.039	31.599	31.599
0	40	-675	25.38	32.692	32.692
0	76.25	-675	40.087	26.46	26.46
0	120	-675	46.665	25.464	25.464
0	152.5	-675	43.476	15.351	15.351
0	152.5	-687.25	49.14	22.046	22.046
0	152.5	-700	51.908	25.216	25.216

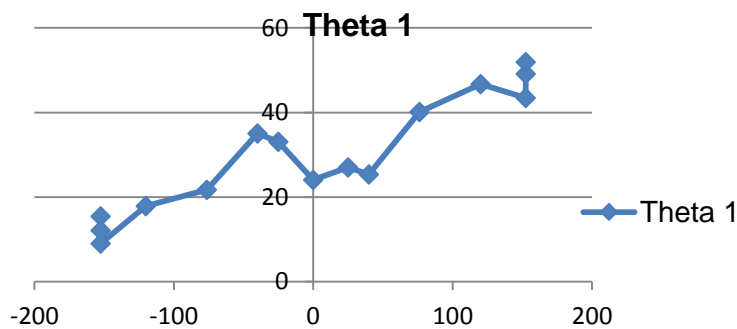


Figure 7: Variation in  $\theta_1$

The theta variation can be best seen in the plots are shown in Figure 7, Figure 8 and Figure 9.

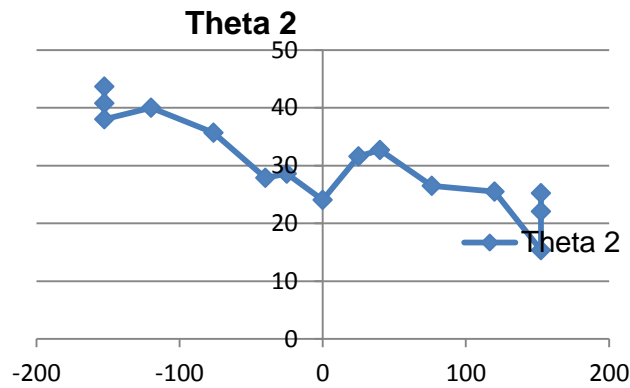


Fig 8: Variation in  $\Theta_2$

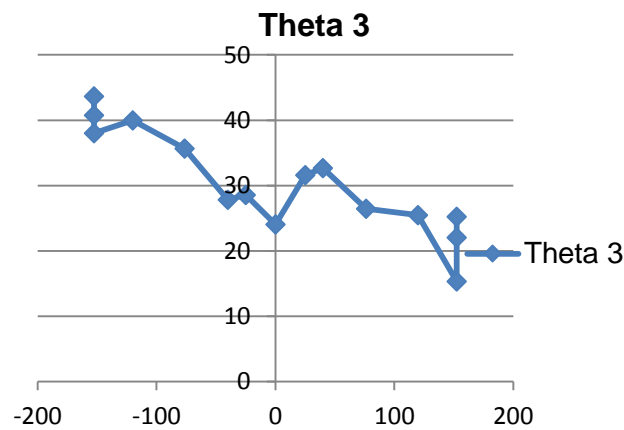


Figure 9: Variation in  $\Theta_3$

The maximum variation in the angular position for the shortest period of time gives the maximum speed that the motor has is shown in Table 2.

delta t1	delta t2	delta t3
0.257569	0.227843	0.227843
0.258041	0.224	0.224
0.272523	0.0604	0.0604
0.088069	0.098149	0.098149
0.368966	0.216248	0.216248
0.131133	0.0482	0.0482
0.36152	0.18076	0.18076
0.11944	0.30184	0.30184
0.1106	0.072867	0.072867
0.40571	0.171917	0.171917
0.150354	0.022766	0.022766
0.098123	0.311169	0.311169
0.462367	0.546531	0.546531
0.217098	0.248627	0.248627
	max values	
t1	0.462367	
t2	0.546531	
t3	0.546531	
max rpm	111.5833	



The maximum rpm thus calculated is 111.5 rpm. The speed can be used for the selection and sizing of the servo motor. Thus the dynamic modeling helped in solving for the maximum speed and torque that the motor needs to provide and the appropriate motor was selected.

### **5. Mechanical Design of Robot:**

The dynamic model is useful in solving for the various dynamic parameters of the system. These parameters are then used for the various strength analyses in the mechanical design of the delta robot. The mechanical design involves the design of the various subassemblies and mechanisms within the system such as the base plate, the bicep assembly, the forearm assembly and the traveling plate.

The basic structure of the delta robot consists of the following:

- ✓ Base plate - holds the motor and gear box and acts as a support structure
- ✓ Bicep Assembly – transfers the motion from the motor to bicep through ball joints.
- ✓ Forearm Assembly – holds the traveling plate and positions it at the desired position.
- ✓ Traveling plate – holds the gripper.

Figure 10 and 11 show the base plate used in the delta robot and the motor mounting plate. The base plate should be a perfect equilateral triangle of side 500mm. The plate holding the motor should be perfectly vertical so that it doesn't affect the kinematics of the system and hence the positioning accuracy. The provisions given in the vertical plate for mounting the bicep assembly and the flange is shown in the above image.



Figure10: Base Plate

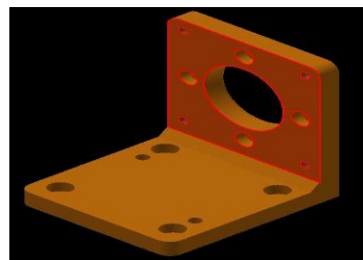


Figure 11: Motor Mount Plate

The motor assembly is mounted over the base plate. The motor assembly is a simple assembly of the gearbox motor and flange. Flange is designed as per the gear box face dimensions. The motor is coupled to the gearbox which is in turn connected to the flange. The bicep assembly of the delta robot consists of the bearing assembly and the ballstuds mounted on the other side of the bicep arm over which the forearms rotate. The bicep assembly of the robot is shown in Figure 12.

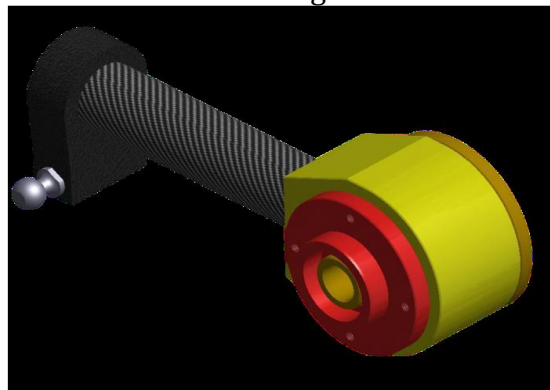


Figure 12: Bicep assembly

The calculated catalogue load for the selected bearing is well below the actual catalogue load of the bearing, which is 6000N. Therefore the selected bearing can operate without any problem for 30000 hours under standard operating conditions. The dimension of the bicep tube is calculated after performing various stress analysis calculations. The loads and torques acting on the bicep are due to the motor torque and the inertial force of the moving mass at very high acceleration. The maximum deformation and the maximum stress developed at the worst case condition is well below the allowable deformation and ultimate tensile strength. Thus the carbon fibre tube of OD 30mm and ID 27mm was selected.

The forearm assembly consists of the carbon fiber tube epoxies with the aluminum heads on either side of the tube. The aluminum heads have provision for the socket. The socket is made up of Torlon material which has very low coefficient of friction and is self-lubricating. These two characteristics make Torlon suitable for this ball joint application. The forearm assembly is given in Fig. 13

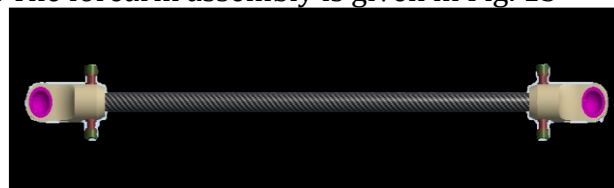


Figure 13: Forearm assembly

The forearms are held together by four springs, two on the top and two at the bottom of the forearm. The cumulative spring force must be enough to hold the forearms together during the motion. The forearms accelerate at very high velocity. The inertial force during motion is therefore very high. The maximum force acts at the bottom of the forearm because of the travelling plate and payload. Hence the force is considered to be shared by only two springs.

The spring is selected so that it can provide a force of 62.5N. The maximum allowable deflection is 13.5mm. Therefore the spring can provide a total force of 78N. In this case the maximum deflection required is only 10mm. The stress analysis results show that the deformation and the stress developed are within the limits. Thus the CFRP tube of OD 10mm and ID 8mm is chosen.

## **6.Results (Stress Analysis):**

The dimensions of the bicep and forearm were decided upon by carrying out stress analysis with Autodesk Inventor. The stress analysis results are shown below. Fig. 14 and Fig.15 shows the stress developed on the bicep and the deformation of the bicep respectively.

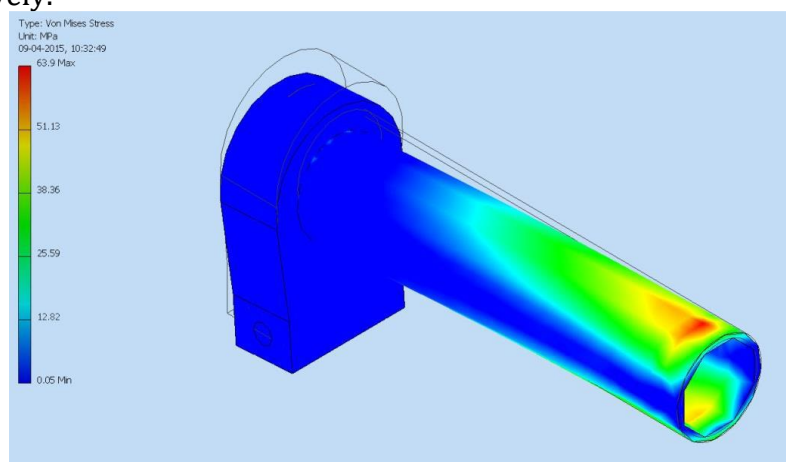


Figure 14: Stress Results of Bicep

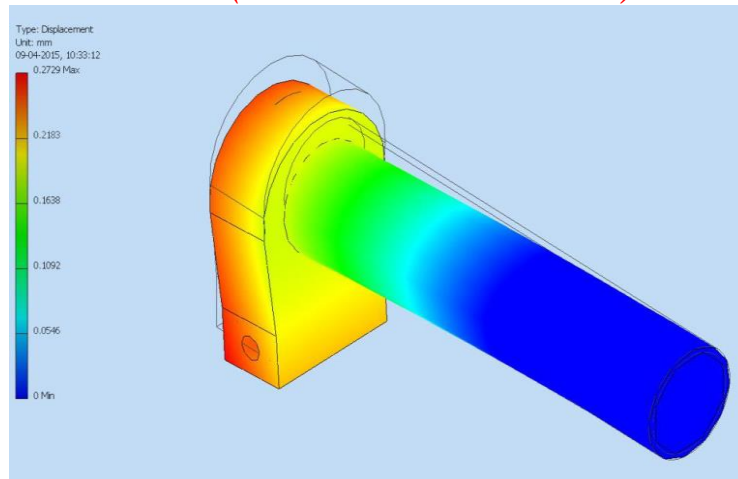


Figure 15: Deformation Results of Bicep

Figure 16 and Figure 17 shows the stress developed on the forearm and the deformation of the forearm respectively.



Figure 16: Stress Results of Forearm

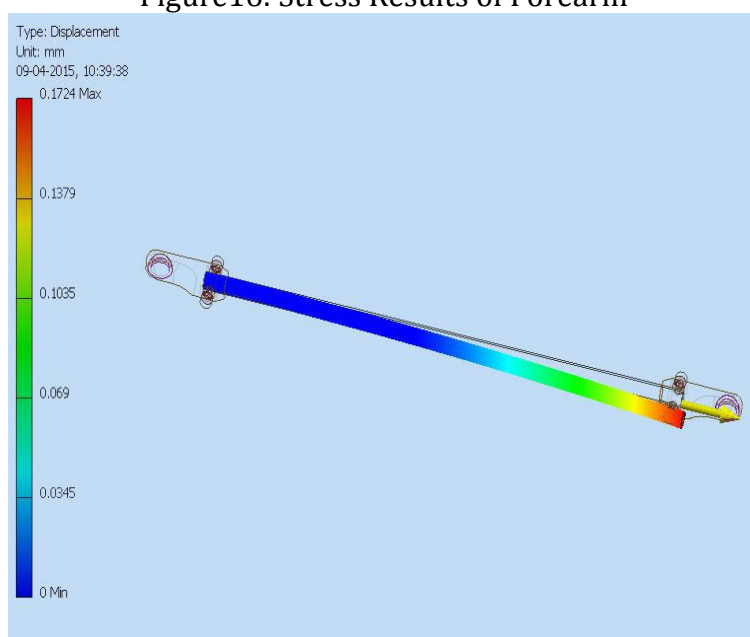


Figure 17: Deformation Results of Forearm

## **7. Conclusion and Future Work:**

The requirement of this paper was to design a Delta robot capable of carrying 1kg payload, achieving a cycle rate of 120 cycles per minute covering a work volume of 400x300x200 mm<sup>3</sup>. The kinematics and the dynamics of the delta robot were studied and the model was developed. The kinematic and dynamic analyses were done to meet the work volume and cycle time requirements respectively. The conceptual design for the delta robot was done to meet the necessary requirements. The various potential failure modes were identified by carrying out Design Failure mode and Effect Analysis (DFMEA). Once the failure modes were identified, the detailed design was done ensuring that failure does not occur. The kinematic and dynamic design of the delta robot has been completed for the desired work volume, speed and accuracy. The drawings were released for manufacturing. The electrical part of the project involves the design and programming of the control system. The control system has been decided to be a soft PLC provided by the industry. The control algorithm has to be implemented by programming the PLC.

The future work is to realize the robot in its physical form. In order to realize the robot in its physical form, a lot of material procurement is to be done and then the work will be to integrate the electrical and mechanical systems together and provide the end user with an easy-to-use user interface. The mechanical parts are likely to be fabricated within the industry and the electrical parts are to be optimally chosen and procured. Most of the mechanical parts will be fabricated within the industry itself except for a few parts like carbon fiber tubes for the arms which will be procured from other manufacturers. The electrical part of the robot will include servo motors and drives and the control system used to run them in an accurate and synchronized manner.

Once the system integration is complete, the robot system has to be put to test runs in real time operating conditions and the system has to be tuned accordingly. Apart from successfully integrating a working system, one has to provide the end user with a proper and easy-to-use interface. The interface is usually a compact HMI providing real time information about the robot or a teach pendant that is hand held by the user or both.

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