Development of 6 DoF Robotic Arm

A DISSERTATION

Submitted in partial fulfilment of the

Requirements for the award of the degree

of

BACHELOR OF TECHNOLOGY

in

MECHANICAL ENGINEERING

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CANDIDATE’S DECLARATION

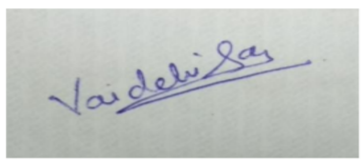
We hereby declare that the work presented in this dissertation entitled “**Development of 6 DoF Robotic Arm”**, submitted in partial fulfillment of the requirements for the award of the degree of **Bachelor of Technology** in **Mechanical Engineering** is an authentic record of work done by our own efforts with suitable acknowledgement to all references.

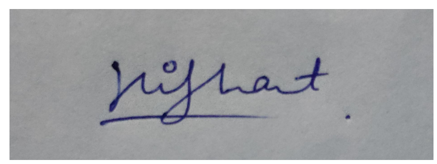
This work has been carried out by me/us/ under the supervision of **Dr. Vijay Pal**, Department of Mechanical Engineering, IIT Jammu during Feb 2021 to June 2021.

We have not submitted the matter embodied in this report for the award of any other degree or diploma to any other institute or university.

Date: 25/06/2021
Place: IIT Jammu

Vaidehi Som , Nishant Kumar





CERTIFICATE

This is to certify that the above statement made by the candidate is true, to the best of our knowledge and belief.

Dr. Vijay Pal
Mechanical Engineering, IIT Jammu.

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We are very thankful to our parents & all of our friends for their never ending encouragement in bringing out this dissertation report to the form as it is now.

Date : 25/06/2021

Place: IIT Jammu **Nishant Kumar, Vaidehi som**

ABSTRACT

Multi-degree of freedom robots are playing a very important role in Industries in various different applications from welding, material handling, and thermal spraying, to painting and drilling. Multi degrees of freedom are providing more work space and accuracy in carrying out a typical procedure as compared to the manual work done by humans. In recent years the design, fabrication and development of robotic arms have been active research areas in robotics all around the world.

This project describes a mechanical system, design concept and prototype implementation of a 6 degree of freedom robotic arm, which should perform industrial tasks such as pick and place of fragile objects operation and various other operations with the help of different end effectors. This robot arm is controlled by microcontrollers and it has a base which supports the whole assembly, a shoulder to provide movement and strength to the upper part, an elbow which increases the reach and workspace of the whole robotic arm, a wrist which comprises of 3 joint that can rotate at three different axes. A PID controller is implemented on each motor. The microcontroller implements forward kinematics and inverse kinematics for the position control of DC motors. This report aims to provide fine manipulation in performing pick and place tasks, while still maintaining the simplicity of design.

Contents

Nomenclature

J1 = Joint 1
J2 = Joint 2
J3 = Joint 3
J4 = Joint 4
J5 = Joint 5
J6 = Joint 6
DoF = Degree of Freedom
DH = Denavit–Hartenberg

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1. INTRODUCTION

In this modern era, the automation industries are growing rapidly with the huge demand in the development of advanced technology, so the chances of error and the speed of workability matters a lot. Now the huge demand is replacing the conventional methods and introducing much faster and accurate machines due to the same reason many industries are going towards the automation technology rather than the traditional methods. Robotic arm can be used from the aerospace to medical field due to its n number of applications like welding and surgical assistant.

Due to the increasing demand for the industrial robots, the engineers must design, simulate, and analyze the optimization of manipulator joints and end effectors using robot visualization software. The robotic arms are basically a combination of links and joints with some kinematic mechanisms where joints provide the allowable movements and links are used to increase the reach. It includes engineering principles and laws during the design and development of the robot. Exceptional design decisions are required while integrating complex components during the beginning of the design.

For the development and to manage the functionalities of a Robotic arm, combined knowledge is required in the field of mechanical, electrical, electronics, and computer software. To minimize the system complexity and functionalities of the system, various softwares help to visualise and optimize the robot system from the beginning of the process.

1.1 Objective of Robotic Arm

In this Project we design the robotic arm for 60cm reach and 6 degrees of freedom and manufacture all the components through a series of manufacturing operations and use various Kinematic models for the smooth motion of the arm. This Robotic Arm has a base which supports the whole assembly and provide rotation around z axis, a shoulder to provide movement to the elbow and strength to the upper part, an elbow which is used to increases the reach and workspace of the whole robotic arm and it also rotate the wrist of robotic arm, a wrist which comprises of 3 joint that can rotate at three different axes and provide the desired movement.

1.2 Components of Robotic Arm.

The following is an overview of the 5 component groups needed:

- **Structural components** - These components are basically the links and form joints.
  There are 27 structural components used in total in the building of this robotic arm.
- **Stepper Motors and Drivers** – There are in total 6 motors, drivers used for the building of this Arm. These motors drive the links with the help of gears and hardware components.
  Motors and Drivers are listed in **Appendix C.**
- **Hardware components** – This includes the bearings, belts, pulleys, sprockets, chain, shafts, pins, machine screws and set screws. These components help in the transmission and move the joints at specific or required positions.
  Hardware Components are listed in **Appendix D.**
- **Electrical components** –There are a lot of electrical components used in the building of this robotic arm. These components are used for power supply to motors and controllers and used to link the motors with controllers.
  Electrical Components are listed in **Appendix E.**
- **3D covers and spacers** - These are used to cover the links and joints and provide the space for the electrical wiring and helps in the better looking of the Arm.
  Covers and Spacers are listed in the **Appendix F.**

1.3 Applications of Robotic Arm

The robotic arm is used for multiple industrial applications here are some of them:-

- Robotic Arms are used in many industries for the uniform and fast welding.
- For the visual inspection and some operations inside a nuclear reactor where the radiation is high and can cause harm to human health robotic arms are used.
- During the surgery chances of contamination is increased so the man power is limited so robotic arms are used as a surgical assistant.
- Robotic arms are used to pick and place in industries as it is quite boring and robotic arms can do it fastly.
- Robotic Arms are used for filming also as it is quite stable on the other hand there are some vibrations and movement in the human body.

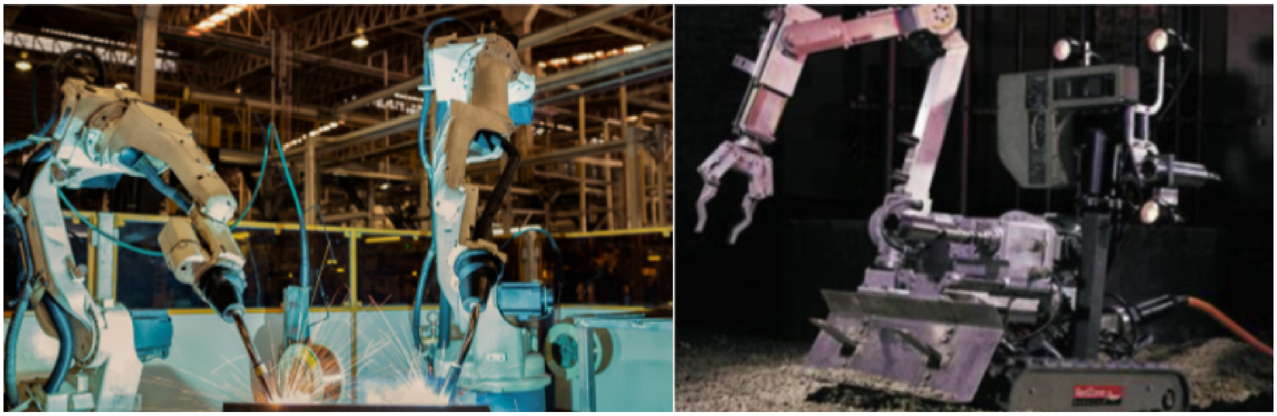

Fig 1.1 : Robotic arm is used for welding in Industries and inspection at Nuclear Sites

2. Literature Review

There are many complex processes involved in the process of robotic arms. Designing and movement of robotic arms are the major areas where a lot of work is required to be done. For the designing and development of robotic arms various kinematic models are used for the smooth functioning of the arm.

Majorly, two kinds of approaches are used to solve the problem of movement of the robotic arm: Forward kinematics and Inverse Kinematics.

2.1 Forward Kinematics:

Forward kinematics refers to the use of the kinematic equations of a robot to compute the position of the end-effector from specified values for the joint parameters.

The forward kinematics equations for the robotic arm are obtained by using a rigid transformation matrix[Z] to characterize the relative movement allowed at each joint and separate rigid transformation matrix[X] to define the dimensions of each link. The result is a sequence of rigid transformations alternating joint and link transformations from the base of the arm to its end effector, which is equated to the specified position for the end link,

$$[T] = [Z1][X1][Z2][X2][Z3][X3]\dots\dots\dots[Zn][Xn]$$

where [T] is the transformation matrix which is used to locate the position of the end effector.

2.2 Inverse Kinematics:

2.2 Inverse Kinematics: Inverse kinematics refers to the use of the kinematic equations of a robot to compute the joint parameters such as angles of joints of the robotic arm from the specified position of the end-effector in 3D space.

2.3 Configuration of Robotic Arms

There are five basic configurations of robots which are:

- **Cartesian Configuration (PPP):** It is the common industrial robotic arm that uses the cartesian coordinate system. It consists of three arms that each function along linear axes of control. Each of these axes is at a right angle to the other two.
- **Cylindrical Configuration (RPP):** These robotic arms are mainly used for cylindrical operations. These robots consist of one revolute and two prismatic joints.
- **Spherical Configuration (RRP):** These arms are presented by the Stanford University and it mainly consists of two revolute and one prismatic joint. All three joints are mutually perpendicular to each other.
- **Articulated/Anthropomorphic Configuration (RRR):** The articulated or joined arm looks like the human hand and it consists of three revolute joints.
- **SCARA Configuration (RRP):** SCARA (stands for selective compliant articulated robotic assembly) mainly consist of two revolute and one prismatic joint that are parallel to each other.

3. Mechanical Design

It is the designing process through which the components of mechanical nature are designed which can provide the desired output as per the requirement of the user. Mechanical design provides establishment of the completely new machine or it can lead to up-grade or enhancement of the current machines that can provide the better results.

Aim is to design a 6 degree of freedom robotic arm with the maximum workspace and reach 60 cm with minimum weight and it should carry fragile objects from one place to desired place. So an Articulated + spherical model is selected for the same purpose because this model is widely used in the industrial sector. By using the CAD software we analyze forces/torque that how much torque/force is required at each joint to move the manipulator and find stresses to ensure that it is under limit and will not damage the component.

The robotic Arms mainly consists of joints and links that form a complete assembly. Joints can be defined as two links meet up points which allow the movement in between the links.

While links are the rigid segments that construct the mechanism and provide reach to the end effector and provide the desired output. Free body diagram of 6 axis robotic arm as shown in figure 3.1

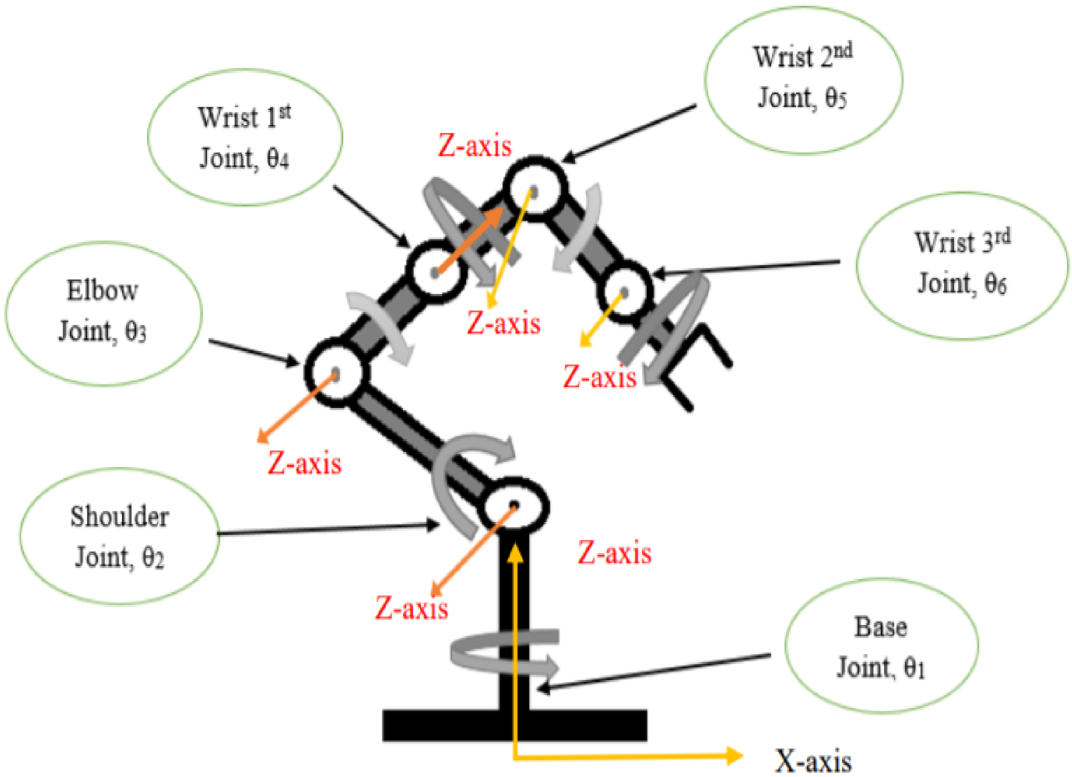

Fig 3.1: Free body diagram

3.1 Material Selection

In any mechanical design and manufacturing process material of selection is one of the important considerations. Aluminium is the material of choice for this robotic arm due to various factors.

- **Ease of Manufacturing -** As we also have to manufacture all the parts so took it into consideration that the cutting of aluminium is easy as compared to steel or iron. And it can be cut into shape and size.

- **Corrosion Resistance -** As we are working under a tolerance limit of +- 0.002mm so we can't put any other layer of paint or lubricant. so the material of choice should have corrosion resistance. As compared to iron, aluminium has higher corrosion resistance when it is exposed to air or humid conditions a layer of oxide is formed which protects it from corrosion.

- **High Strength to weight ratio -** The strength to weight ratio of Aluminium is higher than even of steel.

- **Availability of Material -** Due to covid the availability and shipping of materials is hard. So Aluminium is the easily available material in the market.

Properties	**Aluminum (EN14286)**
Density (kg/m^3)	2660
Elastic Modulus (MPa)	70300
Poisson's Ratio	0.3
Tensile Strength (MPa)	125
Ultimate Strength (MPa)	275
Allowable Maximum Stress (MPa)	93.75

Table 3.1: Mechanical Properties of Aluminium

3.2 SolidWorks Model of 6 Axis Robotic Arm

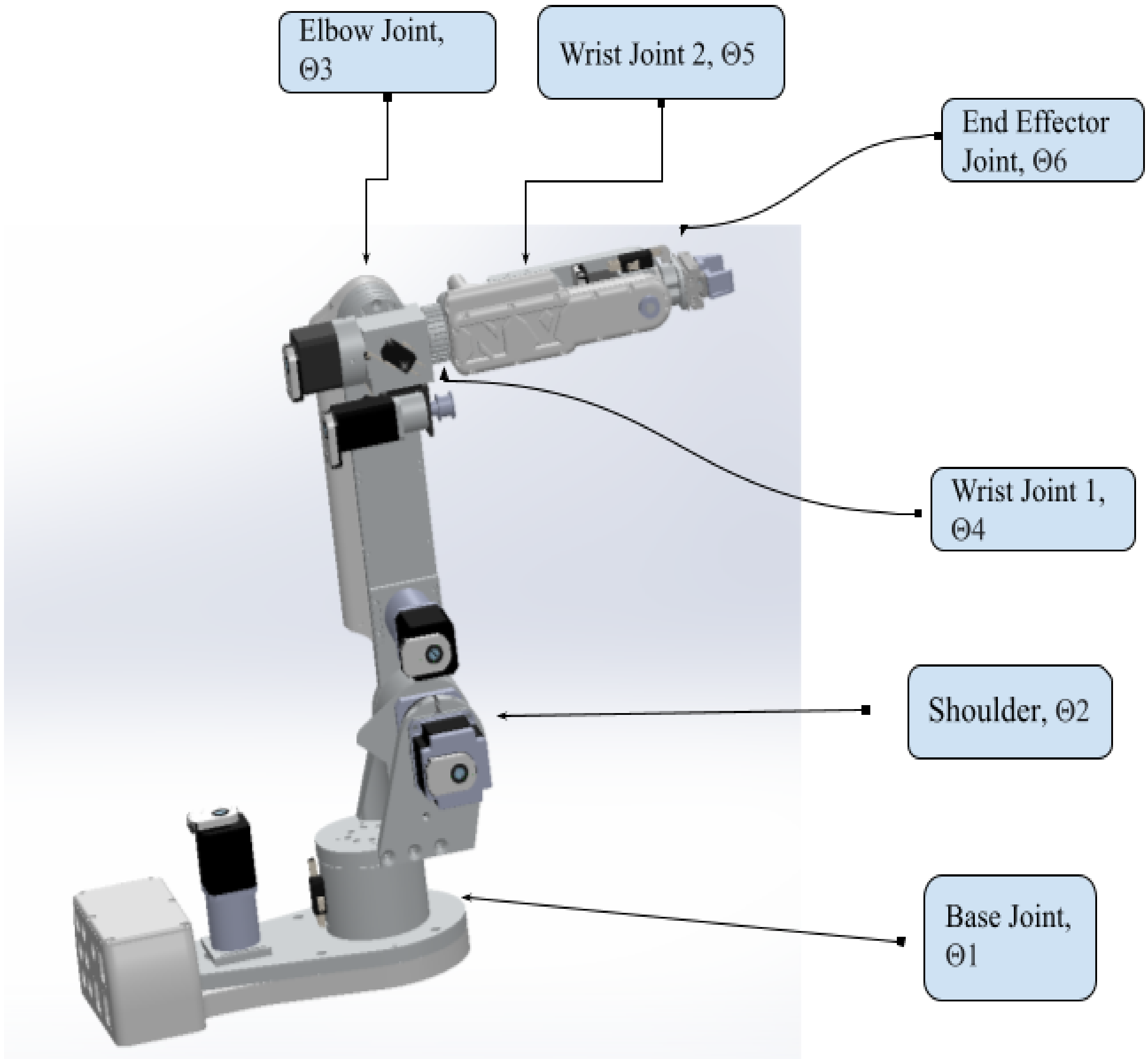

Fig 3.2: Complete CAD Model of Robotic Arm

3.2.1 Base of Robotic Arm

It is used to support the arm and to rotate the whole robotic arm around the z-axis.

It consists of a base plate, Motor mounter, Spindle, Turret Housing, Turret Platform.

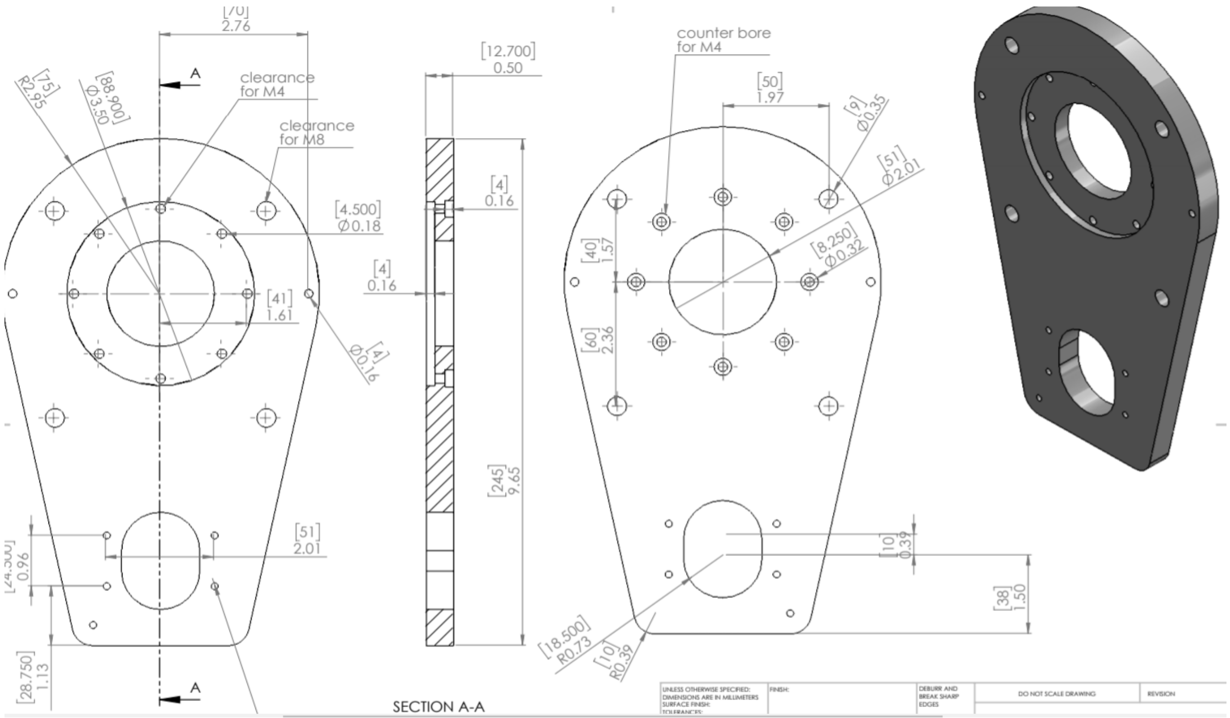

Fig 3.3: Base Plate

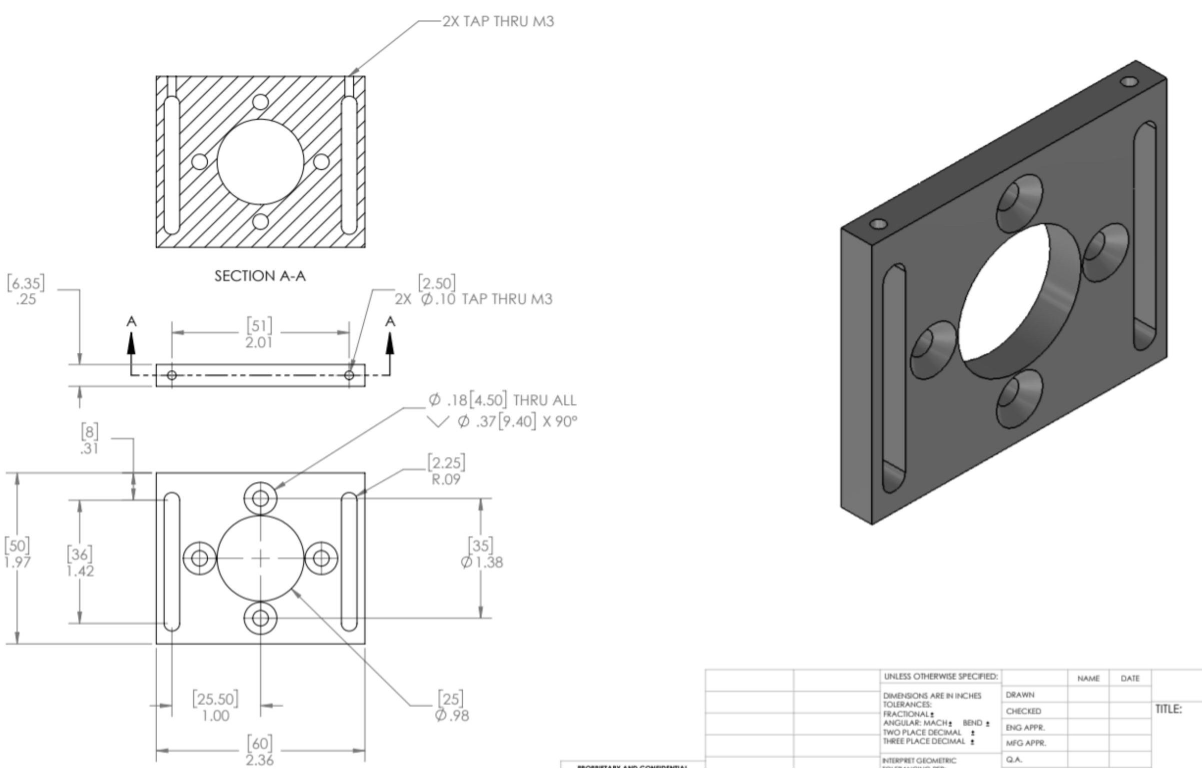

Fig 3.4: Motor Mounter

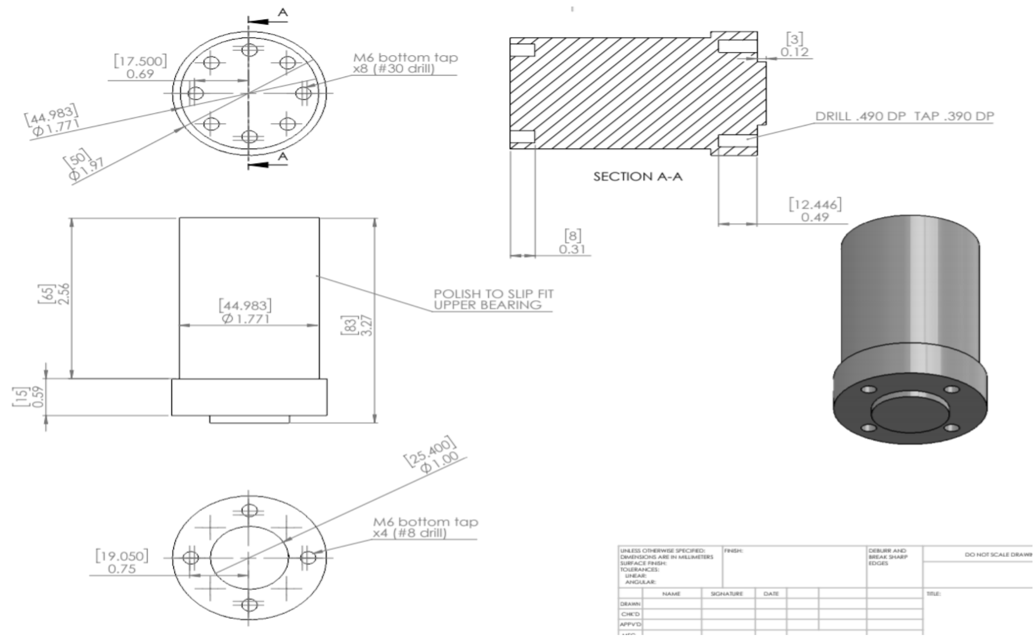

Fig 3.5: Joint 1 Spindle

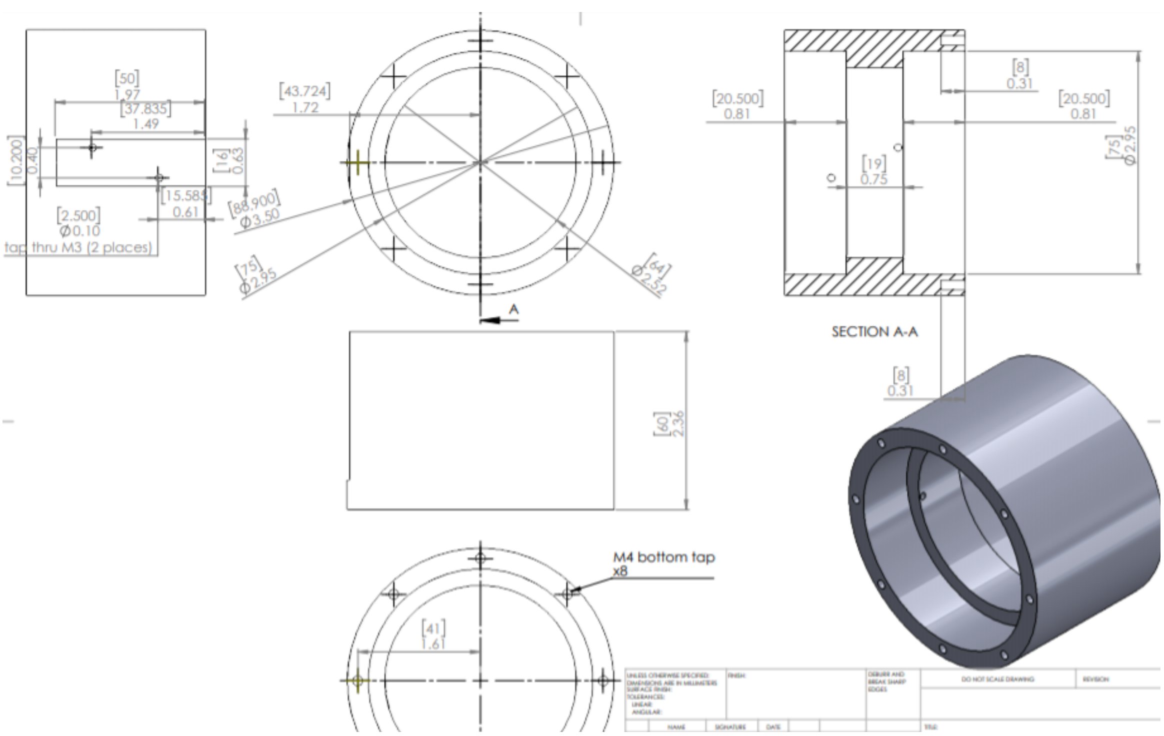

Fig 3.6: Joint 1 Turret Housing

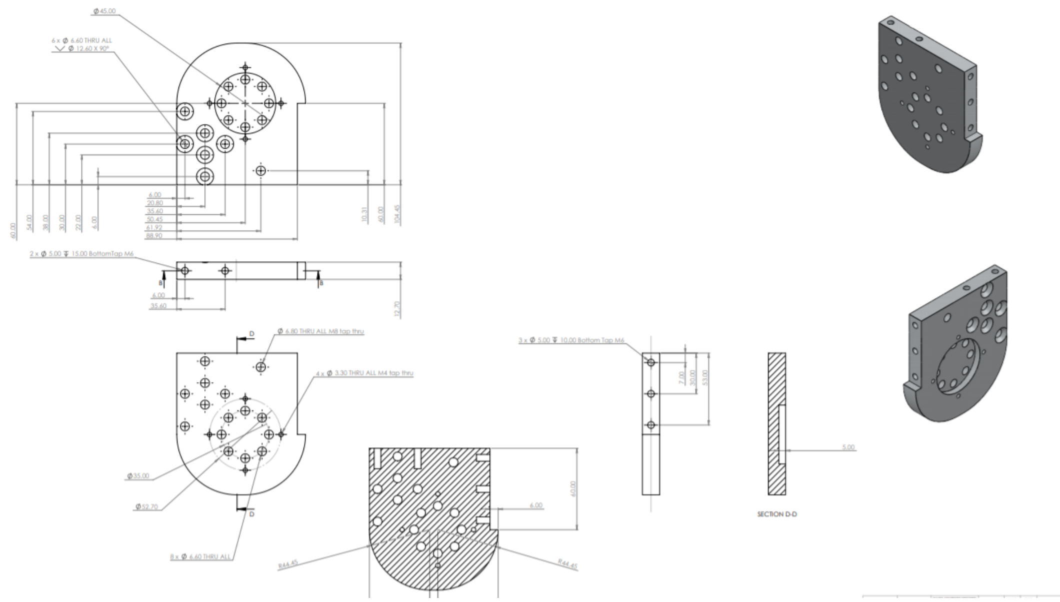

Fig 3.7: Joint 1 Turret Platform

3.2.2 Shoulder Of Robotic Arm

It consists of Turret Platform, Turret Housing, Motor Support and a Tension Ring. It provides the rotation around joint 2.

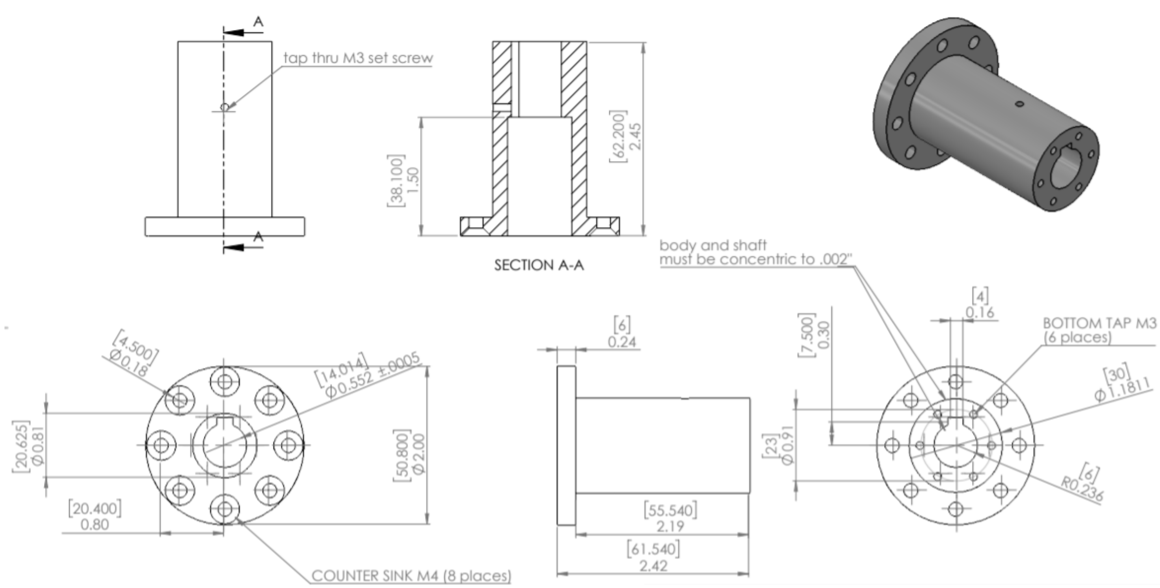

Fig 3.8: Joint 2 Drive Spindle

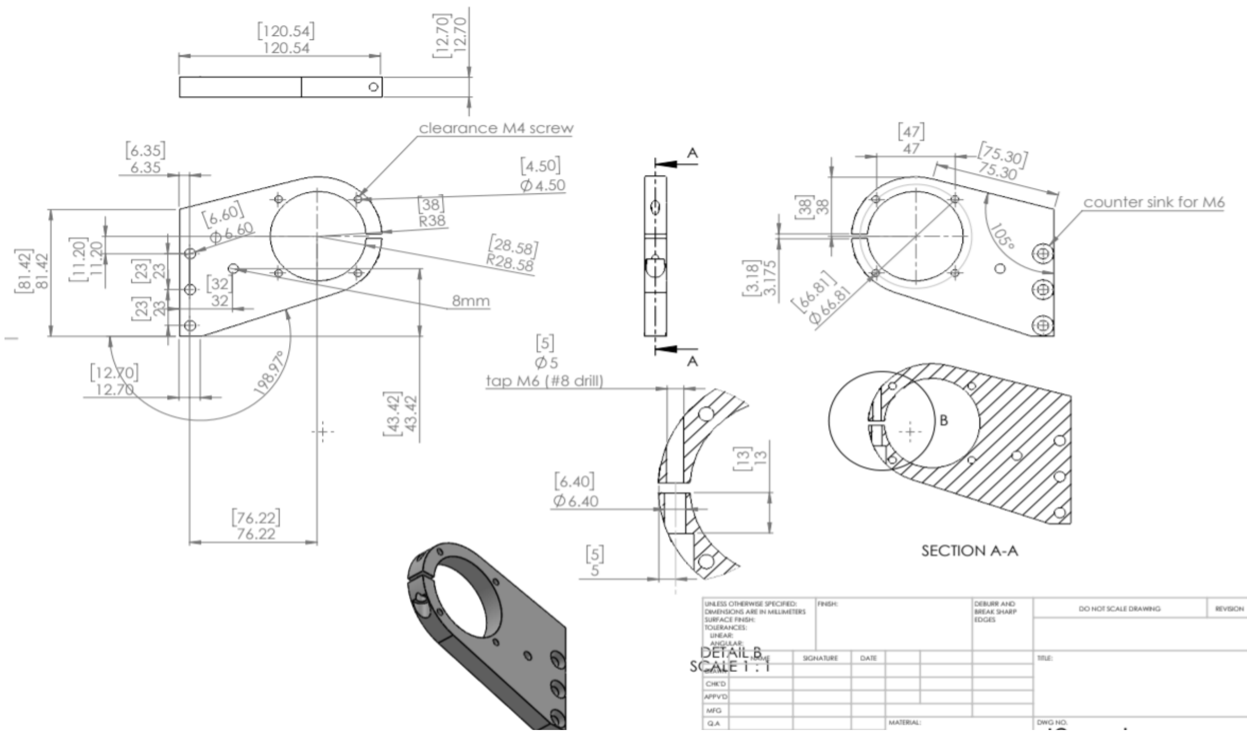

Fig 3.9: Joint 2 Motor Support

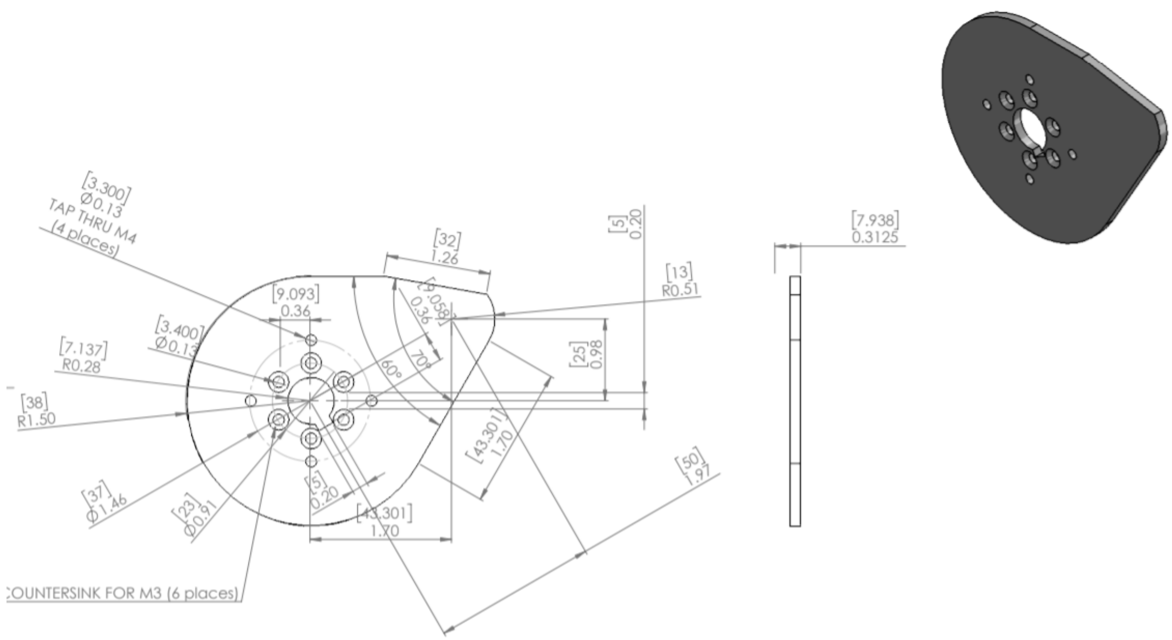

Fig 3.10: Joint 2 Tension Ring

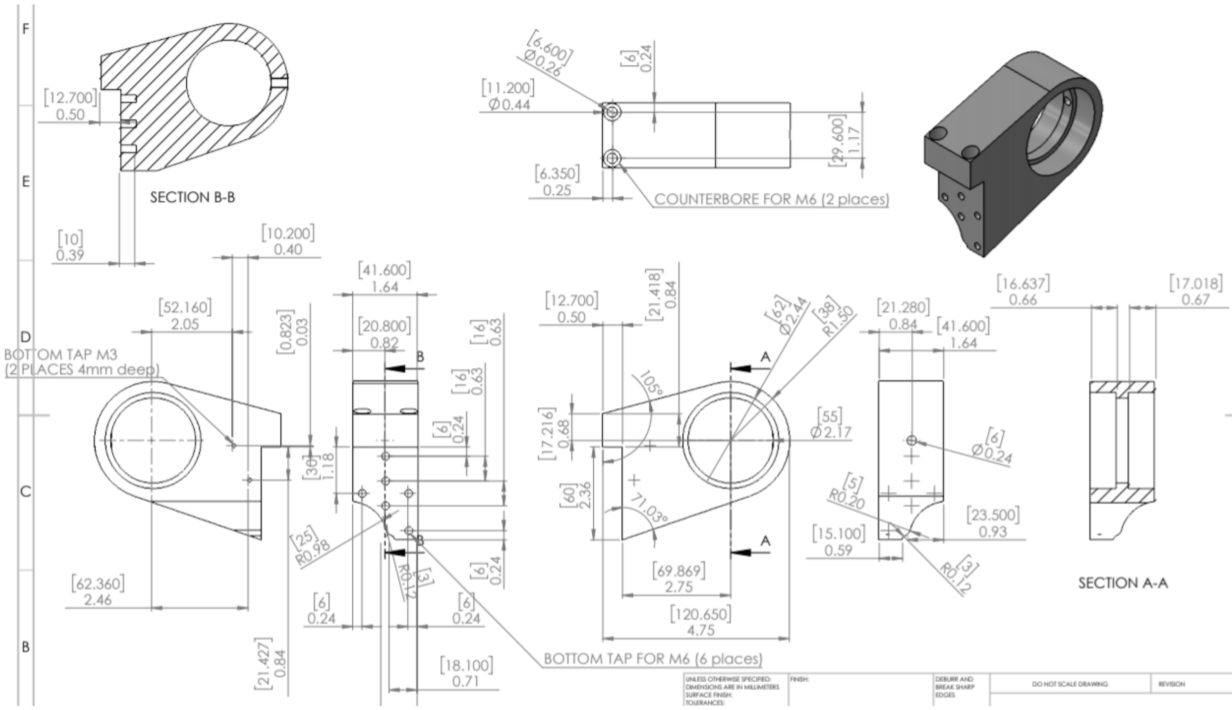

Fig 3.11: Joint 2 Turret Housing

3.2.3 Elbow of Robotic Arm

It provides the reach to our robotic arm and rotates the arm at joint 3. It consists of a arm, bearing cap, Spindle retainer, spindle and a motor support.

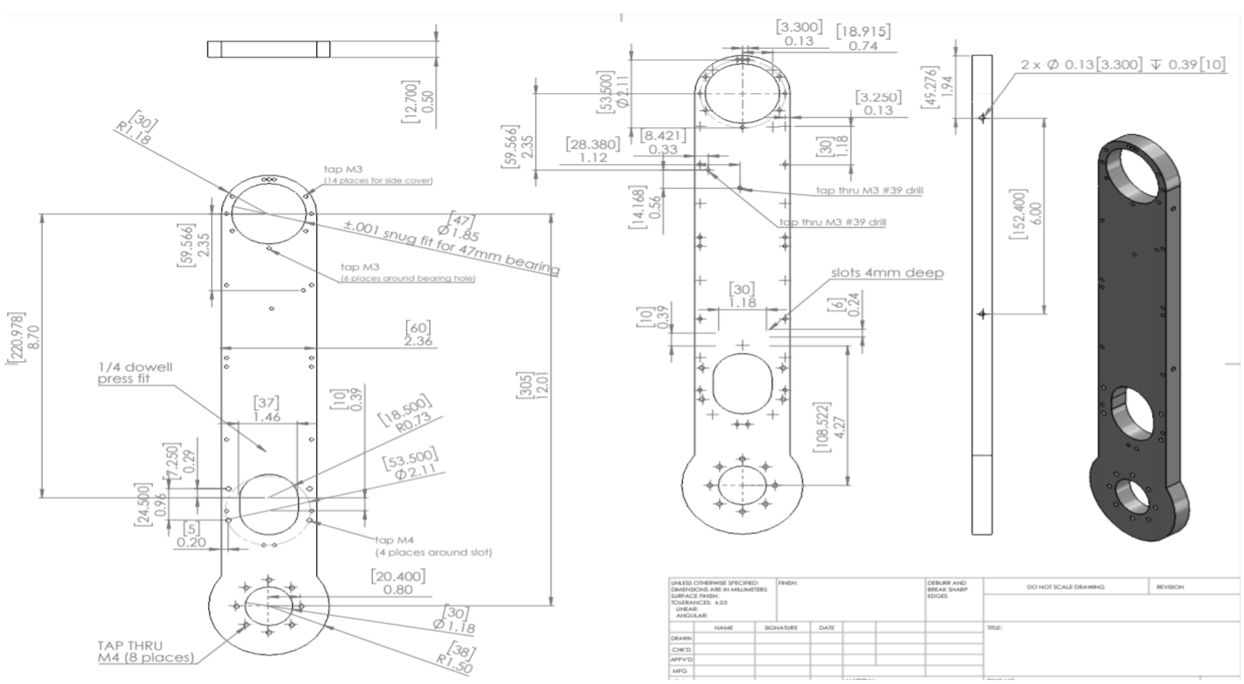

Fig 3.12: Joint 2 Arm

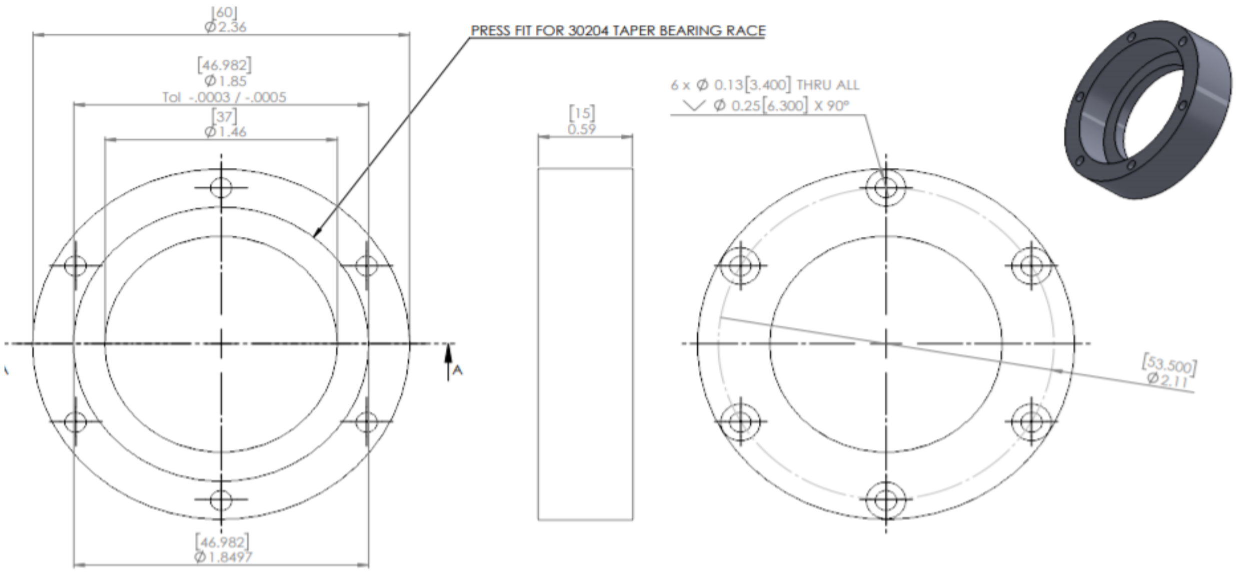

Fig 3.13: Joint 3 Bearing Cap

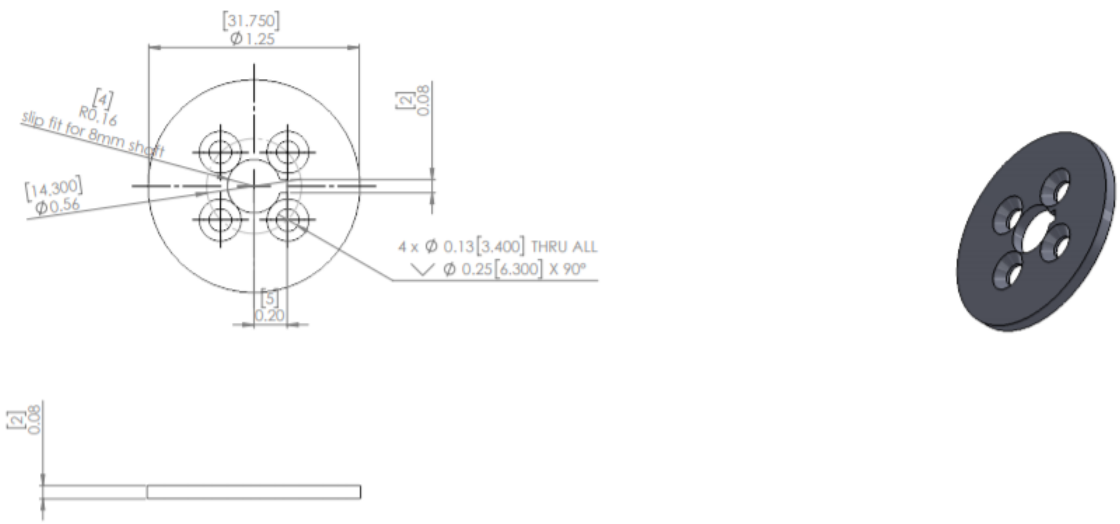

Fig 3.14: Joint 3 Spindle Retainer

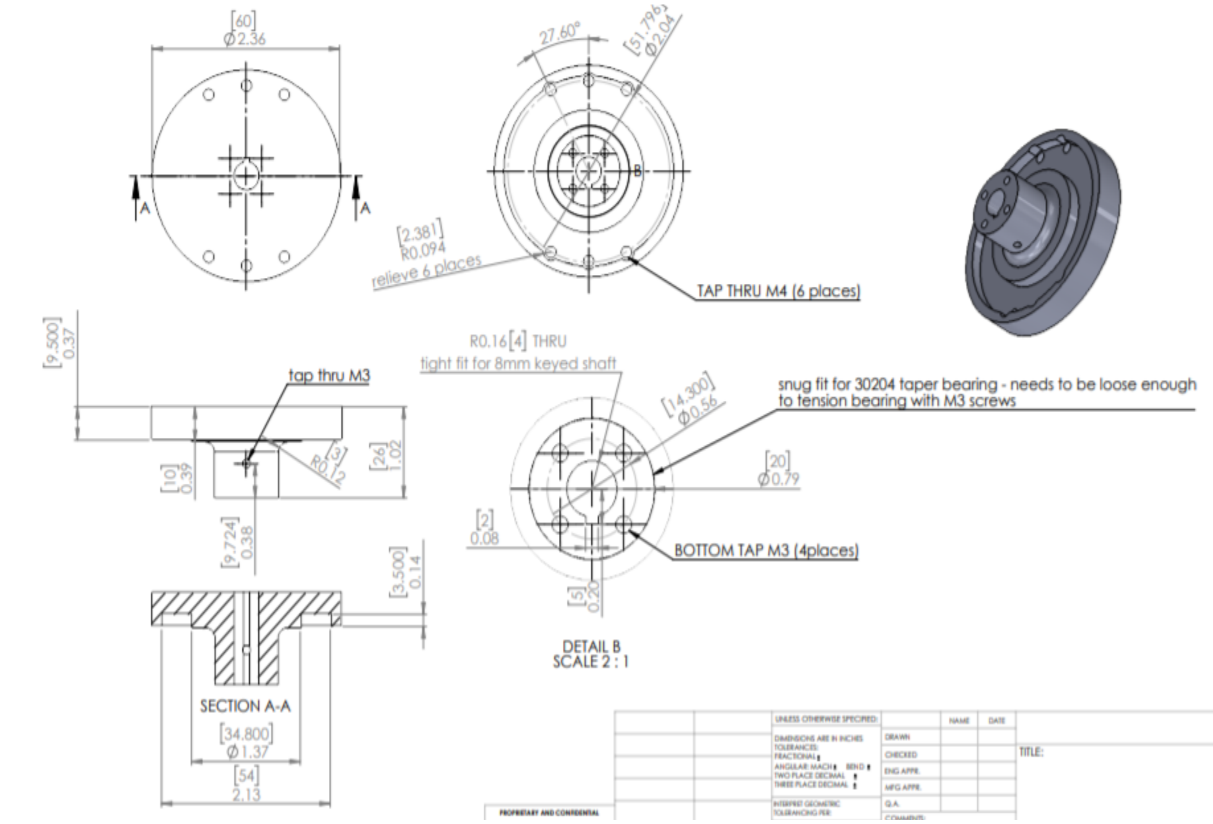

Fig 3.15: Joint 3 spindle

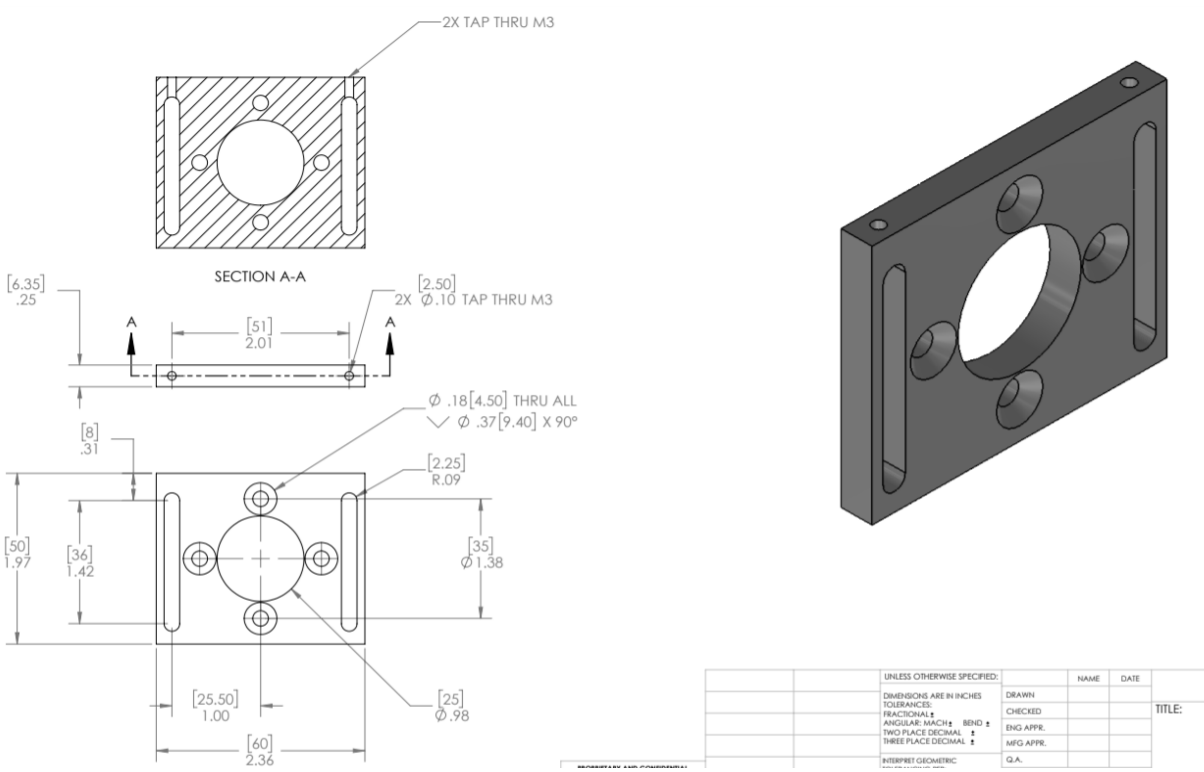

Fig 3.16: Joint 3 Motor support

3.2.4 Wrist of Robotic Arm

It is a combination of 3 different joints which can rotate the arm around 3 different axes. It consists of

- ➢ Joint 4 main shaft, Joint 4 Housing, Joint 4 motor Mount
- ➢ Joint 5 bearing post, Joint 5 belt carrier clamp, Joint 5 belt carrier, Joint 5 housing, Joint 5 Idler tension block, Joint 5 Motor Mount
- ➢ Joint 6 Bearing Cap, Joint 6 Housing, Joint 6 gripper mount and a Joint 6 Bearing Arm

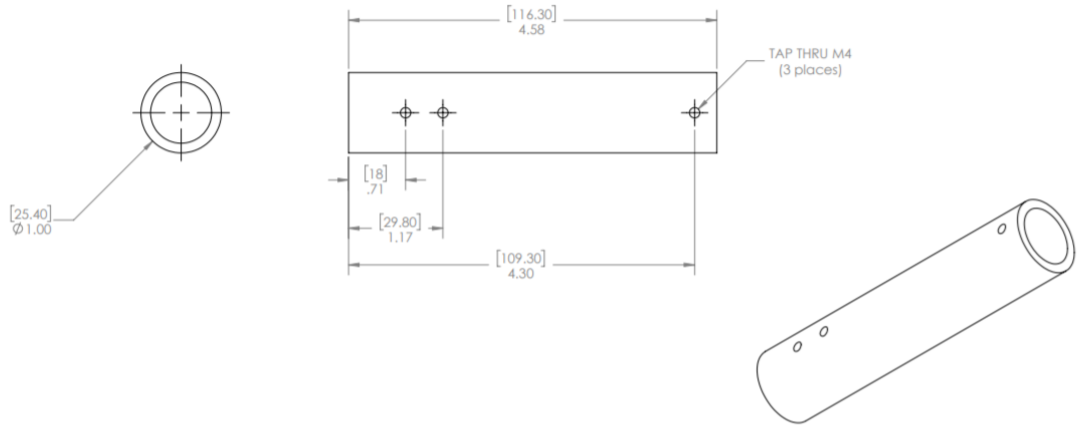

Fig 3.17: Joint 4 main shaft

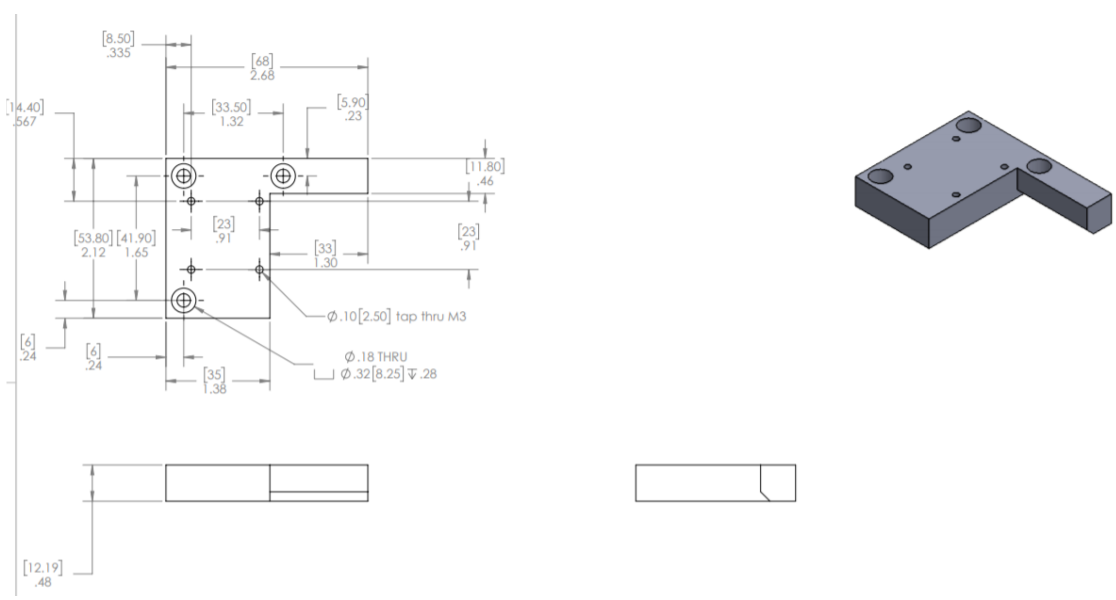

Fig 3.18: Joint 4 motor mount

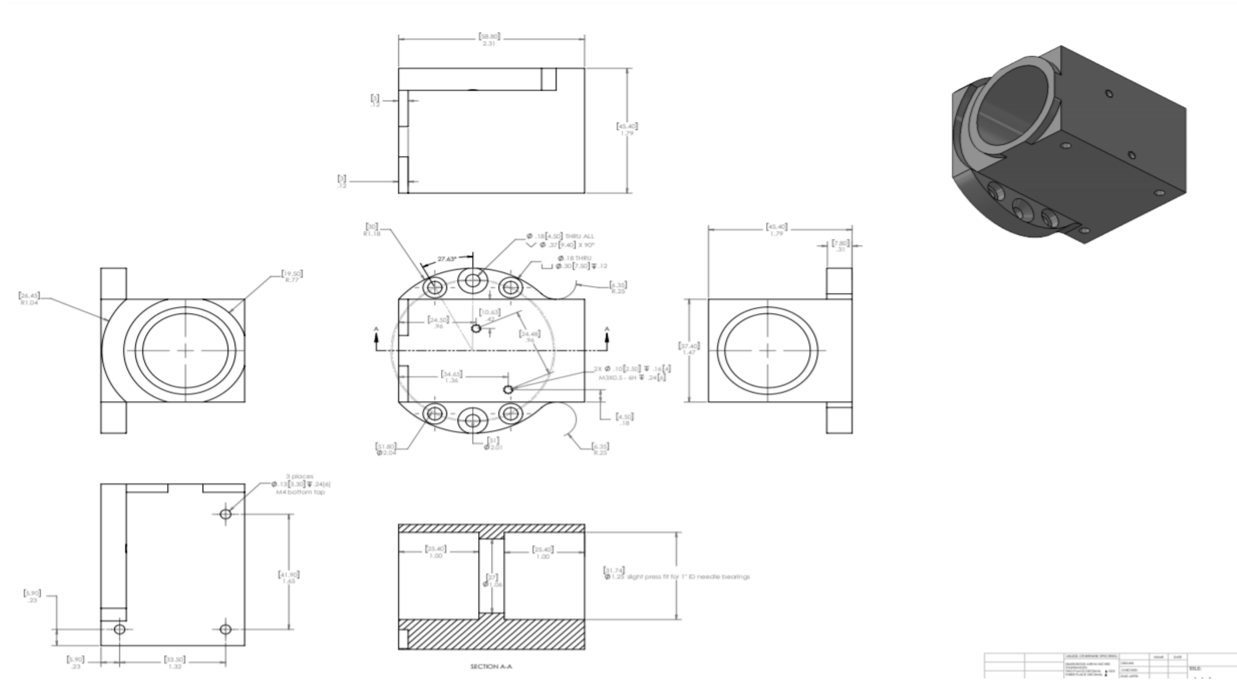

Fig 3.19: Joint 4 Housing

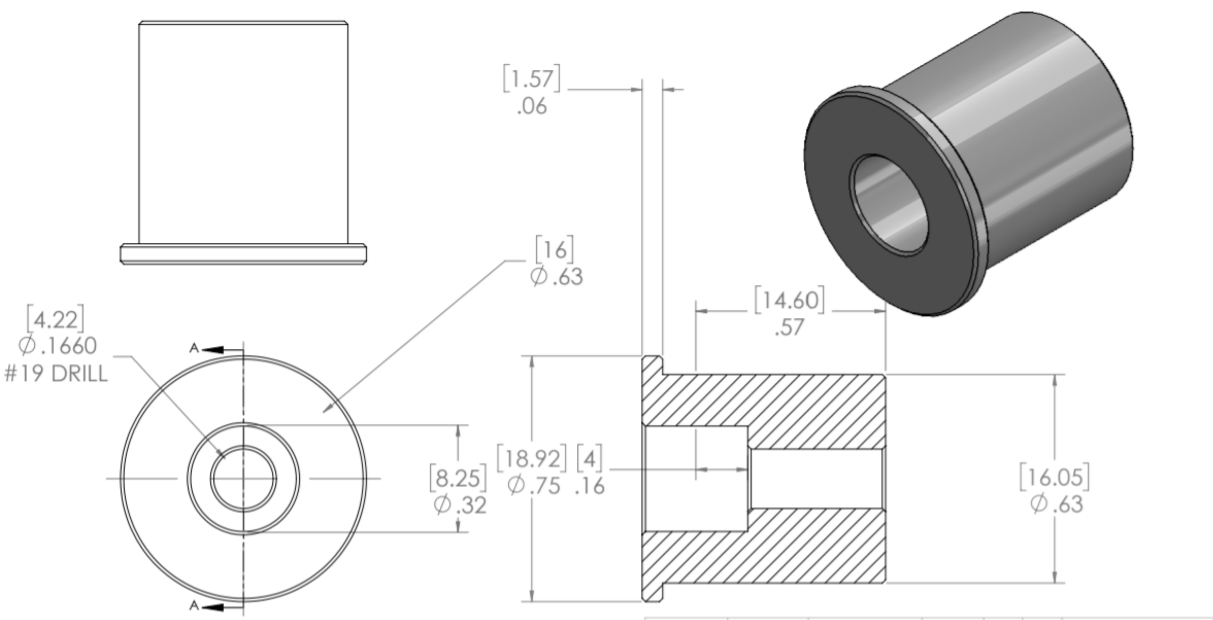

Fig 3.20: Joint 5 Bearing Post

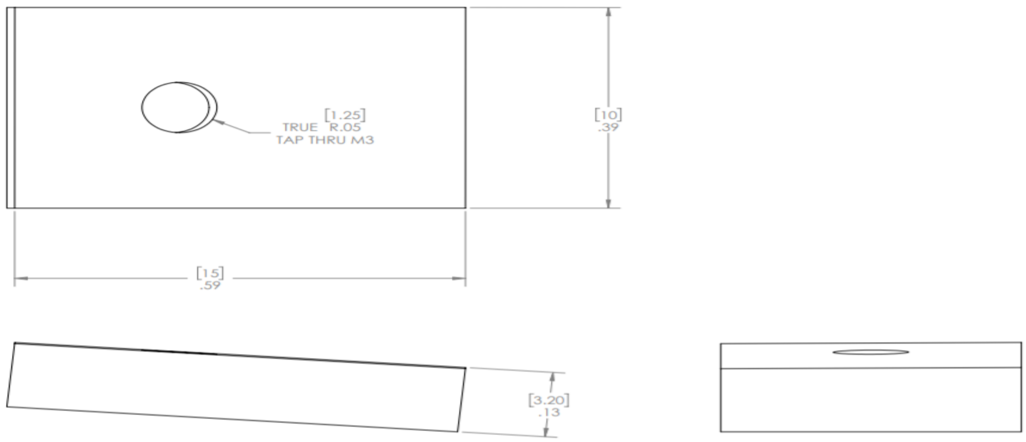

Fig 3.21: Joint 5 Belt Carrier Clamp

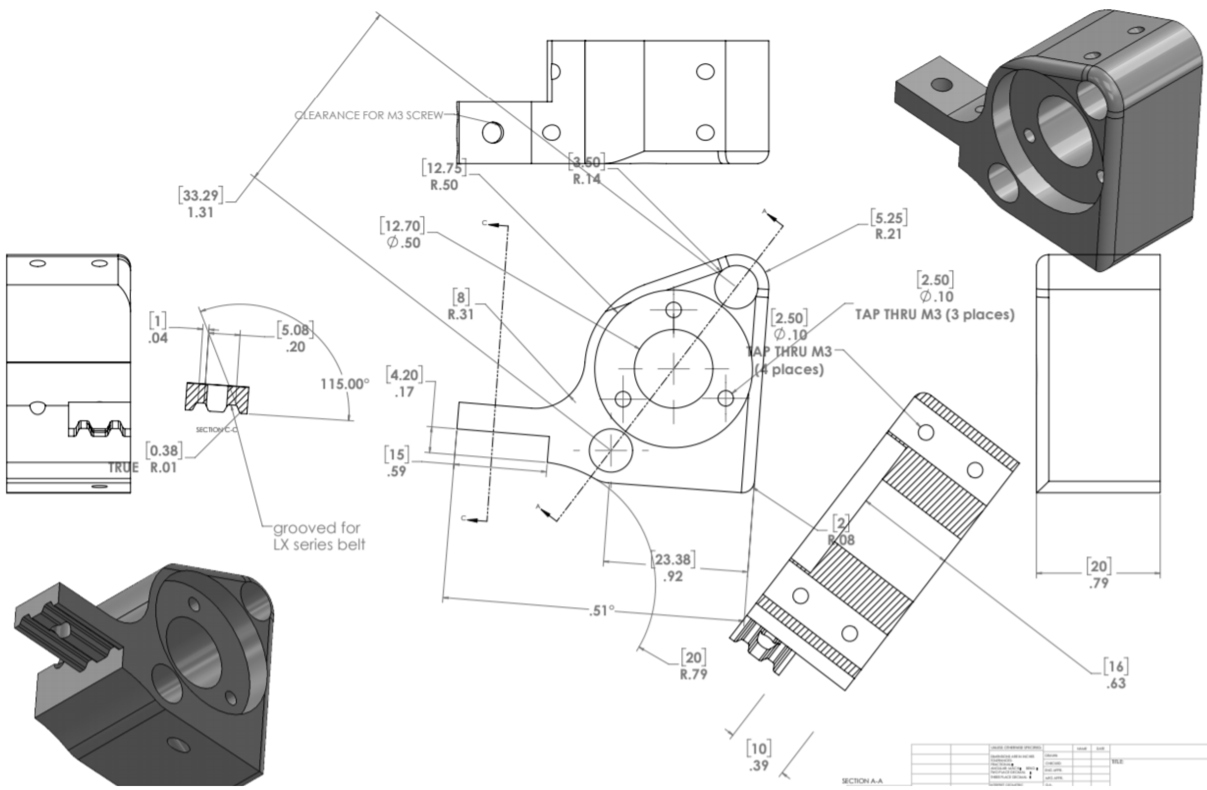

Fig 3.22: Joint 5 Belt Carrier

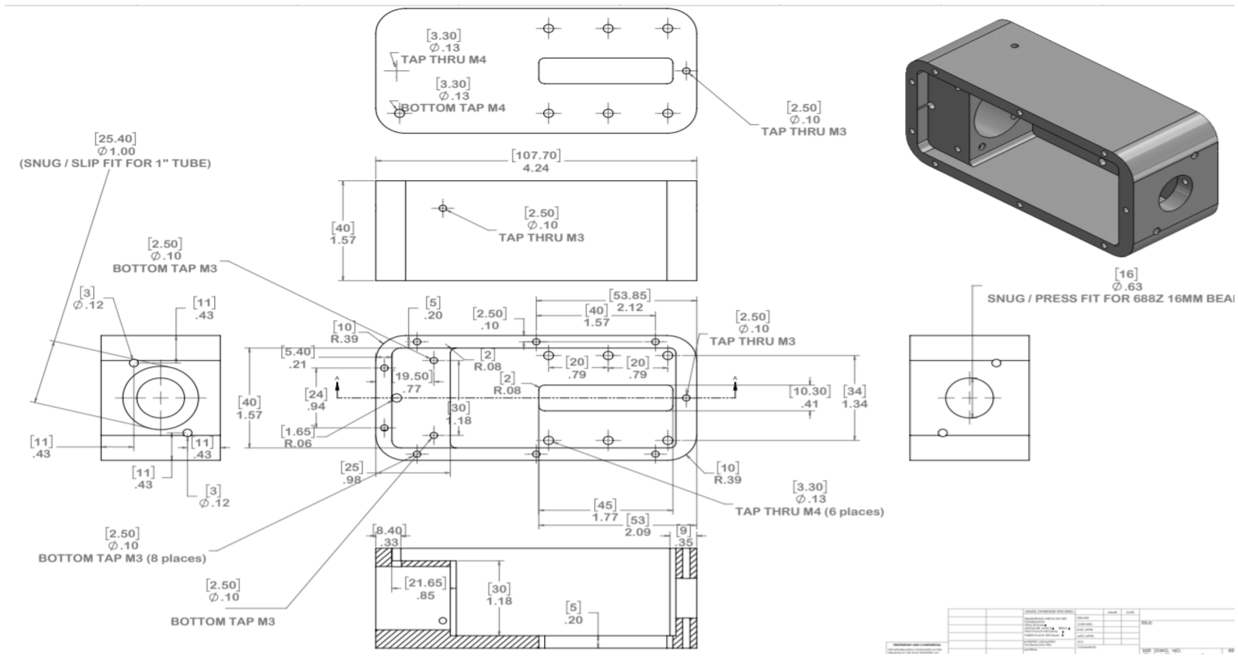

Fig 3.23: Joint 5 Housing

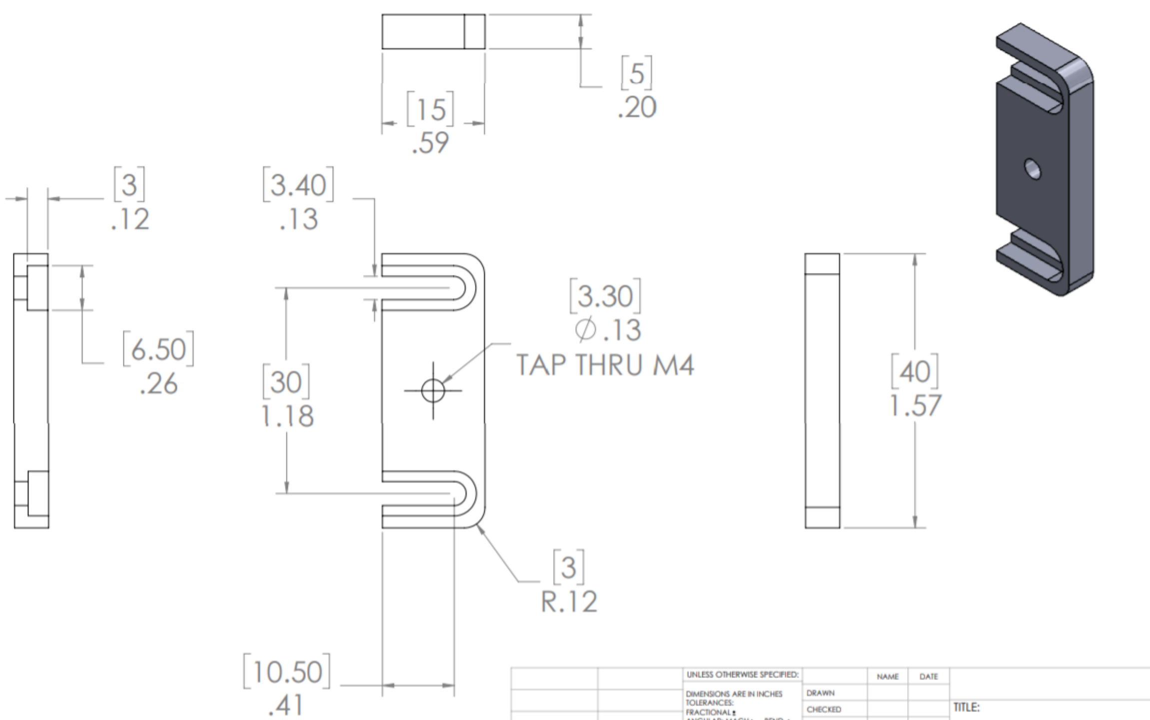

Fig 3.24: Joint 5 Idler Tension Block

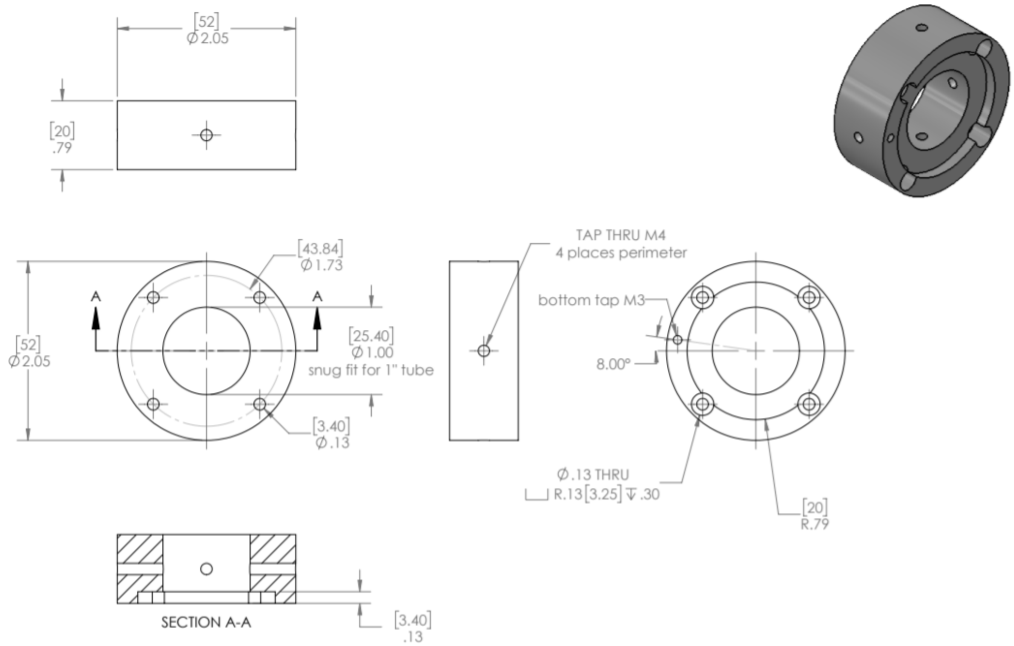

Fig 3.25: Joint 5 Motor mount

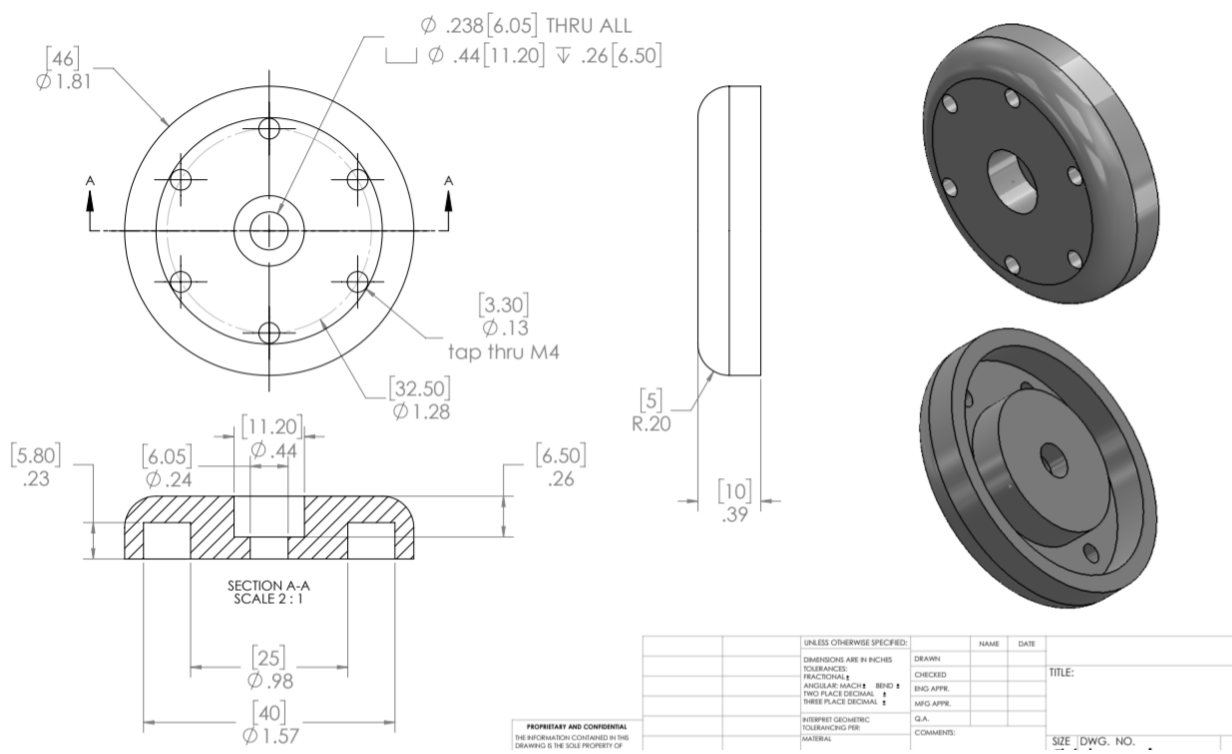

Fig 3.26: Joint 6 Bearing Cap

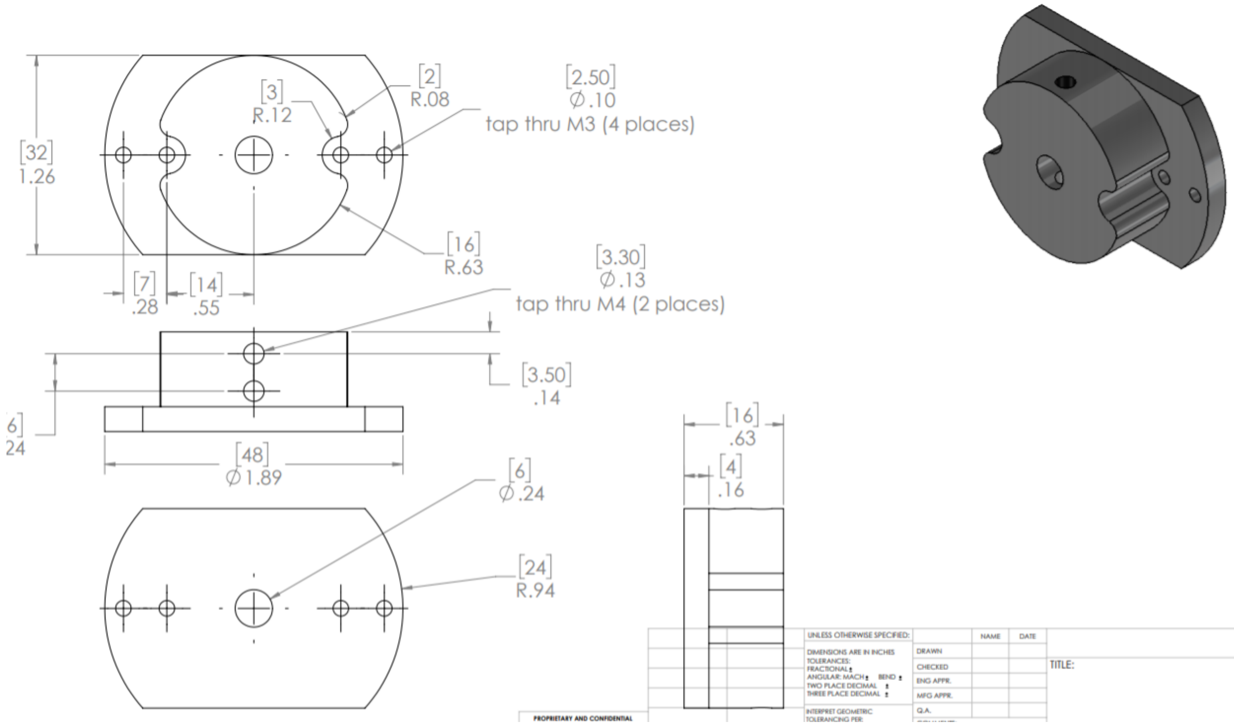

Fig 3.27: Joint 6 Gripper Mount

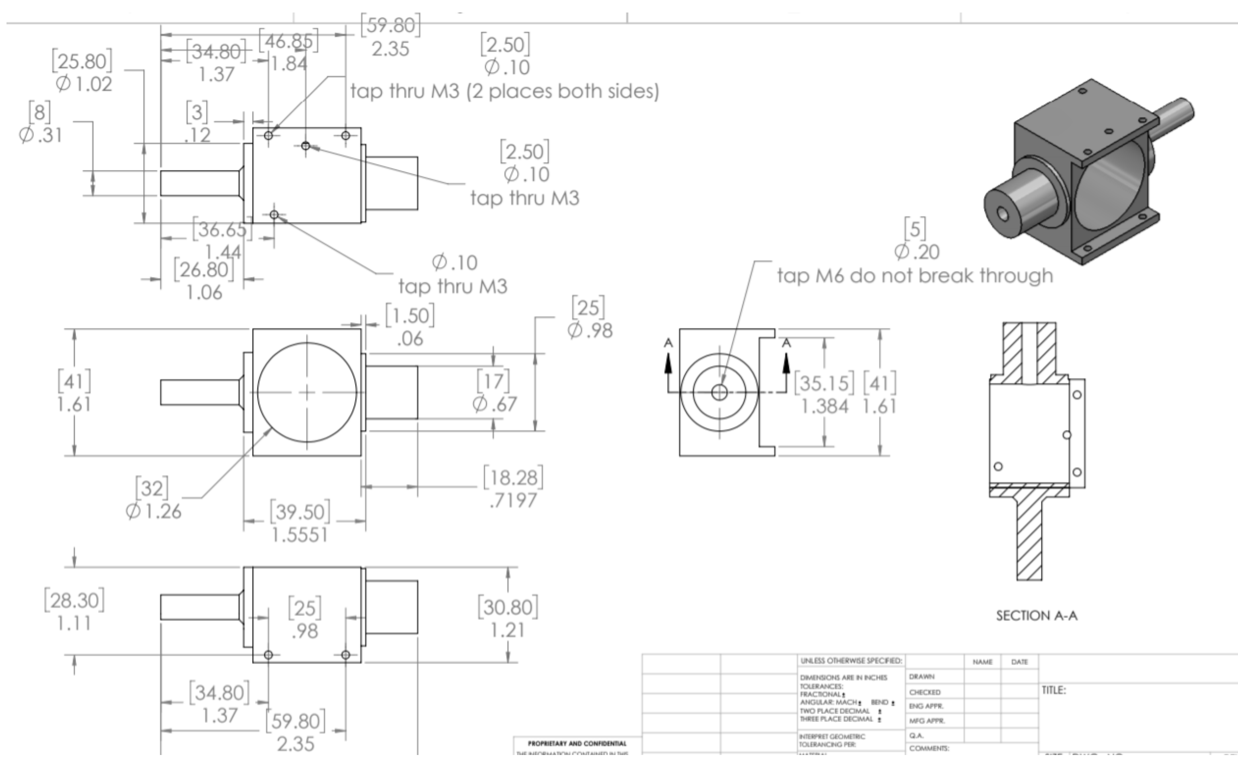

Fig 3.28: Joint 6 Housing

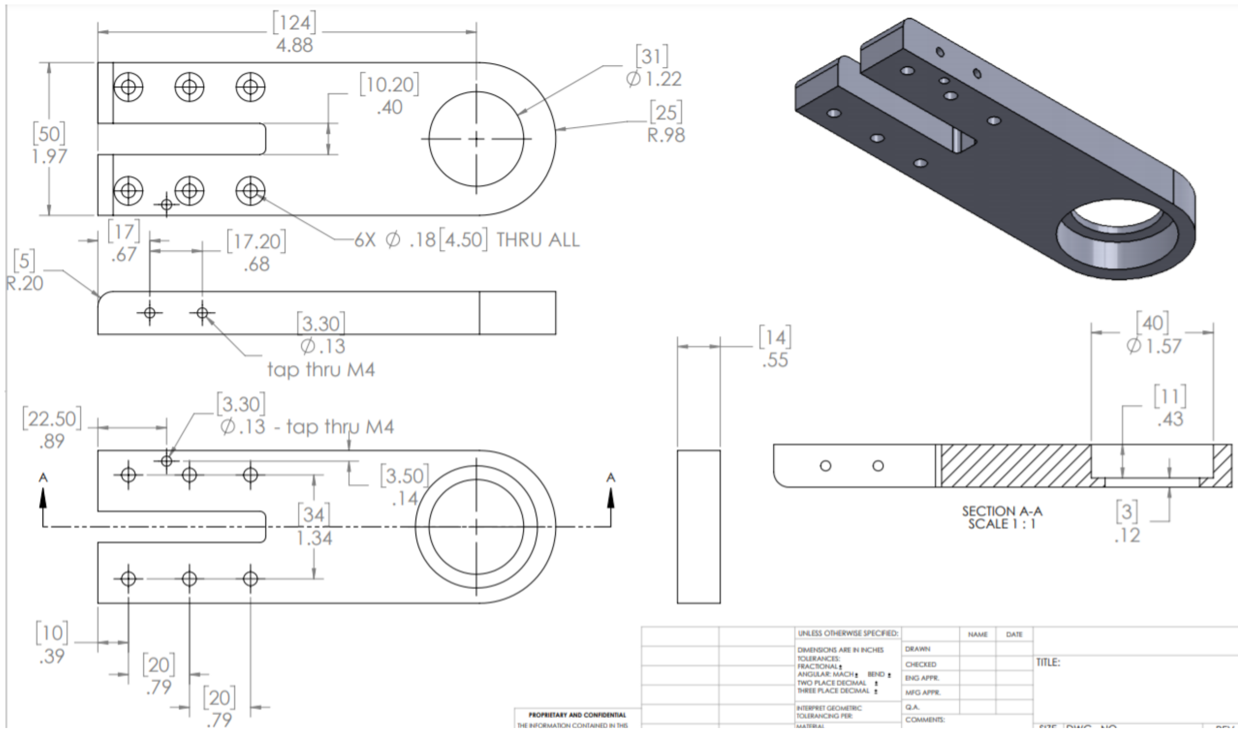

Fig 3.29: Joint 6 Bearing Arm

3.3 Specifications of Arm

Link	Min Angle	Max Angle	Angle Covered
1	-170	170	341
2	-129	0	130
3	1	143	143
4	-164	164	329
5	-104	104	209
6	-148	148	297

Table 3.2: Angle covered by links in degrees

Reach = 24.75 inches = 62.9cm, Weight = 12.25 Kg

Max power Consumption = 8.25 Amp (198 watt)

4. Kinematics & Dynamics of Robotic Arm

Kinematics is the branch of science that examines the movement of manipulator links without regard to the forces that cause it. In that case the motion is determined with trajectory, i.e. position, velocity, acceleration, jerk and additional higher derivative terms. Dynamics deals with the relation between the applied forces/torques and the resulting motion of an industrial robotic arm.

4.1 Forward Kinematics: Forward kinematics deal with the problem of finding end-effector position and orientation with the help of given joint Parameters. There are two methods used for solving forward kinematics equations homogeneous transformation and Denavit–Hartenberg

Most commonly method used for solving forward kinematics is DH transformation which based on four parameter as

θ	It is the joint angle and the amount of rotation around the current z-axis needed to align the previous x-axis with the current x-axis.
α	It is a twist angle between current z-axis and previous z-axis.
d	It is the link offset length measured along the z-axis
a	It is the link length which measure between current x-axis and previous x-axis

Using convention, each homogeneous transformation A_i is represented as a product of four basic transformations matrices

$$A_i = Rot_{z,\theta i} * Trans_{z,di} * Trans_{x,ai} * Rot_{x,\alpha i}$$

$$A_i = \begin{bmatrix} c\theta i & -s\theta i c\alpha i & s\alpha i s\theta & a i c\theta i \\ s\theta i & c\theta i c\alpha i & -c\theta i s\alpha i & a i s\theta i \\ 0 & s\alpha i & c\alpha i & di \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$c\theta i = \text{Cos}\theta i \text{ , } s\theta i = \text{Sin}\theta i, \ c\alpha i = \text{Cos}\alpha i \text{ , } s\alpha i = \text{Sin}\alpha i$$

DH parameter Table

DH parameters	Joint angle	Twist angle	Link offset	Link length
Joint	**Θ**	**α**	**d**	**a**
1	0	-1.570796327	169.77	64.2
2	-1.570796327	0	0	305
3	0	1.570796327	0	0
4	0.0001745329252	-1.570796327	-222.63	0
5	0.0001745329252	1.570796327	0	0
6	3.141767187	0	-36.25	0

Table 4.1 : DH parametric Table

After calculating all the basic transformation matrices, A single transformation matrix from base link to the end-effector link should be chained and multiplied to find the position and orientation of the end-effector for a 6-DOF robotic arm in 3D space, in the same order as below:

$$T = A_1 * A_2 * A_3 * A_4 * A_5 * A_6$$

Transformation Matrix for the forward Kinematics is represented in **Appendix A**

4.2 Inverse Kinematics:

In this case the end effector position is given and we need to find the joint angles through a series of calculations. As the number of DoF increases the amount of inverse kinematics solution also increases.

For six DoF we decouple the robotic arm into two parts Inverse Position and Inverse Orientation.

Inverse position kinematics deals with finding 1st three joint angles while the rest of three (spherical wrist joints) deal by inverse orientation.

For the given set of parameters inverse kinematics are mathematically solved in **Appendix D** to calculate the angles between the joints.

4.3 Jacobian Velocity

The Jacobian matrix helps to find out the relationship between the linear and the angular velocity of the end effector to the velocity of joints. As we have the x and y from the forward kinematics so by partial differentiation of x and y with respect to the yield matrix we can get the jacobian matrix.The jacobian matrix is a function of joint position that linearly related joint velocity to tool point

velocity. The Jacobian matrix is represented by a notation J.

$$\begin{bmatrix} v \\ \omega \end{bmatrix} = J(q_1, q_2, \dots \dots, q_n) \begin{bmatrix} q_1 \\ q_2 \\ \vdots \\ q_n \end{bmatrix}$$

v = Linear Velocity, ω = Angular Velocity

4.4 Singularities

Singular configurations of 6 DoF robotic arms can be determined by using the jacobian matrix. A configuration in which a robotic arm loses one or more degrees of freedom is said to be a singular configuration. There are many ways to avoid the singularity from a system, for example to design a robotic arm in such a way that the end-effector cannot pass through these points which leads to singular configuration. It can also be achieved by defining specific variables into the programming. Singularity of 6 DOF can be found out by decoupling the jacobian matrix into two portions, first three joints and spherical wrist joints.

$$J = \begin{bmatrix} J_{11} & 0 \\ J_{21} & J_{22} \end{bmatrix}$$

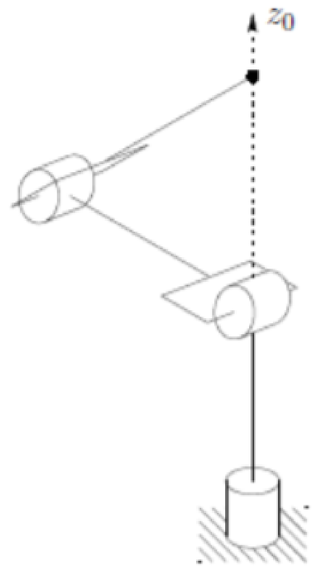

Fig. 4.1 : Singular Configuration

In the case of spherical wrist, due to the revolute joint, the linear velocity Jv term is zero as we calculate it from the jacobian matrix. So arm singularity can be calculated using relation det($J11$) = 0 While for wrist singularity use relation det($J22$) = 0

Singular configuration can be avoided by defining the specific angles.

5. Hardware Components Module

5.1 Stepper Motors and Drivers –

As we need the precise position of the end effector so for the same we use stepper motors in the building of this project**.** In total 6 steppers motors are used with different torques and gear ratio as per the requirement at each link.

Motor drivers are used to control the speed and direction of the motor. These are connected with the Teensy 3.5 and get data from the controller and provide to the stepper motor. Two different types of drivers (in total 6) are used in this project that enables the stepper motor to function the way it should be done.

Motors and Drivers are listed in **Appendix C.**

5.2 Controllers –

Controllers are like the brain of this robotic arm. The controller connects with another machine and decides the function that should be done. The Arduino Mega 2560 and

Teensy 3.5 are the controllers used for this project due to their low cost and both can accept 5vdc inputs and outputs.

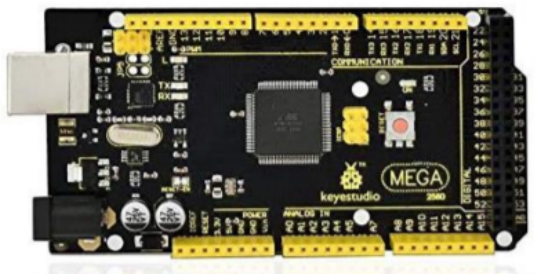

Fig 5.1 : Arduino Mega 2560

Fig 5.2 : Teensy 3.5

5.3 Encoders –

Encoders are used to detect the rotation angle and linear displacement. They are used in a device which needs to be operated with higher accuracy and precision.

There are in total 6 encoders used in this project one with each stepper motor. It is connected with the Teensy 3.5 Controller and used to provide data to the controller so that further action can take place.

Fig 5.3 : Encoder

AMT102-V is the encoder used in this project.

5.4 Limit Switches –

It is an electro-mechanical device that operates with the motion of any machine part. There are 6 limit switches used at each joint to prevent the Robotic arm from damaging. For our robotic arm there are some angle constraints as shown in figure 3.2 so when the arm is approaching at its peak angle it automatically stops the arm from further movement. It is basically used for the safety purpose of our arm.

Fig 5.4 Limit Switch

6. Circuit Diagrams

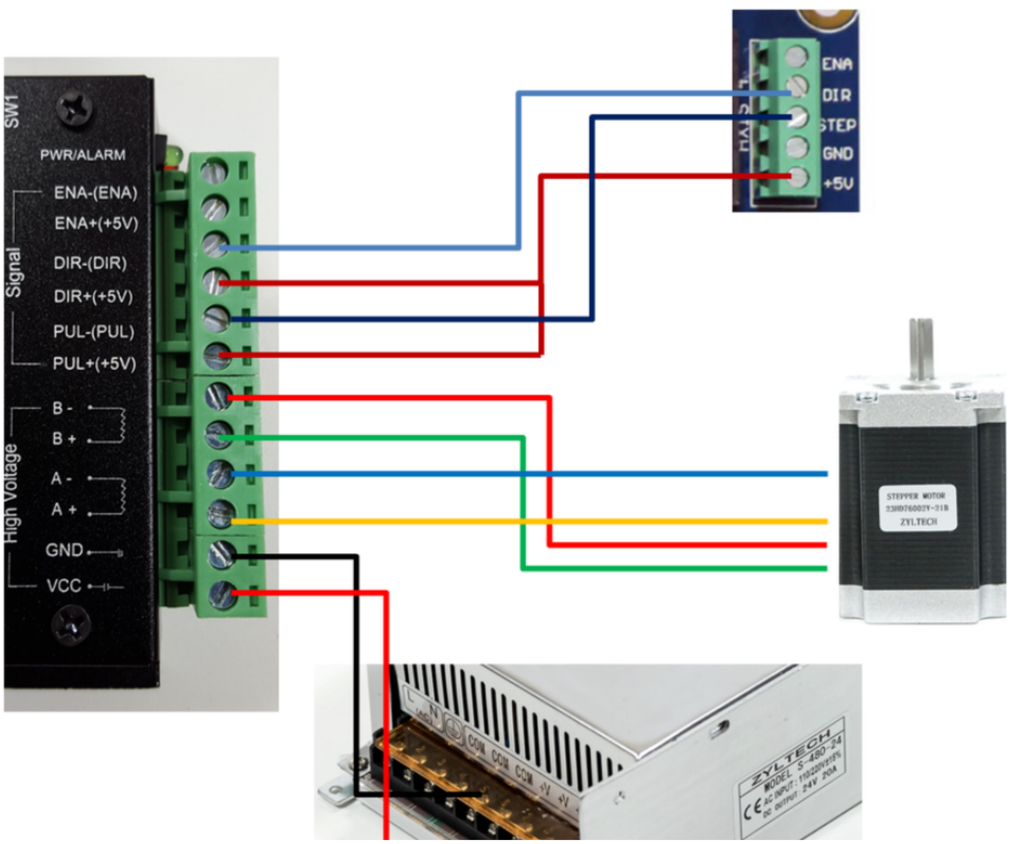

Fig 6.1 : Wiring for Driver

Pic Source : ZYLtech Toshiba

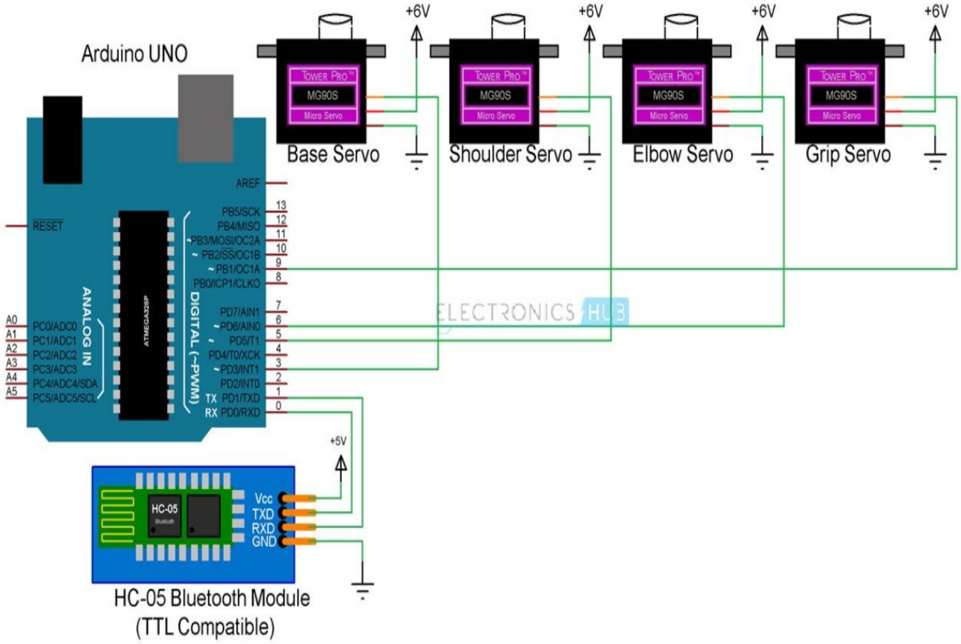

Fig 6.2 : Wiring for Controller and Motor
Pic Source : Electronics HUB

With taking these connections into reference we did the wiring for all the drivers, encoders and limit Switch with Controller and servo motor.

7. Conclusion

In the 21th century the industries are growing rapidly so the chances of error and fast working is preferred. So, we in this project developed and fabricated a 6 DoF robotic arm with 62.9 cm reach and maximising the workspace.

In the development of this arm we use Solidworks for the designing and use Forward and Inverse Kinematics to plan the path/trajectory that should be followed by the Robotic arm. To control the position of the end effector various encoders are used with the stepper DC motor.

The optimization of the design, fabrication of robotic arm, kinematic and dynamic model and motion studies has been successfully analysed that leads to reducing the effort and cycle time in the automobile, aerospace, electronics, medical, etc. industries.

Fig 5.1 : Actual Picture of 6 DoF Robotic Arm

8. Future Scope

For the better and faster process to move the end effector at a desired position further work needs to be done on the velocity control of actuators.

Some sort of Artificial intelligence can be introduced which plans the trajectory that should be followed or to plan a path to perform a task that leads to minimise the time taken by the end effector to perform a task.

In our case one actuator is working at a time which increases the time to perform any complex task So for the smooth running of robotic arm and minimise the time a complex model that leads to the parallel working of the actuators can be introduced.

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APPENDIX

Appendix A

Forward Kinematics

$$\mathrm{DH}_{i-1}^{i} = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i)\cos(\alpha_i) & \sin(\theta_i)\sin(\alpha_i) & a_i\cos(\theta_i) \\ \sin(\theta_i) & \cos(\theta_i)\cos(\alpha_i) & -\cos(\theta_i)\sin(\alpha_i) & a_i\sin(\theta_i) \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Angle Constraints for joints	degrees	radians
J1 * (-170 / 170)	0	0
J2 * (-130 / 0)	-90	-1.570796327
J3 * (1 / 140)	90	0
J4 * (-164 / 164)	0.01	0.0001745329252
J5 * (-104 / 104)	0.01	0.0001745329252
J6 * (-148 / 148)	0.01	3.141767187

DH Parameters

DH params	joint angle	twist angle	link offset	link length
joint	**Θ**	**α**	**d**	**a**
1	0	-1.570796327	169.77	64.2
2	-1.570796327	0	0	305
3	0	1.570796327	0	0
4	0.0001745329252	-1.570796327	-222.63	0
5	0.0001745329252	1.570796327	0	0
6	3.141767187	0	-36.25	0

Workframe matrix

1	0	0	0
0	1	0	0

0	0	1	0
0	0	0	1

Joint 1

1	0.00E+00	0	64.2
0	6.12E-17	1	0
0	-1	6.12E-17	169.77
0	0	0	1

Joint 2

6.12E-17	1	0	1.87E-14
-1	6.12E-17	0	-305
0	0	1	0
0	0	0	1

Joint 3

1	0	0	0
0	6.12E-17	-1	0
0	1	6.12E-17	0
0	0	0	1

Joint 4

0.9999999848	-1.07E-20	-0.0001745329243	0
0.0001745329243	6.12E-17	0.9999999848	0
0	-1	6.12E-17	-222.63
0	0	0	1

Joint 5

0.9999999848	-1.07E-20	0.0001745329243	0
0.0001745329243	6.12E-17	-0.9999999848	0
0	1	6.12E-17	0

0	0	0	1

Joint 6

-0.9999999848	0.0001745329243	0	0
-0.0001745329243	-0.9999999848	0	0
0	0	1	-36.25
0	0	0	1

A rotation of ψ radians about the x-axis is defined as

$$R_x(\psi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi & -\sin\psi \\ 0 & \sin\psi & \cos\psi \end{bmatrix}$$

Similarly, a rotation of θ radians about the y-axis is defined a

$$R_y(\theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$$

Finally, a rotation of ϕ radians about the z-axis is defined as

$$R_z(\phi) = \begin{bmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$RotX(\psi) = \psi = arctan2\left(\frac{T(3,2)}{\cos(\phi)}, \frac{T(3,3)}{\cos(\phi)}\right)$$

$$RotY(\phi) = \phi = arctan2\left(-T(3,1), \sqrt{T(1,1)^2 + T(2,1)^2}\right)$$

$$RotZ(\theta) = \theta = arctan2\left(\frac{T(2,1)}{\cos(\phi)}, \frac{T(1,1)}{\cos(\phi)}\right)$$

R 0 1

1	0.00E+00	0.00E+00	64.2
0	6.12E-17	1.00E+00	0
0	-1.00E+00	6.12E-17	169.77
0	0.00E+00	0.00E+00	1

R 0 2

6.12E-17	1.00E+00	0.00E+00	6.42E+01
-6.12E-17	3.75E-33	1.00E+00	-1.87E-14
1.00E+00	-6.12E-17	6.12E-17	4.75E+02
0.00E+00	0.00E+00	0.00E+00	1.00E+00

R 0 3

6.12E-17	6.12E-17	-1.00E+00	6.42E+01
-6.12E-17	1.00E+00	6.12E-17	-1.87E-14
1.00E+00	6.12E-17	6.12E-17	4.75E+02

0.00E+00	0.00E+00	0.00E+00	1.00E+00

R 0 4

6.12E-17	1.00E+00	-1.07E-20	2.87E+02
1.75E-04	-9.33E-25	1.00E+00	-3.23E-14
1.00E+00	-6.12E-17	-1.75E-04	4.75E+02
0.00E+00	0.00E+00	0.00E+00	1.00E+00

R 0 5

1.75E-04	6.12E-17	-1.00E+00	2.87E+02
1.75E-04	1.00E+00	3.05E-08	-3.23E-14
1.00E+00	-1.75E-04	1.75E-04	4.75E+02
0.00E+00	0.00E+00	0.00E+00	1.00E+00

R 0 6

-1.75E-04	3.05E-08	-1.00E+00	3.23E+02
-3.49E-04	-1.00E+00	3.05E-08	-1.10E-06
-1.00E+00	3.49E-04	1.75E-04	4.75E+02
0.00E+00	0.00E+00	0.00E+00	1.00E+00

R 0 T

-1.75E-04	3.05E-08	-1.00E+00	3.23E+02
-3.49E-04	-1.00E+00	3.05E-08	-1.10E-06
-1.00E+00	3.49E-04	1.75E-04	4.75E+02
0.00E+00	0.00E+00	0.00E+00	1.00E+00

End effector position

X	3.23E+02
Y	-1.10E-06
Z	4.75E+02
yaw	-89.98
pitch	90.01

roll	-89.99999825

Appendix B

Inverse Kinematics

Input Parameters

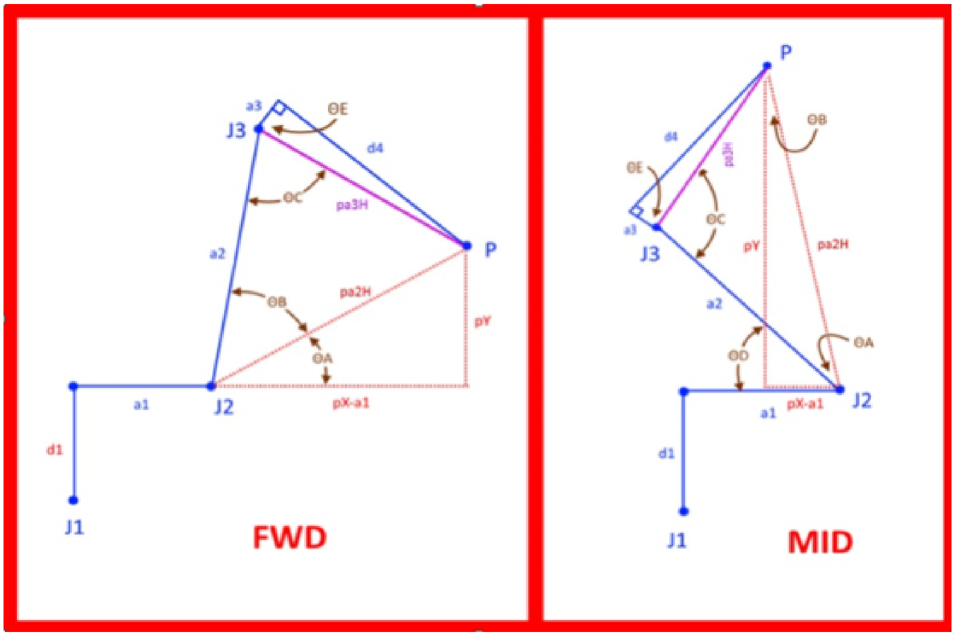
X	3.23E+02
Y	-1.10E-06
Z	4.75E+02
yaw	-89.98
pitch	90.01
roll	-89.99999825

Calculating angles of joints

$$\begin{pmatrix} \cos[\alpha]\cos[\gamma]-\cos[\beta]\sin[\alpha]\sin[\gamma] & \cos[\gamma]\sin[\alpha]+\cos[\alpha]\cos[\beta]\sin[\gamma] & \sin[\alpha]\sin[\beta] \\ \cos[\beta]\cos[\gamma]\sin[\alpha]+\cos[\alpha]\sin[\gamma] & \cos[\alpha]\cos[\beta]\cos[\gamma]-\sin[\alpha]\sin[\gamma] & -\cos[\alpha]\sin[\beta] \\ \sin[\beta]\sin[\gamma] & \cos[\gamma]\sin[\beta] & -\cos[\beta] \end{pmatrix}$$

J1 angle = 0

TO CALCULATE J2 AND J3 ANGLE (note that only arm forward and arm mid are used. Arm back config not used and elbow back is not used - to flip robot center of wrist "P" back past center line of J1 would require arm configuration parameters be attached to each move command).



	FWD	MID
pX	286.83	same
pY	3.05E+02	same
pX-a1	222.63	-222.63
pa2H	377.6097415	377.6097415
pa3H	222.63	same
ΘA	53.87300691	36.12699309
ΘB	36.12699309	-36.12699309
ΘC	90	90
ΘD	na	90
ΘE	90	same
J2 ∠	-90	-90
J3 ∠	90	90

WORK FRAME			
1	0	0	0
0	1	0	0
0	0	1	0
0	0	0	1

J1

1	6.07E-33	0	64.2
0	6.12E-17	1	0
0	-1	6.12E-17	169.77
0	0	0	1

J2

2.83E-16	1	0	8.64E-14
-1	2.83E-16	0	-305
0	0	1	0
0	0	0	1

J3

1	0	0	0
0	6.12E-17	-1	0
0	1	6.12E-17	0
0	0	0	1

R 0-1

1	6.07E-33	9.92E-17	64.2
0	6.12E-17	1.00E+00	0
0	-1.00E+00	6.12E-17	169.77
0	0.00E+00	0.00E+00	1

R 0-2

2.83E-16	1.00E+00	9.92E-17	6.42E+01
-6.12E-17	-9.92E-17	1.00E+00	-2.50E-14
1.00E+00	-2.83E-16	6.12E-17	4.75E+02
0.00E+00	0.00E+00	0.00E+00	1.00E+00

R 0-3

2.83E-16	1.60E-16	-1.00E+00	6.42E+01

-6.12E-17	1.00E+00	1.60E-16	-2.50E-14
1.00E+00	6.12E-17	2.83E-16	4.75E+02
0.00E+00	0.00E+00	0.00E+00	1.00E+00
R 0-3 transposed			
2.83E-16	-6.12E-17		1.00E+00
1.60E-16	1.00E+00		6.12E-17
-1.00E+00	1.60E-16		6.12E-17

Kinematic Decoupling

R 0-T			
0.0001745329217	0.0000000304617415	-0.9999999848	3.23E+02
-0.0003490658407	-0.9999999391	0.00000003046174184	-1.10E-06
-0.9999999238	0.0003490658407	0.0001745329217	4.75E+02
0	0	0	1
R 0-T offset by work frame			
-0.0001745329217	0.0000000304617415	-0.9999999848	3.23E+02
-0.0003490658407	-0.9999999391	0.00000003046174184	-1.10E-06
-0.9999999238	0.0003490658407	0.0001745329217	4.75E+02
0	0	0	1.00E+00
TOOL FRAME			
1	0	0	0
0	1	0	0
0	0	1	0
0	0	0	1
INVERT TOOL FRAME			
1	0	0	0
0	1	0	0
0	0	1	0
0	0	0	1

R 0-6

-1.75E-04	3.05E-08	-1.00E+00	3.23E+02
-3.49E-04	-1.00E+00	3.05E-08	-1.10E-06
-1.00E+00	3.49E-04	1.75E-04	4.75E+02
0.00E+00	0.00E+00	0.00E+00	1.00E+00

Remove R 0-6

-1	1.22E-16	0	0
-1.22E-16	-1	0	0
0	0	1	36.25
0	0	0	1

R 0-5 (center spherical wrist)

1.75E-04	-3.05E-08	-1.00E+00	2.87E+02
3.49E-04	1.00E+00	3.05E-08	-2.84E-14
1.00E+00	-3.49E-04	1.75E-04	4.75E+02
0.00E+00	0.00E+00	0.00E+00	1.00E+00

R 3-6 (spherical wrist orientation)

1.00E+00	-3.49E-04		1.75E-04
3.49E-04	1.00E+00		3.05E-08
-1.75E-04	3.05E-08		1.00E+00

$$\theta_4 = \mathbf{atan2}(r_{13}, r_{23})$$
$$\theta_6 = \mathbf{atan2}(-r_{31}, r_{32})$$

$$\theta_5 = \mathbf{atan2}\left(r_{33}, \pm\sqrt{1 - r_{33}^{\,2}}\right)$$

$$\theta_4 = \mathbf{atan2}(-r_{13}, -r_{23})$$
$$\theta_6 = \mathbf{atan2}(r_{31}, -r_{32})$$

Output Angles of Joints

Joint 1	0		
Joint 2	-90		

Joint 3	90		
Joint 4	0.01	0.01	-179.99
Joint 5	0.009999999984	0.009999999984	-0.009999999984
Joint 6	0.009999999998	0.009999999998	-179.99

Appendix C

Motors and Drivers

Components	**Quantity**	**Torque**
Nema 17 Dual Shaft Stepper Motor L=39mm Gear Ratio 10:1 High Precision Planetary Gearbox 9.5mm Rear Shaft Length	1	150
Nema 23 Dual Shaft Stepper Motor L=56mm Gear Ratio 50:1 High Precision Planetary Gearbox 9.5mm Rear Shaft Length	1	250
Nema 17 Dual Shaft Stepper Motor L=39mm Gear Ratio 50:1 High Precision Planetary Gearbox 9.5mm Rear Shaft Length	1	150
Nema 11 Dual Shaft Stepper Motor Bipolar L=51mm w/ Gear Ratio 14:1 Planetary Gearbox 9.5mm Rear Shaft Length	1	30
Nema 17 External 48mm Stack 1.68A Lead 8mm/0.31496" Length 200mm	1	44
Nema 14 Dual Shaft Stepper Motor Bipolar L=28mm w/ Gear Ratio 19:1 Planetary Gearbox 9.5mm Rear Shaft Length	1	30
250W 24V 10A 115/230V Switching Power Supply	1	
DM542T digital stepper driver.	5	
DM320T digital stepper driver.	1	
Bracket for stepper motor	1	

Appendix D

Hardware Components

Components	**Quantity**
32009 (45x75x20mm) taper roller bearing	2
30206 (30x62x17.25mm) taper roller bearing	2
30204 (20x47x15.25mm) taper roller bearing	1

AXK3552/AS3552 (35x52x4mm) thrust bearing with washers	1
NTA1625 (1.00x1.5625x0.0781 inch) thrust bearing	3
TRA1625 (1.000x1.5625x0.0312 inch) thrust washer	4
TRD1625 (1.000x1.5625x0.125 inch) thrust washer	2
B1616 (1x1-1/4x1 inch) needle roller bearing	2
HK1612 (16x22x12mm) needle roller bearing	1
3mm x 85mm shaft	1
LM3UU 3mm linear rod bearing bearings	4
688Z (8x16x5mm) groove ball bearing bearings	1
30203 (17x40x13.25mm) taper roller bearing	1
180XL037 belt	1
connecting link 04B link for 6mm chain	1
84XL037 belt	1
J5 belt	1
60T XL pulley	1
XL 15 tooth 8mm bore pulley	2
XL 10 tooth 6mm bore pulley	1
04B 13 tooth 8mm bore 6mm pitch sprocket	2
2mm x 2mm keystock	1
1” OD aluminum tube	1
8mm keyed rotary shaft	1
8mm square head screw	1

Appendix E

Electrical Components

Components	**Quantity**
BUD Industries NBF-32026 Plastic ABS NEMA Economy Box	1
BUD Industries NBX-32926-PL ABS Plastic Internal Panel	1
BUD Industries IPV-1115 IP32 Air Vent, 3.2" x 3.2“	1
Box #6 x 3/8 thread forming screws.	1

5 meters of flexible 18 awg silicon hook up wire.	1
20ft - 22awg red and black flexible silicone wire.	1
20ft - 22awg white flexible silicone wire.	1
18awg 4 conductor cable.	1
Roll 26awg twisted pair wire 5 meters long.	1
18awg primary electrical wire.	1
6’ long Ethernet cables.	6
Set of breadboard jumper wires.	1
Roll of 1⁄2” and 1⁄4”braided sleeves.	1
PG-21 gland nuts.	1
DIN rail and terminal blocks.	1
straight lever XV-152-1C25 limit switch	1
roller tip SV-166-1C25 limit switches	5
AC Rocker Switch 3 Pin IEC320 C14 Inlet Module Plug Fuse.	1
Emergency Stop Switch Push Button Switch	1
RJ45 CAT5e Feedthru Panel Mount Jack	3
USB-B to USB-A Feedthru Panel Mount Jack	2
GX16-2 aviation plugs.	1
GX16-4 aviation plugs.	2
16awg wire ferrules	1
AMT102-V encoder.	6
3019_0 (50cm high speed encoder cable).	3
8 channel 5vdc relay module.	1
2.54mm female header pins	1
Teensy 3.5 controller without pins.	1
Arduino Mega 2560 controller.	1
5vdc power supply	1
SMC MHF2-8D1 pneumatic gripper.	1
3mm OD flexible tubing	1
M3 thread x 3mm tube fitting.	2

Appendix F

Covers and Spacers

Covers and spacers	Quantity
Joint 1 base enclosure part 1	1
Joint 1 base enclosure part 2	1
Joint 1 base enclosure cap	1
Joint 2 upper and lower side covers	1
Joint 2 upper and lower arm cover spaces	1
Joint 5 side cover	1
Joint 5 side cover spacer	1
Joint 5 side cover cap	1
Joint 6 limit switch tip	1
Joint 4 motor spacer-4mm	1