Hochschule Schmalkalden

Mechanical Engineering

Project Work Report

Design and Fabrication of a 4-DOF Robotic Arm

Prepared by

Jayabadhrinath Krushnan

Matriculation Number: 312646

In Study Program

Mechatronics and Robotics

Master of Engineering

Supervisor 1: Prof. Dr.-Ing. Frank Schrödel

Supervisor 2: Mr. Christoph Schreiber

Schmalkalden, den 05.12.2022

ACKNOWLEDGEMENT

I would like to thank prof. Frank Schroedel for this wonderful opportunity and his guidance in building up the robotic arm. He supported me all the time. One best example would be that when I made my first prototype, it failed since I was not aware of the intrinsic details involved in building up the robotic arm. During this instance he motivated me saying “Failure is the stepping stone of success” and not every project becomes a successful in the very first attempt. This motivated me a lot during the entire course of the project when some mechanisms don’t work. In addition to this he is a great mentor and I am thankful for all the opportunities he has provided me with. Also thank you for helping me to mould into a better person who I am today.

Mr. Christoph Schreiber has supported me with his valuable knowledge. He made me realise the mistakes that I made while designing the robot and helped me with the methodological approach to build it in a standard way.

Mr. Richard Vogt and Mr. Tizian Regner Pascal have extended their wonderful support with building the hardware structure in the Mechanical Workshop. I am happy that I found a wonderful friend Tizian, who helped me learn many things with respect to the German culture.

Last but not the least, I would like to thank Mr. Krushnan Prakalathan (DAD) and Mrs. Lakshmi Krushnan (MOM) for supporting me every time and making me realise that I am not alone. Thank you for all the opportunities you have provided me.

ABSTRACT

This 4 DOF robotic arm is used for the purpose of automated storage and retrieval system in the benchmark Industry 4.0 plant to pick an empty bottle from the storage rack and place it on a conveyor. This project report gives a detailed insight into the inner working of a robotic arm along with the concepts of an open loop and a closed loop functions through feedback systems.

This robotic arm was mainly built from an educational point of view and also to demonstrate a proper mechatronics system. All wonderful and cost-effective solutions have been used in building up this robotic arm for both mechanical and the electronics aspect. Arduino Mega 2560 was used as the controller since most of the students are familiar with Arduino and its easy to program IDE will allow anyone to program the robot with few practices.

In this project the mechanical procedures to build up a robotic arm, various electronic modules and a simplistic approach to program the robot arm will be discussed. The robot was designed for a payload of 200 grams with a safety factor of 2.5.

Furthermore, by using this project report anyone can easily build up a cost-effective robotic arm to enhance their skills about a mechatronics system and also to carry on with a fun project that helps to gain more knowledge about technology.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

The use of robotic arm in Industries has been from the third industrial revolution where they were used to move goods from one place to the other. But in the later stages they provided the possibility to work in areas which are not safe for humans to work. Through advancement in technology the robotic arm was capable of performing tasks much quicker and with precision than humans. This was beneficial in the fields where repetitive tasks was demanded. Robotic arm with vision systems have proved to perform intelligent tasks in industries with higher speeds and accuracy. In simple words, it can be said that the robotic arm plays an important role in Industries as seen in Figure 1. Highly advanced and flexible manufacturing systems like Industry 4.0 demands the need of robotic arms in the manufacturing systems. It can be seen in figure 1, how the robotic arm was introduced in the 3rd industrial revolution and robotic arm being integrated in smart factories.

As stated by Universal robots, Industry 4.0 means the fourth generation of technological advancement and automation. It is the use of modern and smart technologies, mostly in manufacturing processes, to increase operational excellence, and involves Artificial Intelligence, the Internet of Things, Machine Learning, Cloud Computing, Cognitive Computing, Data Analytics, and Cyber-Physical Systems.

Advanced robotics Technology plays a major role in Industry 4.0. As technologies used in manufacturing processes have equipped the industries to become fast-paced by introducing new methods for improved production, advanced robotics has become very crucial. These robots are now more digitally connected and sensor to sense their surroundings. Industry 4.0 technologies embedded with advanced robotics have increased the overall return on investment.

Since Industry 4.0 is a recent trend in the Industrial sector with multitude of advantages, An Industry 4.0 lab setup is presented in the University lab to enable students to have an opportunity to understand the industry 4.0 systems. As stated by universal robots, Industry 4.0 system and the robots are well connected. Because of this reason, a robotic arm was designed and implemented in the industry 4.0 plant with the aim of understanding the maximum utility of the robotic arm in the manufacturing systems. In this project, the robotic arm is used to pick up an empty bottle from the storage rack and to place it on the conveyor. This marks the start of the production process in the industry 4.0 plant. The robotic arm was built for educational purpose and to replicate an exact industrial scenario this robot arm can be mounted on to a rail which can move to different location based on different inputs given to the robotic arm. This would represent an automated storage and retrieval system in an Industry.

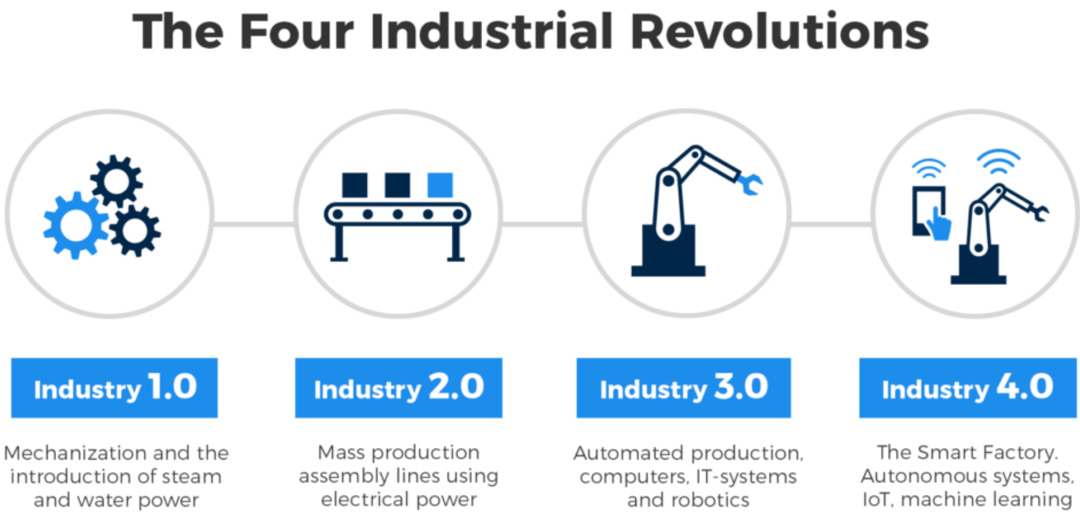


Figure 1: Revolution of Industry 4.0 (Spectral Engines 2018)

In the later section we will discuss about the introduction to robotic arm and its types followed by the task description for which the robotic arm was built. A detailed discussion on how to build the robotic arm will be discussed in the designing of the robotic arm section followed by electrical and electronics design along with programming of the open loop control for the robotic arm.

2 ROBOTIC ARM:

Robotic arm is a mechanical arm with similar functionalities as that of a human arm. With the provision of programming capabilities and vision systems the robotic arm can be used to perform various industrial operations. The length wise elements in a robotic arm are called as links. The links are connected together with joints which provide the freedom of movement. These joints are then actuated with the help of actuators. All these elements combine together to form a freely movable mechatronic system. But unlike a human which has 6 DOF, the robotic arms are basically designed with the required degrees of freedom to suit the user-based application. The area covered by the robotic arm is known as the robot workspace. To understand the workspace, we can consider a human hand which has a semi-spherical workspace as seen in Figure 2.

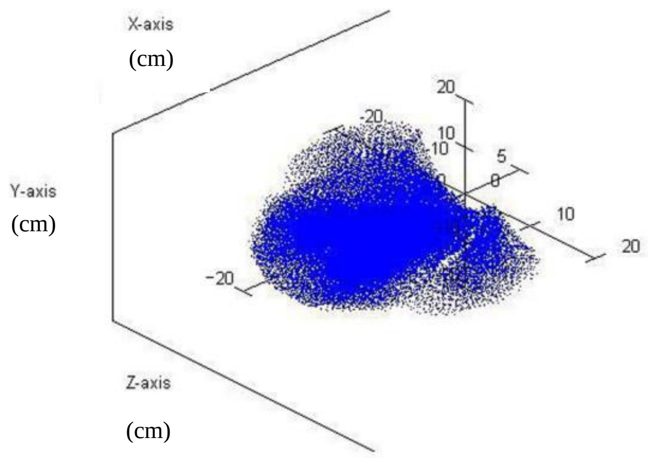


Figure 2: Human hand working rage (Dragulescu 2007)

Based on these criteria of the robot workspace, the robots can be classified into the following types (Wikipedia 2007),

1. Cartesian robot / Gantry robot: Used for pick and place work, application of sealant, assembly operations, handling machine tools and arc welding. It is a robot whose arm has three prismatic joints, whose axes are coincident with a Cartesian coordinator.
2. Cylindrical robot: Used for assembly operations, handling at machine tools, spot welding, and handling at die casting machines. It is a robot whose axes form a cylindrical coordinate system.
3. Spherical robot / Polar robot: Used for handling machine tools, spot welding, die casting, fettling machines, gas welding and arc welding. It is a robot whose axes form a polar coordinate system.

4. SCARA robot: Also known as Horizontal Knick arm in German, is used for pick and place work, application of sealant, assembly operations and handling machine tools. This robot features two parallel rotary joints to provide compliance in a plane.
5. Articulated robot: Also known as Vertikaler Knick arm in German, is used for assembly operations, diecasting, fettling machines, gas welding, arc welding and spray-painting. It is a robot whose arm has at least three rotary joints.
6. Parallel robot: One use is a mobile platform handling cockpit flight simulator. It is a robot whose arms have concurrent prismatic or rotary joints.
7. Anthropomorphic robot: It is shaped in a way that resembles a human hand, i.e., with independent fingers and thumbs.

Figure 3 represents the most commonly used robots in the industries,

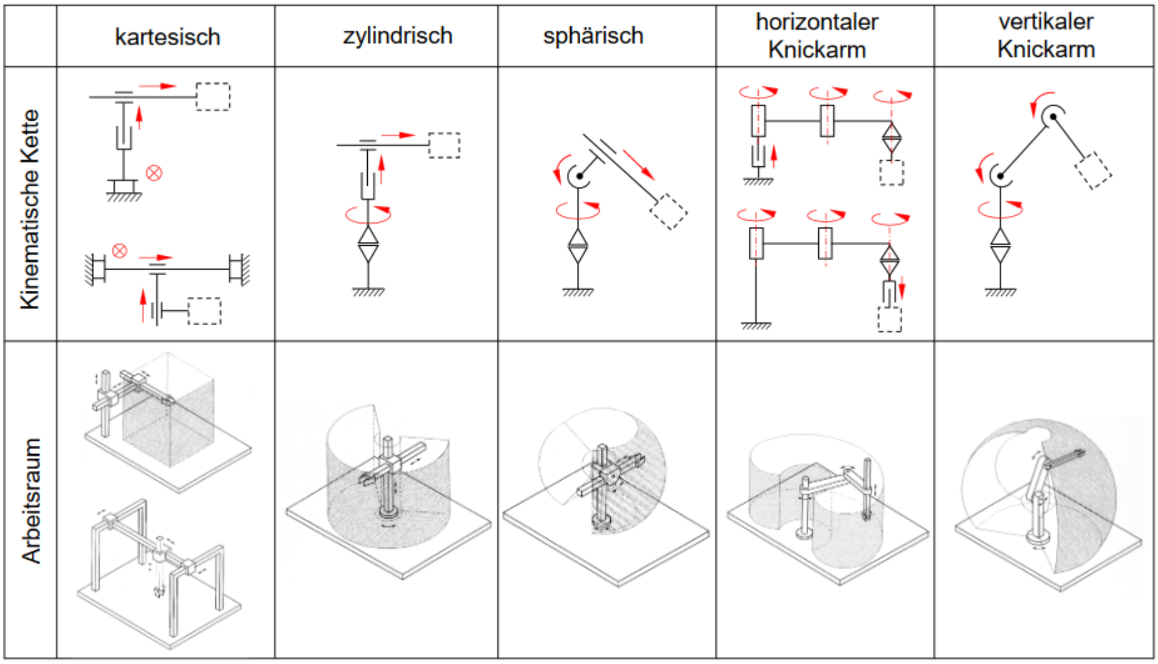
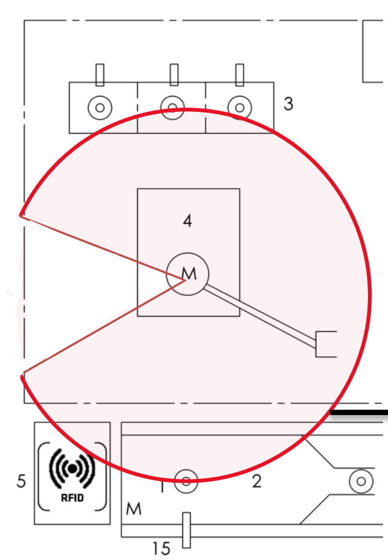


Figure 3: Different types of robots based on the workspace (Woernle 2019)

So, from the above-mentioned types of robots, SCARA robots can also be used for pick and place but it wouldn't have the flexibility as compared to that of a Articulated robot. In SCARA robots the horizontal link is fixed in size and takes up huge space compared to that of a articulated robot. For these reasons, an articulated robot is built in this project.

3 TASK DESCRIPTION:

The main purpose of the robotic arm is to pick an empty bottle fixed with RFID tag from the storage rack and place it on the conveyor. Before placing the bottles on the conveyor, the robot arm should take the bottles to the RFID scanning station where the production details are scanned. So, after the RFID is scanned then the robot can place the bottles on the conveyor band. A proximity sensor will sense the presence of the bottle and start the conveyor band. Also, the robot arm should be capable of picking up bottles from a movement robot and stack up the storage rack if the storage rack is empty. This forms the use case of the robotic arm. Now the workspace of the robotic arm is to be decided. The robot will be placed on a table of dimension, 2100 x 750mm, in which the useable area for the robotic arm would be a cylindrical workspace of 300mm. So based on these criteria, the robot was decided to be a 4-axis robot for which the dimension of the links was designed and discussed in the following section.



1. Bottle
2. Conveyor band
3. Storage rack
4. 4 DOF Robotic arm
5. RFID scanning station
15. Proximity sensor to start the conveyor band.

Operating range

Figure 4: 2D Layout of the Robotic arm

The red circle in Figure 4 indicates the robots operating range which is 300mm in radius. Due to the wirings, the robot does not complete a full 360-degree rotation.

4 DESIGNING OF THE ROBOTIC ARM

4.1 IDEATION

As the operating range or the robot workspace is known, this helps to decide the number of joints required and the length of each link in the robotic arm. The primary task is to pick and place bottle for which a 4 DOF robotic arm. A robotic arm with 4 joints is known as an underactuated robots since it cannot achieve all the possible orientations. In this particular case, a roll or yaw about the gripper is not required since the positioning of the bottle on the conveyor belt can be adjusted with the pitch to the gripper. Another important consideration is to make sure that the robot arm does not topple during its full-length extension. The base of the robotic arm is made as a cuboid. This does not provide any support to the base but in order to make it compact in size, the base is fixed with a heavy bearing block supporting the base rotation as well as providing stability to the base. The length of the robot link is chosen in such a way that it would make the robotic arm perform the task as required in the operating range. The robot is classified into Base, Link1, Link2, Link3 and gripper. In order to maintain the centre of gravity of the robotic arm as low as possible, the link 1 was designed longer compared to the other links and gradually the link length was reduced. The length of link 1 is 250mm, link 2 is 165mm and the link 3 is 64mm. The base dimension was approximated to half of the operational length of link 1 which is 105mm and the length of the base is 200mm. Due to compactness, the base was designed as cuboid instead of a cube with a height of 53mm in order to accommodate a NEMA 17 motor for the base rotation of the robot. The material for building the robot will be Aluminium since it is light in weight and easy to manufacture.

4.2 MECHANICAL DESIGN

In order to start with the Mechanical design, the torque at each joint has to be determined for choosing the drive mechanisms. We can use the simply formula, Torque = Force x distance, to calculate the torque at each joint. Since we know the length of each link, the weight of the links can be found through the density of aluminium which constitutes to the force. The weight of the links was decided through Solidworks software under the material properties, where the material was selected as Aluminium 6061 alloy. Therefore, the weight of 1 piece of link 2 is around 121 grams. So along with the bolt fixtures and the gripper along with link3, the weight was approximated to 550 grams. Therefore, the total torque required at joint 2 would be,

Torque 2 = 0.550 Kg x 27.5 cm = 15.1 Kgcm

Since we have the requirement to keep the robot compact, Nema 17 motor was chosen. The torque of a Nema 17 motor is 4.8 Kgcm at a current of 2A. This current rating is far less compared to the torque calculated. So, any other motor with the calculated torque has to be used or a gear setup has to be used. For this purpose, there are stepper motors with gear box setup which increases the size of the robot. So, the other option is to use gears for torque multiplication.

4.2.1 GEARS:

A gear is a rotating circular machine part having cut teeth or, in the case of a cogwheel or gearwheel, inserted teeth (called cogs), which mesh with another (compatible) toothed part to transmit (convert) torque and speed.

There are many types of gears broadly classified by looking at the positions of axes such as parallel shafts, intersecting shafts and non-intersecting shafts.

1. Parallel gears
    1. Spur Gears
    2. Helical Gears
    3. Double Helical or Herringbone Gears.
2. Perpendicular axis gears
    1. Non intersection perpendicular axis
    2. Intersection perpendicular axis gear
3. Intersecting gears
    1. Spiral gears
    2. Bevel Gears
4. Non-intersecting and non-Parallel gears.
    1. Worm Gears
5. Rack and Pinion gears

The different types of gears mentioned can be visualised in Figure 5.

Figure 5: Different types of Gears (M 2022)

Among the various types of gears mentioned above, the non-intersecting and non-Parallel gears known as the worm gears are best suited for a robotic arm which will be explained in the worm gears section.

4.2.2 WORM GEARS:

A worm drive as seen in Figure 6, is a gear arrangement in which a worm (which is a gear in the form of a screw) meshes with a worm wheel (which is similar in appearance to a spur gear). The two elements are also called the worm screw and worm gear.

A gearbox designed using a worm and worm wheel is considerably smaller than one made from plain spur gears, and has its drive axes at 90° to each other. With a single-start worm, for each 360° turn of the worm, the worm wheel advances by only one tooth. Therefore, regardless of the worm's size (sensible engineering limits notwithstanding), the gear ratio is the "size of the worm wheel - to - 1". Given a single-start worm, a 20-tooth worm wheel reduces the speed by the ratio of 20:1. With spur gears, a gear of 12 teeth must match with a 240-tooth gear to achieve the same 20:1 ratio.

There are three different types of gears that can be used in a worm drive.

The first are non-throated worm drives. These don't have a throat, or groove, machined around the circumference of either the worm or worm wheel. The second are single-throated worm drives, in which the worm wheel is throated. The final type are double-throated worm drives, which have both gears throated. This type of gearing can support the highest loading. In this project, we are using a single throated worm gear as seen in Figure 6.

Figure 6: Worm gear setup (Framo Morat 2014)

The irreversibility feature (Self-locking of worm gears), or the inability to reverse the direction of power, is one of the biggest benefits of using a worm. It's extremely hard for a wheel to start the worm moving because of the friction that exists between the worm and the wheel. The motors do not need to be running when the robot is motionless to maintain the position because of this bigger benefit. As a result, the robot is energy-efficient. It is the preferred solution for a driving mechanism in part because a greater gear ratio may be possible.

Another reason to choose worm gear is, it changes the rotational movement by 90 degrees, and the plane of movement also changes due to the position of the worm on the worm wheel. This perfectly suits the robotic arm since it allows to keep the robot compact by occupying less space compared to other options of having a stepper motor with gear box or using other types of gears in order to match the necessary torque required at the joints. Selection of gear with respect to the torque calculations,

The weight of 1 piece of link 1 is around 160 grams. So along with the bolt fixtures and the gripper along with link3, the weight was approximated to 320 grams. Therefore, the total torque required at joint 1 would be,

Torque 1 = (0.550 Kg + 0.250 Kg + 0.320 Kg) x d

Torque 1 = 1.27 Kg x d

From the Solidworks assembly file, the center of mass was determined to lie at d = 52.5 cm at the full extension of the robot arm. Therefore,

Torque 1 = 1.27 Kg x 52.5 cm = 66.6 Kgcm

Table 1 describes about the torque required at each joints and the gear ratios selected along with the gear specifications.

Description	Arm 1	Arm 2	Base
Torque required	70 Kgcm	20 Kgcm	11 Kgcm
Gear ratio	20:1	5:1	-
Center distance	33	25	-
Worm shaft (dia)	21.96 mm	21.2 mm	-
Worm wheel (dia)	50.5 mm	34.8 mm	-
Torque output	130 Kgcm	66.28 Kgcm	-

Table 1: Torque comparison table for Robotic Arm joints

The torque output mentioned here is based on using mineral oil as lubrication oil for the worm gear setup.

The next step would be to realise the actuation of the robotic arm using the drive mechanisms decided. So, to support the drive mechanisms without inhibiting their actions, bearing and couplings are to be used. This helps us to drive the link and connect the drive mechanisms along with the robot.

4.3 SLEEVE FLANGE BASED ROBOTIC ARM (PROTOTYPE 1)

Based on the above-mentioned design parameter, the robot was designed as follows, using PVC sleeve flange bearing. Initially flange bearing were used to support all the shafts. The criticality of the worm gears lies in the assembly where the gear is not to be fully meshed. Because if the gears are fully meshed then the friction between the gears increases which makes it completely difficult to rotate. So, the worm and the worm wheels should be meshed in such a way that the gears are free to rotate and also the centre distance has to be maintained. In this project there are two sets of worm gears,

1. 33mm Centre distance
2. 25mm Centre distance

The links of the robotic arm are connected together with the help of a shaft to which the worm wheel is fixed. The worm is fixed to the motor again using a shaft and a coupling.

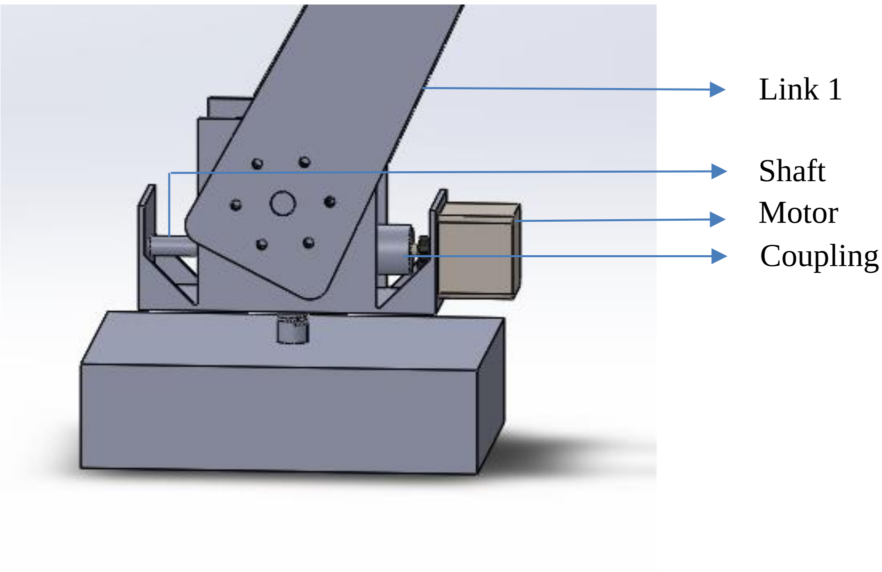


Figure 7: CAD model of prototype 1 (Sleeve bearing)

In the prototype 1 the rotating shafts were supported with sleeve bearings with flange. Sleeve bearings are mostly suited for vertical mountings and not for shaft centre line. Due to this reason, the meshing of the worm gear resulted in a problem that the gears were jammed making it not to rotate freely. In order to check the feasibility to improve this problem, the mounting holes were made bigger so that the worm wheel could be lifted little bit up to remove the jamming. When this was done, the centre distance was not maintained constant. If the centre distance is not constant, the main feature of worm gear setup won’t be applicable which is the self-locking of the gears. So, when the mounting holes were made bigger, the arm lifts up and doesn’t stand in the position and falls down immediately when the motor is stopped. There was a lot of noise, which made the option of using the sleeve bearing rule out. Figure 8 shows a PVC flange bearing. The white surface which is called as sleeve is made out of Teflon to reduce friction during rotation and unlike ball bearings, these sleeves does not rotate along with the shaft and there is no provision to lock the shaft with the sleeve.

Figure 8: PVC Sleeve flange bearing (RS Online 1983)

So overall, the sleeve bearings only guide the shafts. Since the shafts were not locked in position, it makes the shaft to move either left or right due to the tangential force generated in the gears during rotation causing the system to wobble too much.

4.4 BALL BEARING BASED ROBOTIC ARM (PROTOTYPE 2)

In prototype the problems faced in prototype 1 was completely eliminated. The problems that prototype 1 majorly depends on the bearing. So, in prototype, the PVC flange sleeve bearings were replaced with pillow block or Plummer block bearings. The pillow block fixed with ball bearings have a better performance since the ball bearings have very less friction. The shafts can also be locked with the housing of the Plummer block thereby eliminating the problem of the shaft moving left or right and holding it in the position. For coupling the shafts, simple solid couplers were used. In the following the assembly of the robotic arm is discussed in detail for the prototype 2.

4.4.1 BASE CONNECTING SHAFT

So, the complete assembly of the robot will be discussed in this section along with the details of the individual part drawings.

The base will be connected with the robot links through a single shaft as shown in Figure 9.

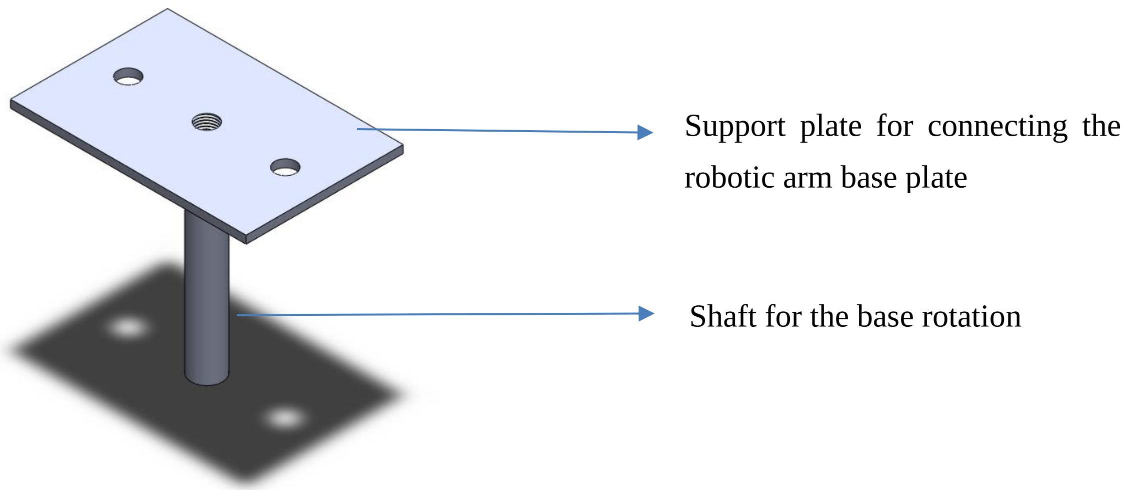


Figure 9: Base connecting rod

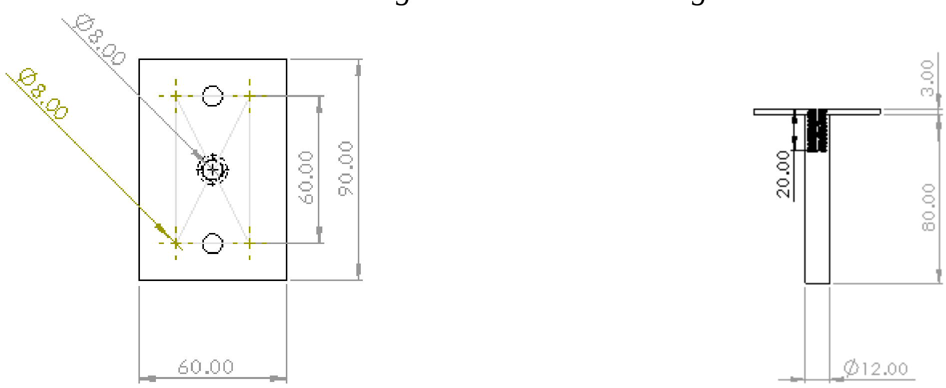


Figure 10: Dimensions of the Base connecting rod

A 12mm ID square flange bearing (UCF 201) as seen in Figure 11 was used for the rotation of the base. The shaft passes through the bearing allowing the robotic arm to rotate about the base. The bearing is fixed to the base using 4 M10 bolts.

Figure 11: UCF 201 Flange ball bearing (RS Online 1937)

4.4.2 BASE

The following is the base design as seen in Figure 12 with side cut out for mounting the robot to the aluminium profile.

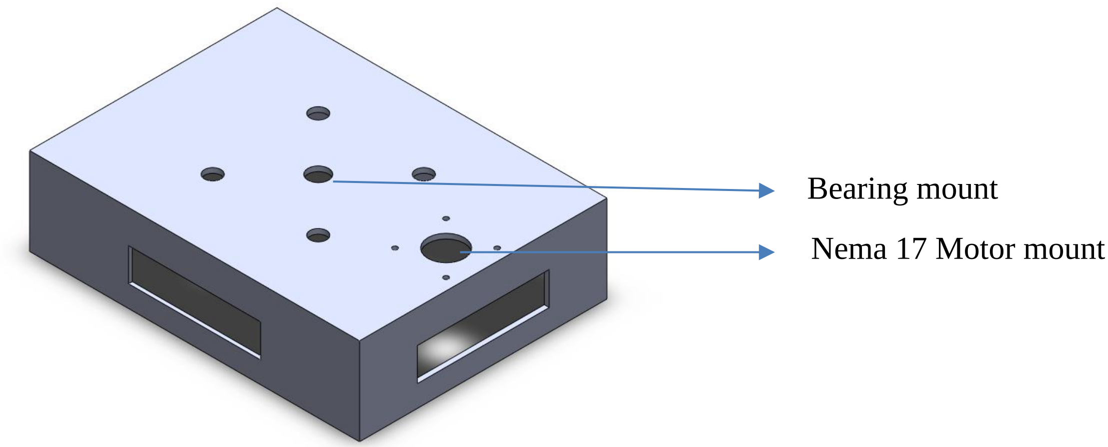


Figure 12: CAD Model of the base

Figure 13 shows the dimensions of the base.

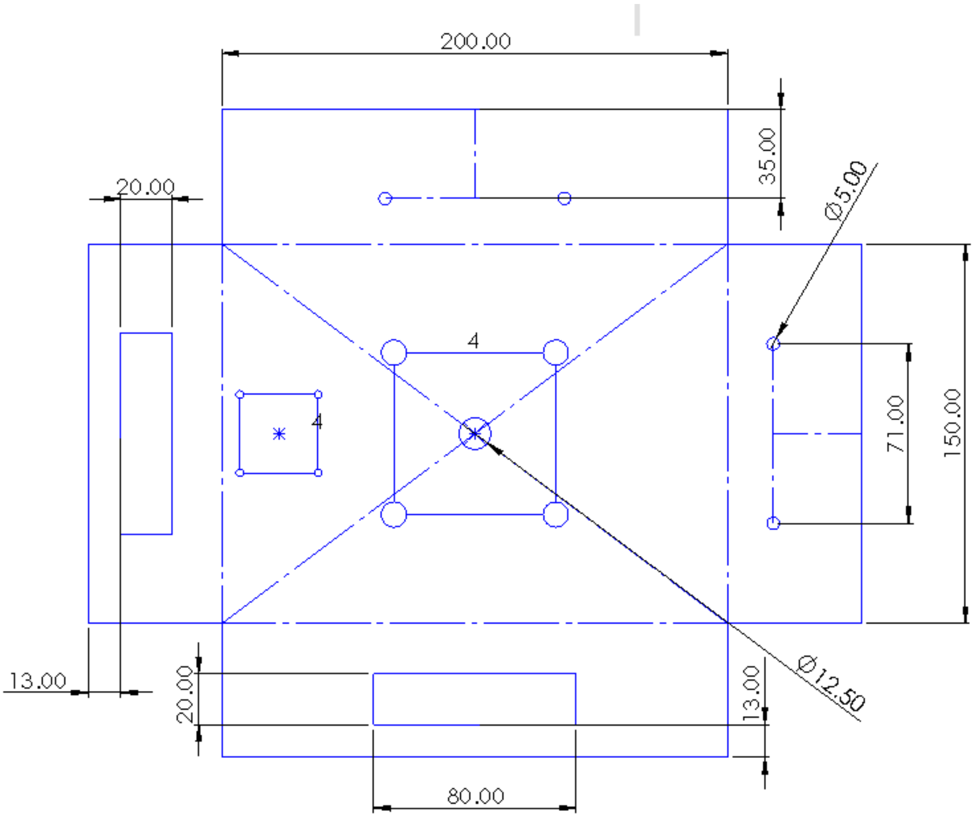


Figure 13: Dimensions of the base

After fixing the base connecting plate and the base along with the Nema 17 motor for the base rotation, the assembly looks like its shown in Figure 14.

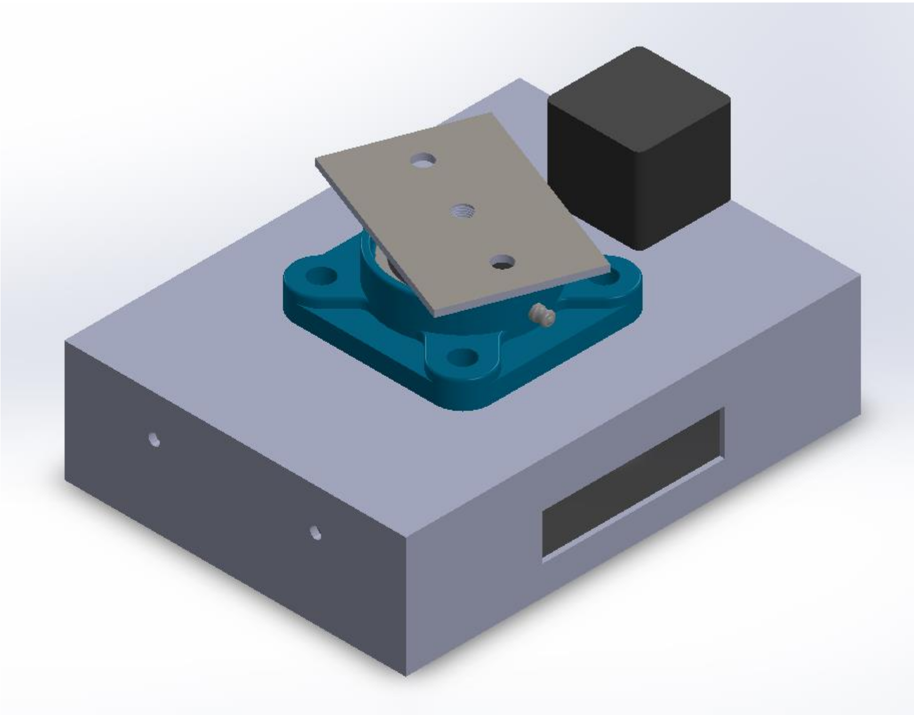


Figure 14: CAD Assembly of the Base

4.4.3 ARM 1 ASSEMBLY

The base connecting plate as seen in Figure 15 connects the robotic arm with the base for rotation.

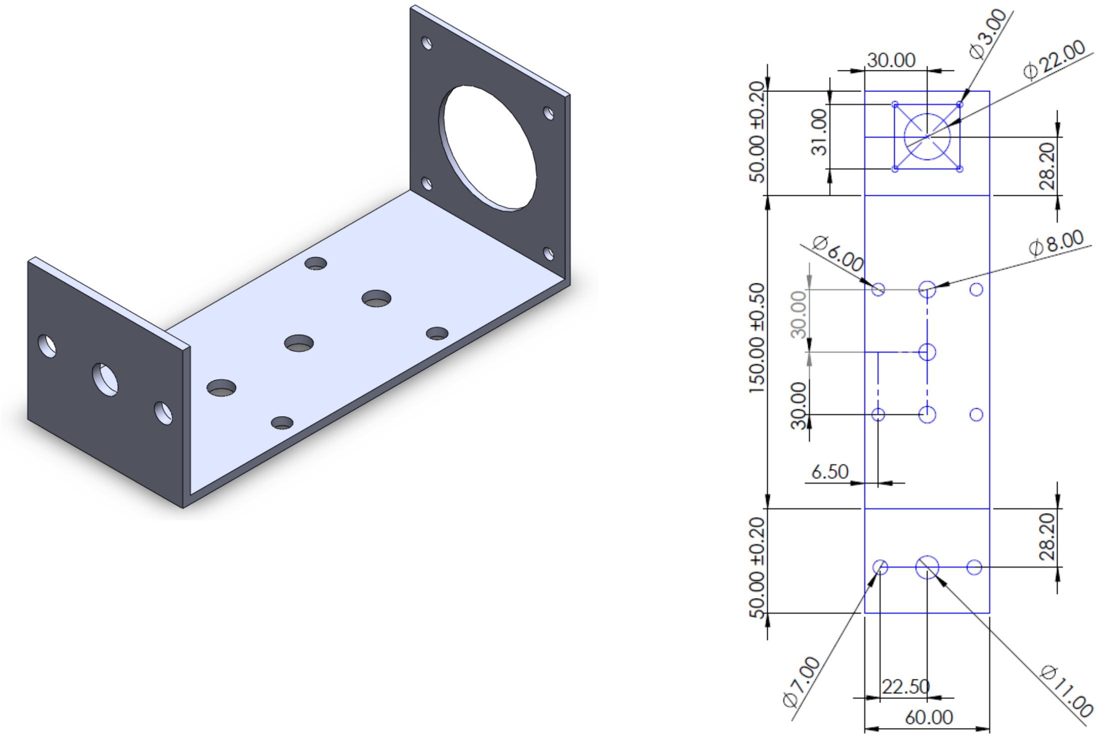


Figure 15: CAD model and dimensions of the Base connecting plate

The base connecting plate is fixed to the base connecting rod using M6 bolts. A Nema 23 motor is used for actuating the Arm 1. A shaft as seen in Figure 17 along with the worm gear will be connected to the motor using a connector as seen in **Error! Reference source not found.** . The other end of this shaft is supported with a bearing.

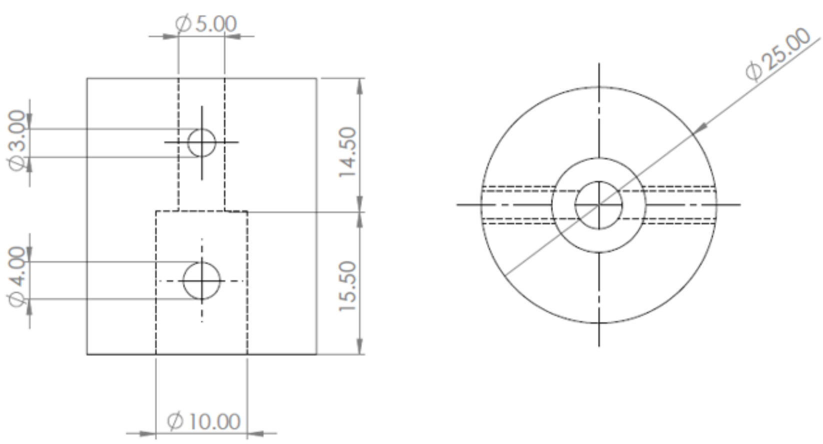


Figure 16: Dimensions of 5mm to 10mm connector

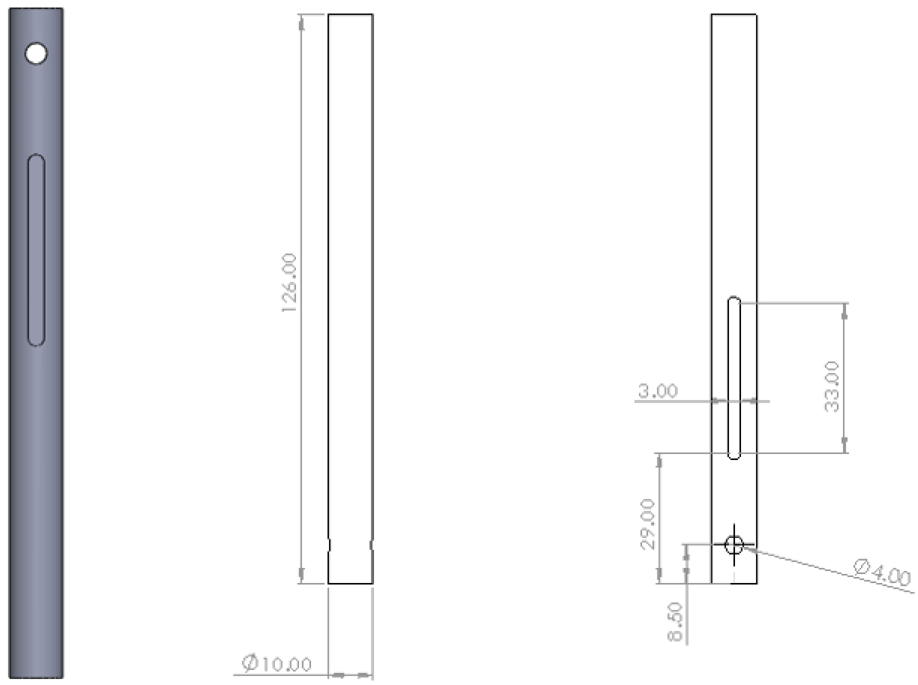


Figure 17: CAD model and dimensions of Arm 1 worm gear shaft

From the previous assembly steps, the worm gear is fixed. Now the worm wheel has to be fixed to the base connecting plate along with the Arm 1 to finish the entire assembly of Arm1. We use the bearing block holder as shown in Figure 18. The bearing block holder is connected to the base connecting plate using M6 bolts.

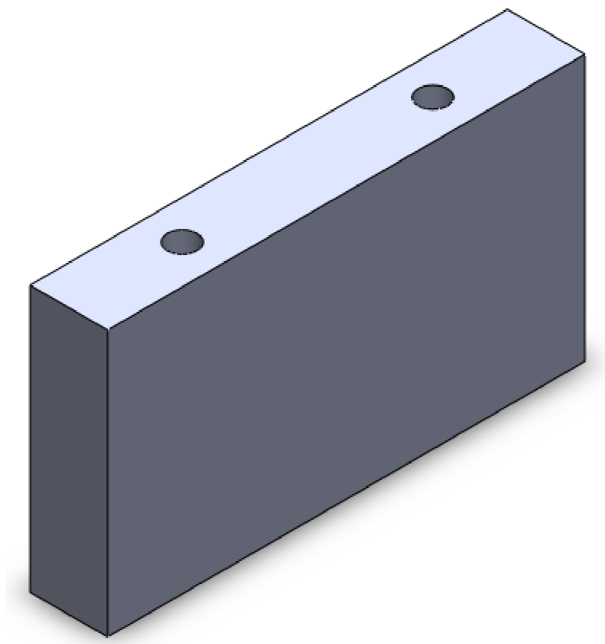


Figure 18: CAD Model of the Bearing block holder

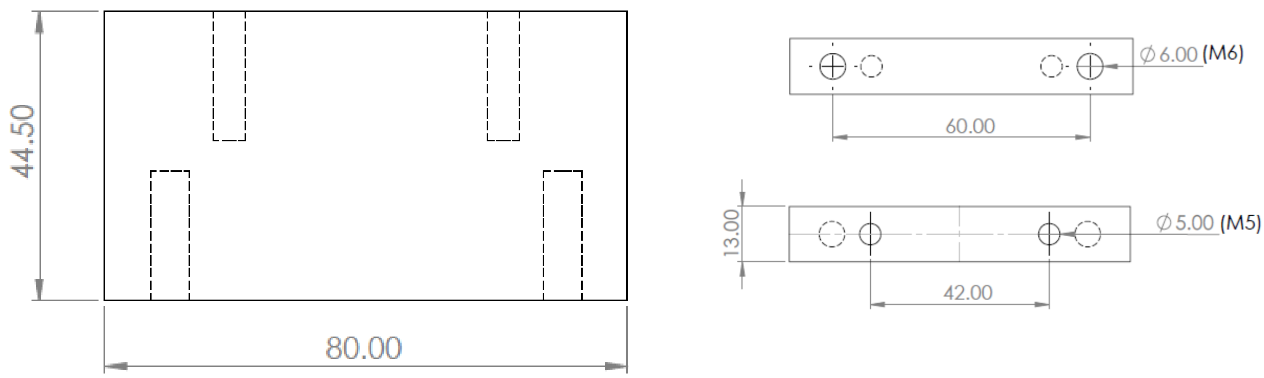


Figure 19: Dimensions of the bearing block holder

The bearing used for supporting the worm wheel shaft is a KP08 Plummer block bearing.

Figure 20: KP08 Plummer block bearing (Jadeshay Store 2018)

The Plummer block bearings as seen in Figure 20 are connected to the bearing holder using M5 bolts. The worm wheel is fixed to the Plummer block bearings thus making it free to rotate. Here some washers are used to adjust the meshing of the worm wheel with the worm gear. The centre distance between the worm wheel and the worm gear is 33mm. So, this distance has to be maintained in order to make the worm gear setup work smoothly. The worm wheel shaft can be locked with the Plummer block bearing using the grub screws provided in the bearings block so the shaft does not move left or right and stays in position there by transferring the rotational motion to the arm.

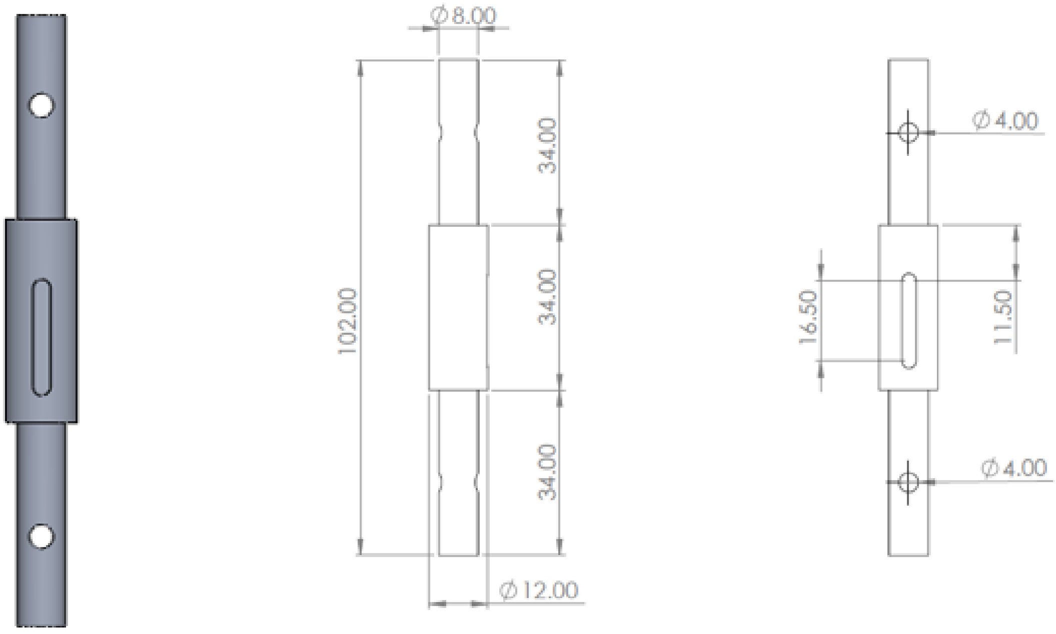


Figure 21: CAD model and dimensions of the Arm 1 worm wheel

The Arm 1 is connected to the worm wheel shaft using a hub as seen in Figure 22. This hub is modelled as seen in Figure 22 and manufactured using 3D printing. The Arm 1 is fixed to this hub using the six M5 bolts. The hub is connected to the worm wheel shaft using a M4 bolts. The connecting bolt runs through the worm wheel shaft thus providing a constant hold of the hub to the shaft.

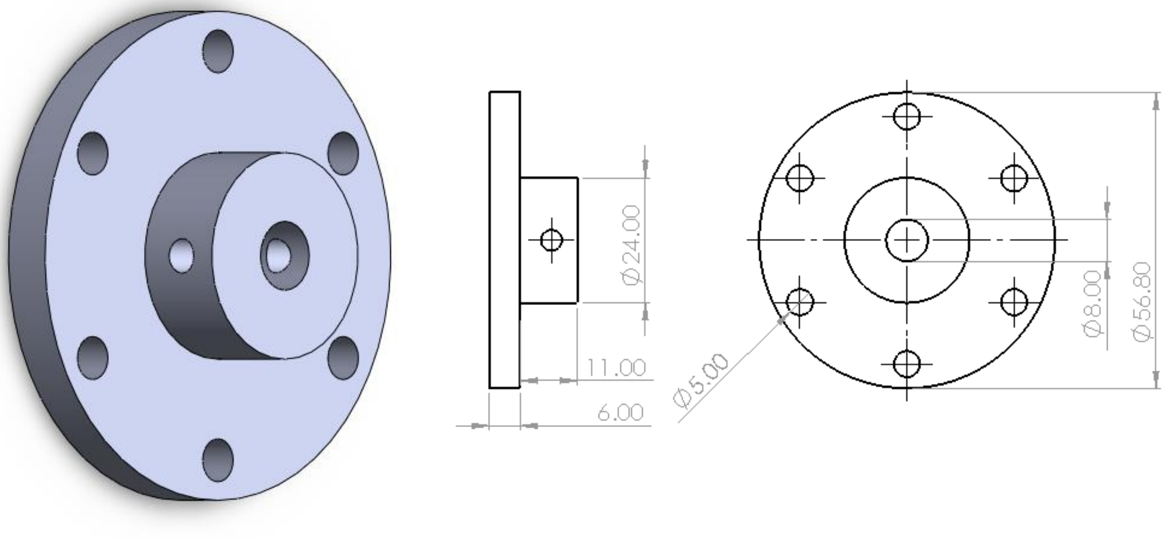


Figure 22: CAD Model and dimensions of Arm 1 hub

Arm 1 as seen in Figure 23 is the left-hand side of the arm and the right-hand side is identical as to the left.

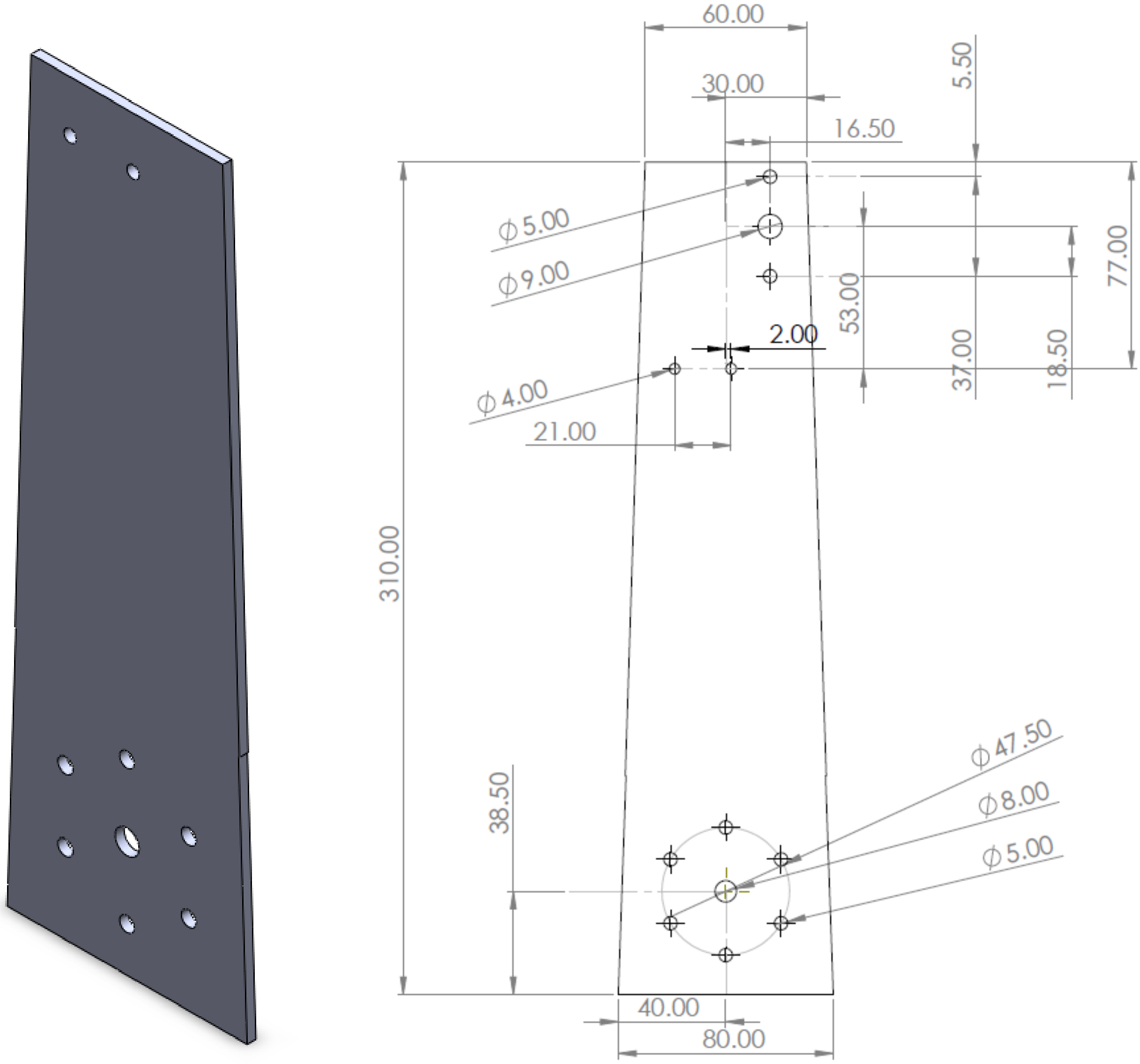


Figure 23: CAD model and dimensions of Arm 1

After setting up all the components as mentioned above, the final assembly of Arm 1 looks like as seen in the Figure 24

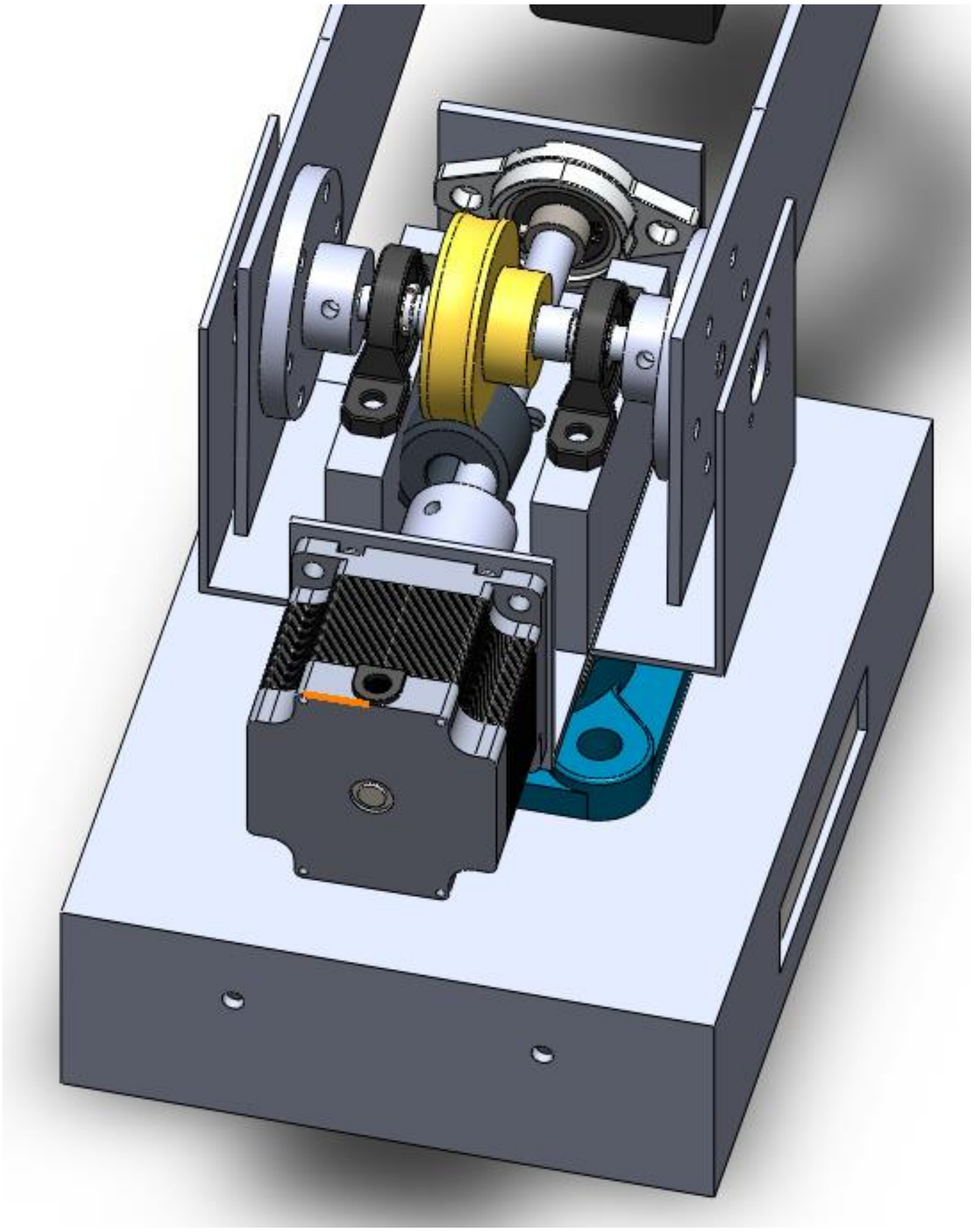


Figure 24: CAD Model of Final Assembly of Arm 1

The exploded view of Arm 1 can be seen in Figure 25 for easier assembly and understanding.

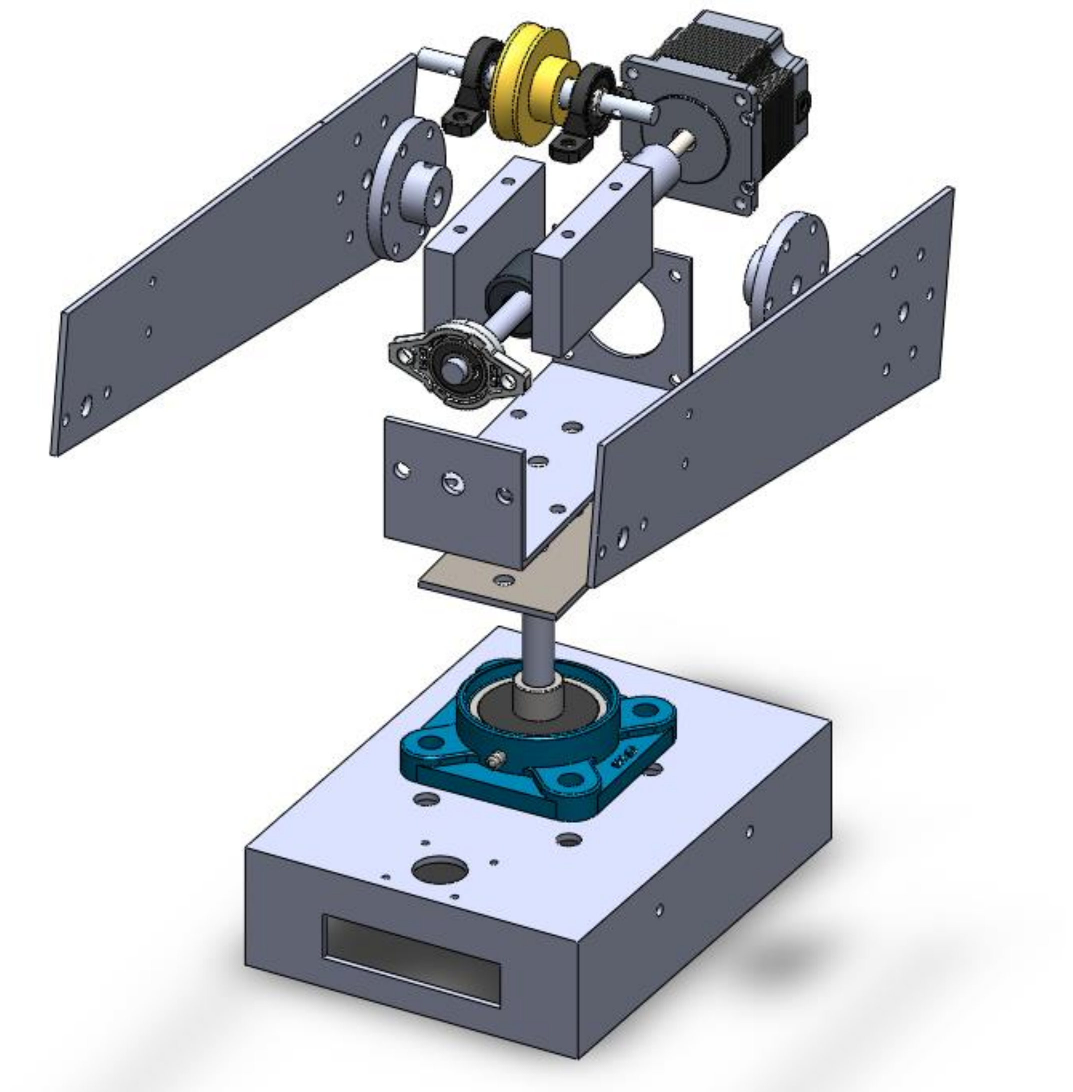


Figure 25: Exploded view of Arm 1

4.4.4 ARM 2 ASSEMBLY

The assembly of Arm 2 is similar to the assembly of Arm 1. Initially the Nema 17 stepper motor is mounted to the Arm using a motor clamp as seen in Figure 26, which is fixed to the Arm1 using M5 bolts. The Nema 17 motor is connected to the worm gear shaft as seen in Figure 29 using a connector as seen in Figure 28.

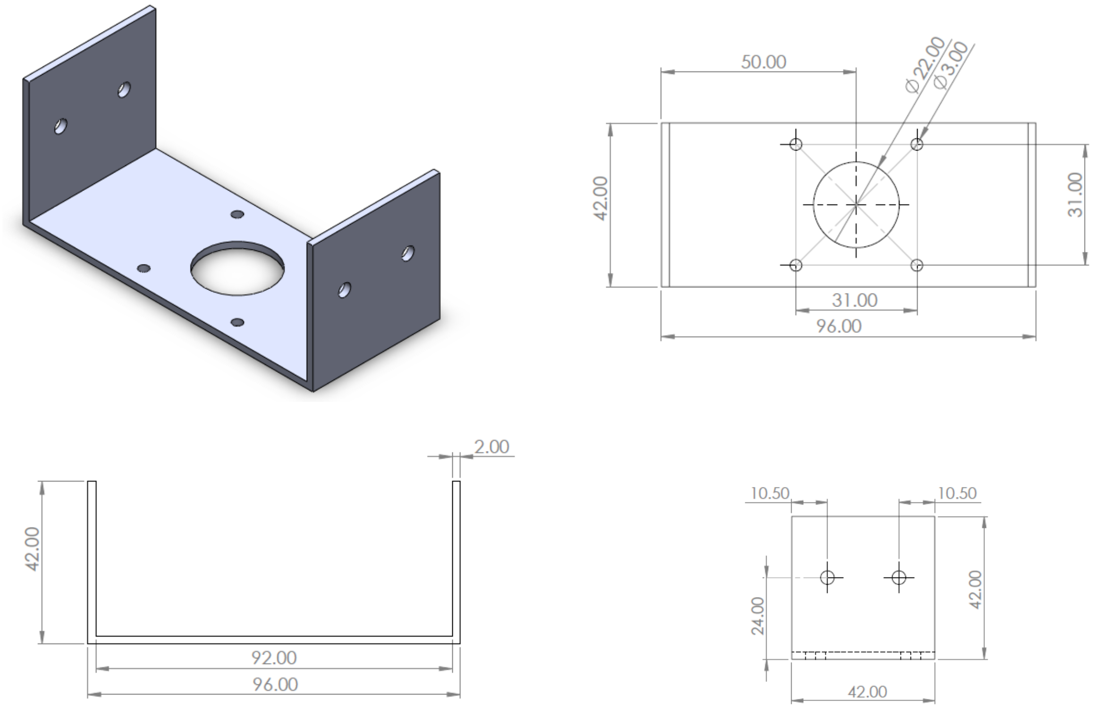


Figure 26: CAD Model and dimensions of Arm 2 motor mount clamp

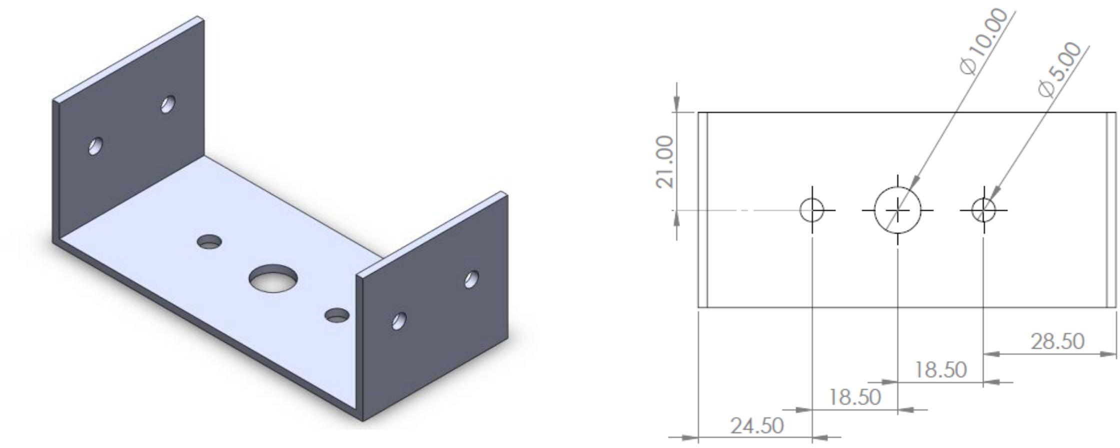


Figure 27: CAD Model and dimensions of Arm 2 motor mount upper part

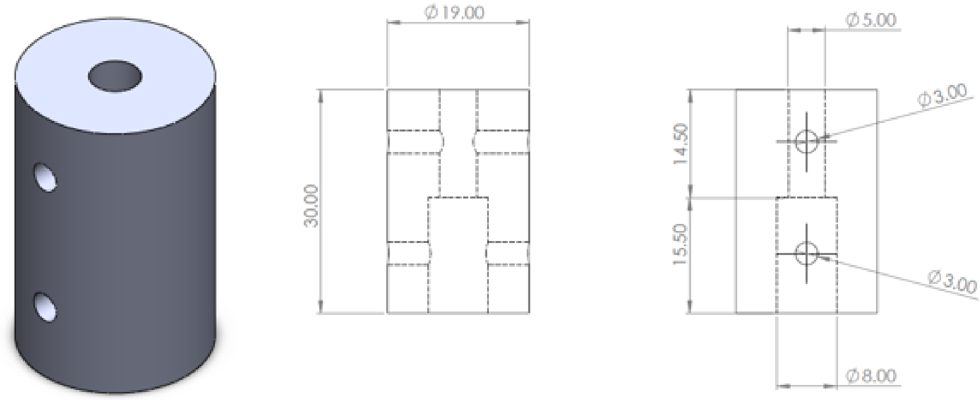


Figure 28: CAD model and dimensions of the 5mm to 8mm connector

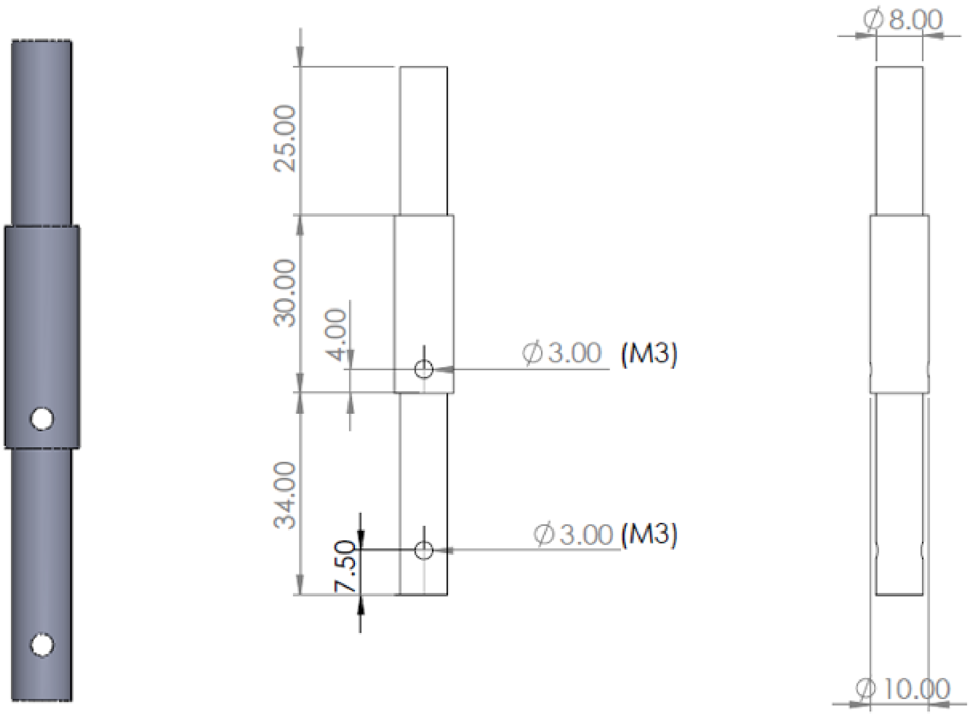


Figure 29: CAD model and dimensions of Arm 2 worm gear shaft

Since, this worm gear shaft is only supported on one end which is connected to the motor, the other end has to be supported in order to rotate the worm gear smoothly. As well as it should be free to rotate at the supported ends so it has to be supported with a bearing. In order to solve this issue a worm gear shaft support bracket as seen in Figure 31 was developed and KFL08 bearings as seen in Figure 30.

Figure 30: KFL08 bearing (ROBU.in 2018)

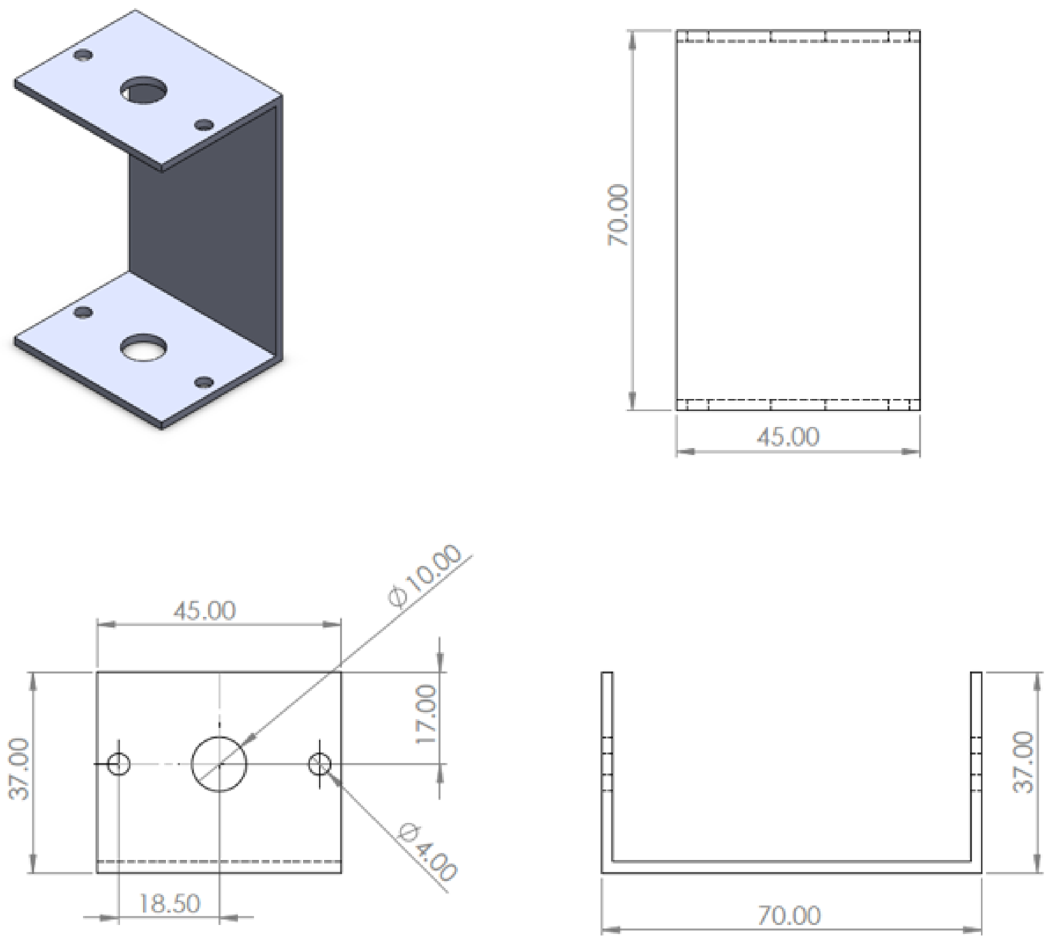


Figure 31: CAD model and dimensions of Arm 2 worm gear shaft suport bracket

The worm wheel is connected to the worm shaft and supported at both the ends using a bearing block holder as seen in Figure 32 and a KP08 bearing.

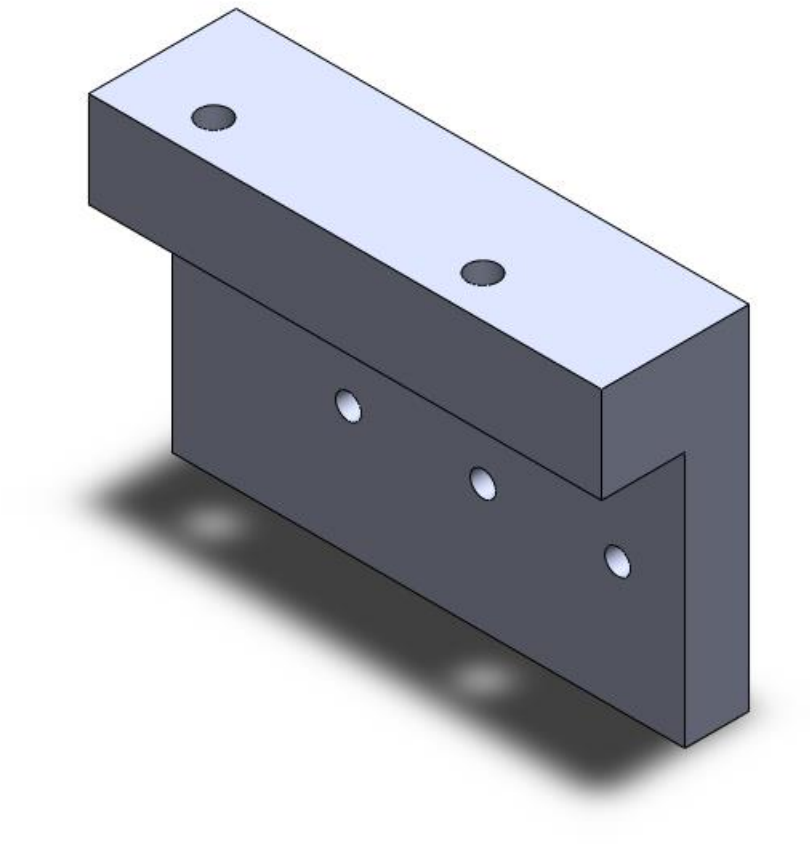


Figure 32: CAD model of Arm 2 bearing block holder

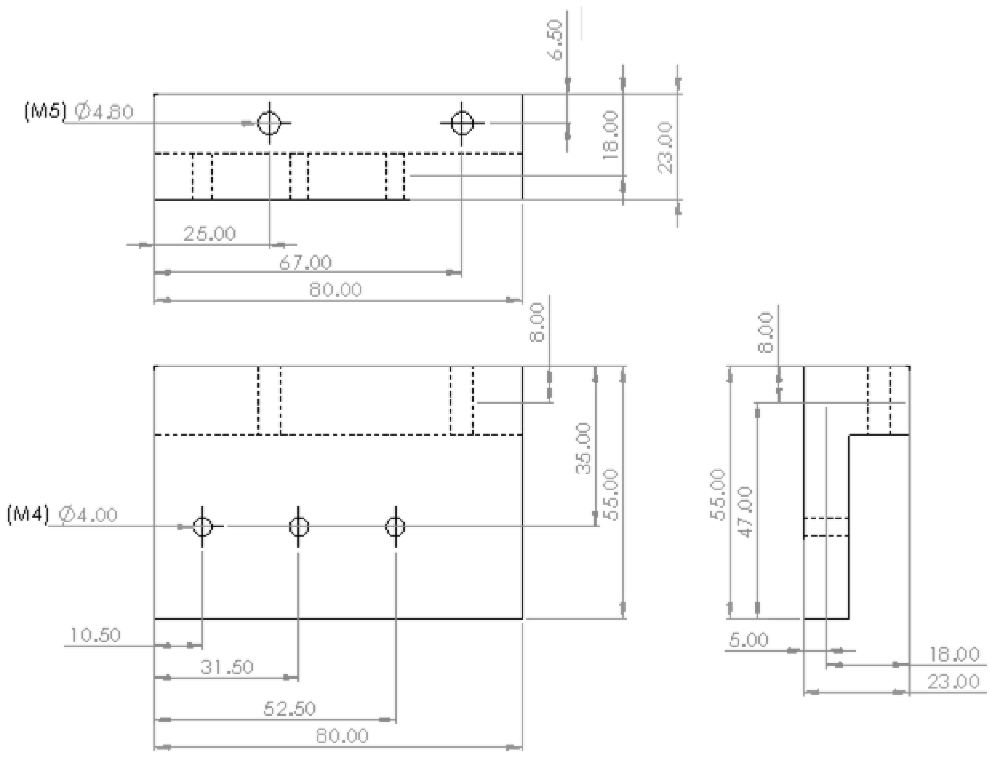


Figure 33: Dimensions of Arm 2 bearing block holder

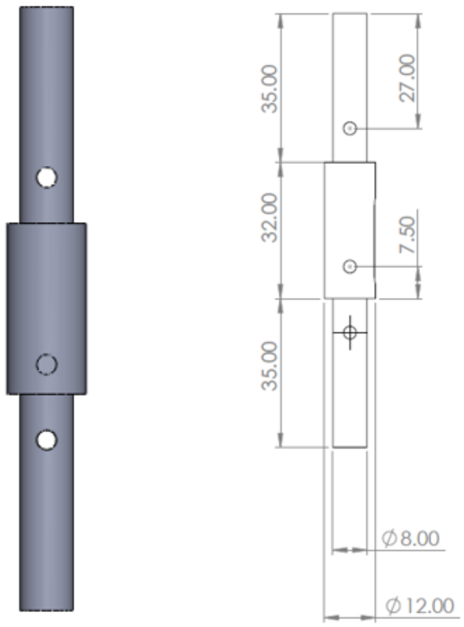


Figure 34: CAD model and dimensions of Arm 2 worm shaft

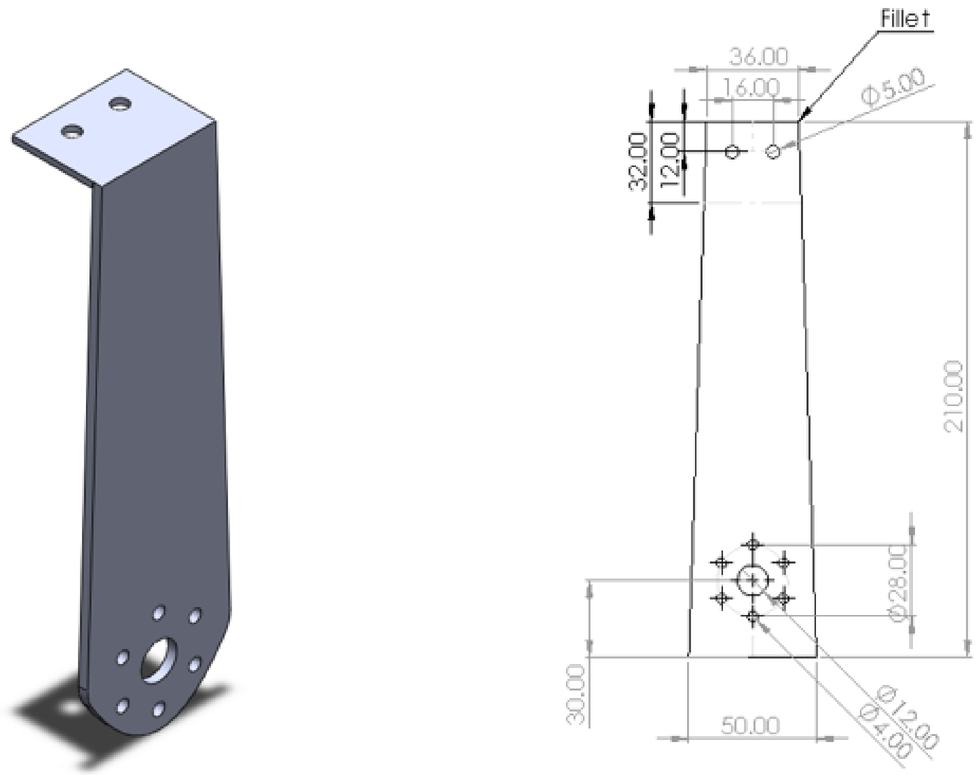


Figure 35: CAD model and dimensions of Arm 2

Figure 35 shows the CAD model and dimensions of Arm 2.

After following the above-mentioned steps, the assembly of Arm 2 looks like as seen in Figure 36.

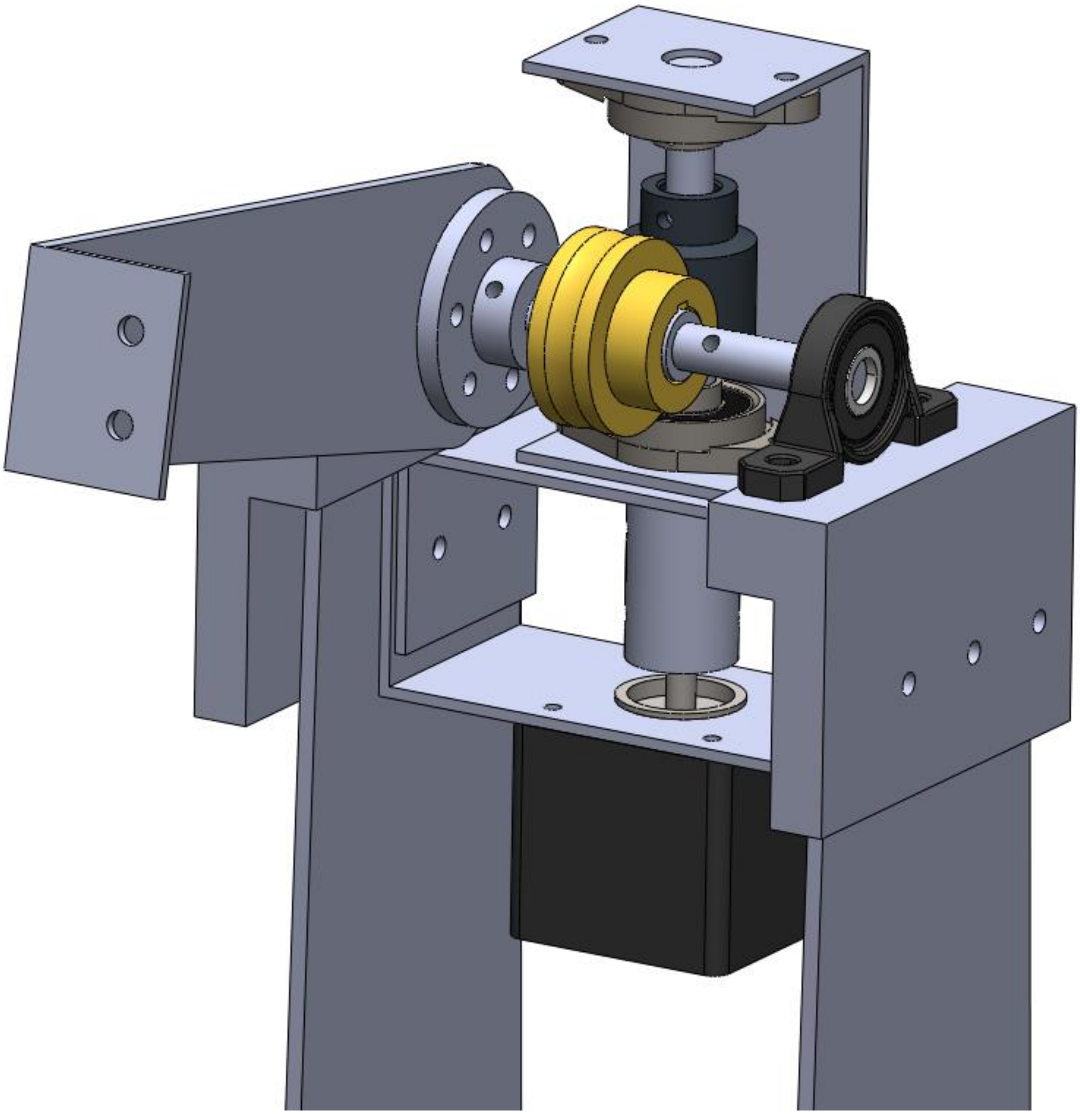


Figure 36: CAD model of Arm 2 assembly

Figure 37 shows the exploded view of the assembly of Arm 2 for easier understanding.

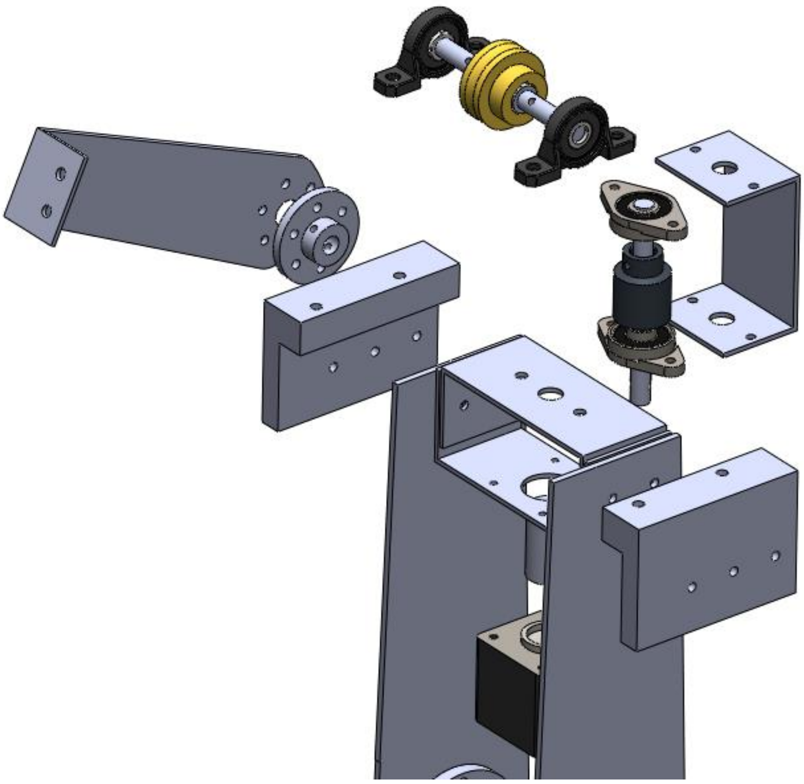


Figure 37: Exploded view of Arm 2

4.4.5 LINK 3 AND GRIPPER

Link 3 is a mount for a servo motor as seen in Figure 38 for the pitch movement along with the base support for the gripper. A Servo MG995 micro servo motor as seen in Figure 51 is used for the pitch movement.

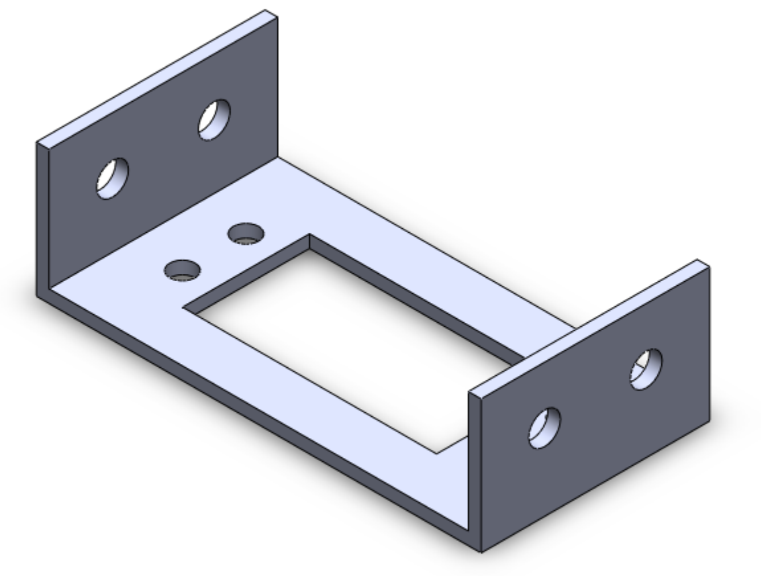


Figure 38: CAD model of Arm 3 servo mount

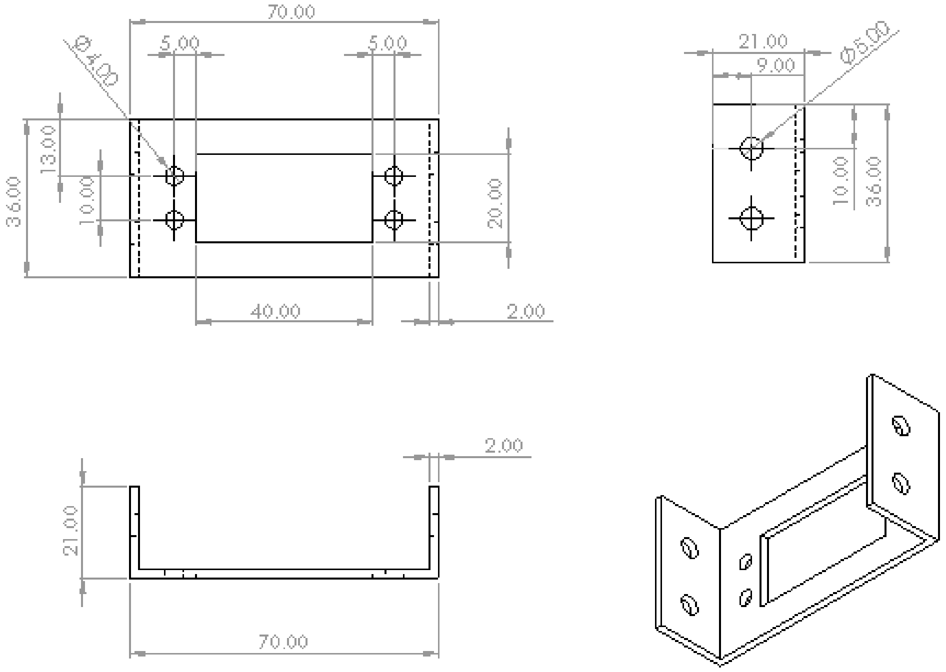


Figure 39: Dimensions of Arm 3 servo mount

The gripper assembly is connected to the MG995 Servo motor using the servo horns. The gripper assembly as seen in Figure 40, is manufactured using FDM process (Fused deposition modelling) as the weight of the entire assembly is less and actuated using a micro servo motor. The infill percentage was set at 50% and the entire weight is around 100 grams along with the fixtures.

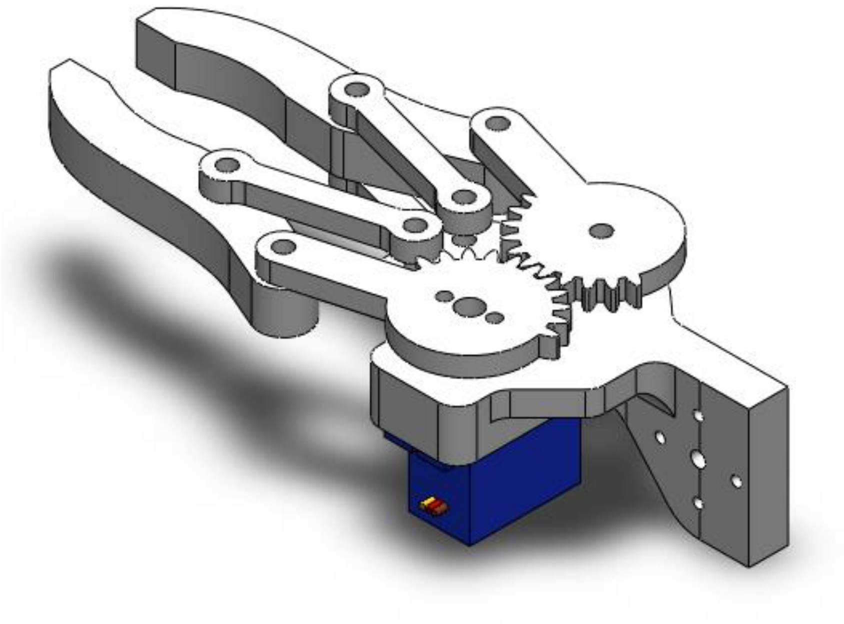


Figure 40: Gripper assembly

4.4.6 FINAL ASSEMBLY

This marks the end of the assembly process. As it can be noticed that all of the fixtured were fixed using a standard metric bolt. This can be modified by the user to replace it with suitable fixtures. The final assembly looks like as seen in Figure 41.

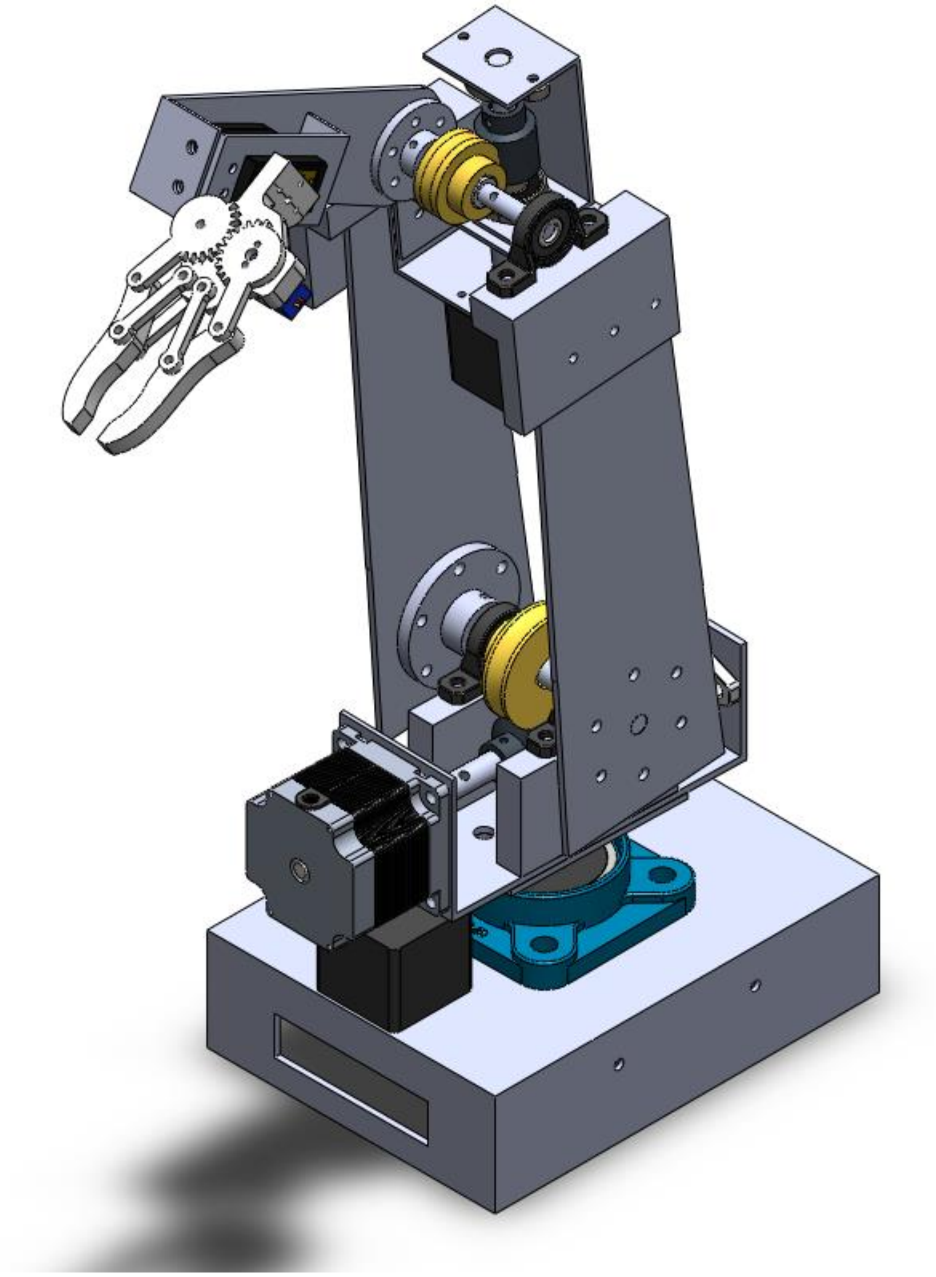


Figure 41: CAD model of the robotic arm final assembly

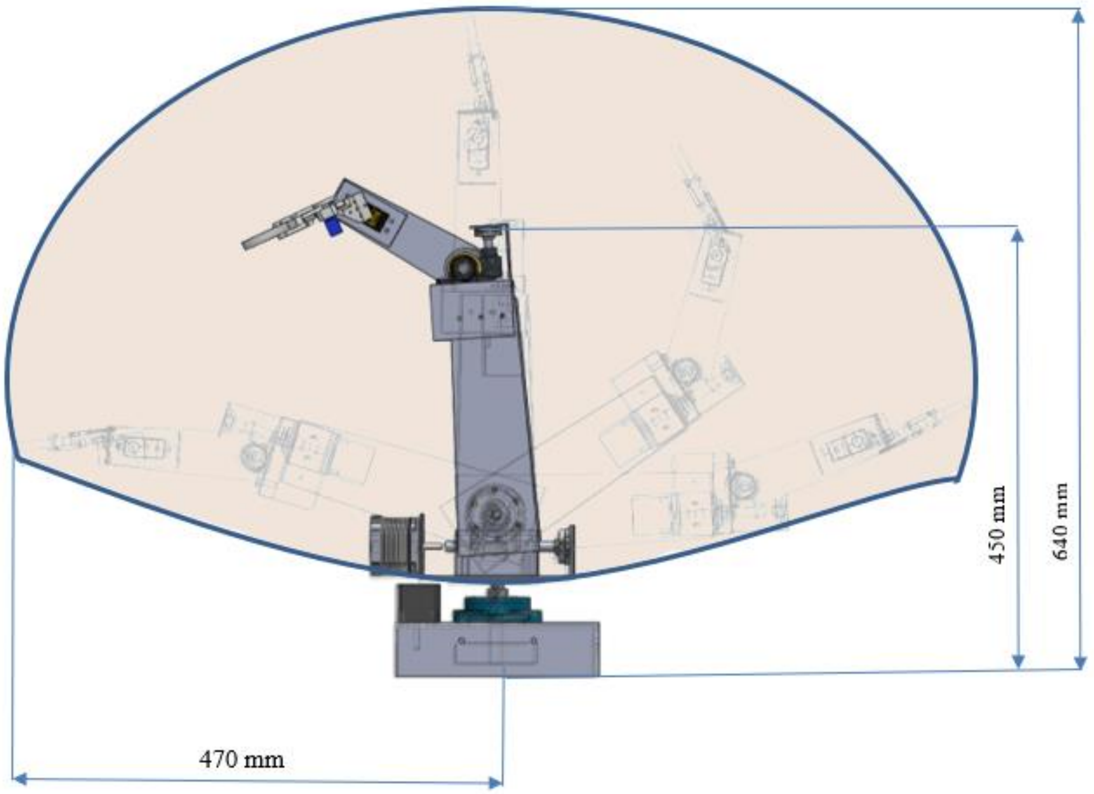


Figure 42: Robotic Arm Workspace

Figure 42 shows the Robotic arm workspace indicated by the light brown area. As it can be seen that the maximum range reached by the robot is more than the range it was designed for which is an advantageous point.

5 ELECTRICAL AND ELECTRONICS

Power supply plays an important role to power a robotic arm since not all the modules work on the same voltage. The various voltage at which the modules operate are 3.3V, 5V, 6V, 12V and 24V. Before stepping into the circuits, it’s better to know the various electrical and electronics components used in order to understand.

5.1 POWER SUPPLY

Since there are various voltage required, we would have to either a transformer to step down or step up the voltage, or it’s also better to use individual power source.
In this project individual power sources were used as it was necessary to meet the current requirements.

5.1.1 24V POWER SUPPLY

As stated by the supplier, the output of the power supply module as seen in Figure 43 is 24V and 5A current. This power supply module is used to power the 24V Nema 23 Stepper motor which is used to control Arm 1.

Figure 43: 24V Power supply module (Docooler 2016)

In this project we are using a Nema 23 Dual shaft motor as seen in Figure 44. The Nema 23 motor works on 24V and 2A maximum current. It has a torque rating of 90 Ncm. The step angle of the stepper motor is 1.8 deg. The dimensions of the stepper motor are 16.6 x 12.6 x 10.2 cm. The stepper motors generally require a motor driver to control the functionality of the motors. Using relevant motor drivers, it is possible to control the step angles of the stepper motor. This process of controlling the step angles of the stepper motor is known as micro-stepping. So, the selected motor driver should be capable of micro-stepping. The Nema 23 Stepper motor looks like as seen in the figure .

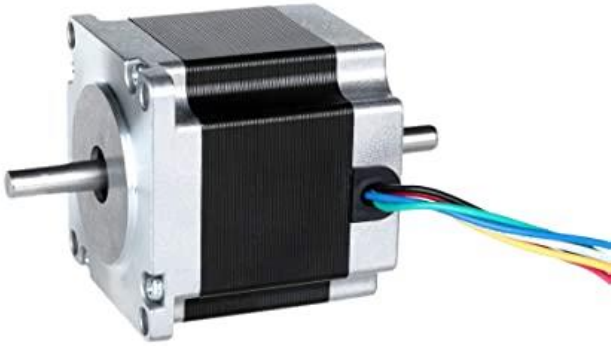


Figure 44: Nema 23 dual shaft stepper motor (ACT Motor store 2016)

DM556 as seen in Figure 45 is the motor driver used for controlling the Nema 23 stepper motor. It different combination of switches which can be used to adjust the step angle and the required current at which it should operate. The stepper drivers give a lot of insight about micro-stepping, current chopping, Indexing and also helps to understand how to decide the power supply impedance. Another interesting factor with this stepper driver is the optical coupling because of which it isolates the device and there is no need to have a common ground.

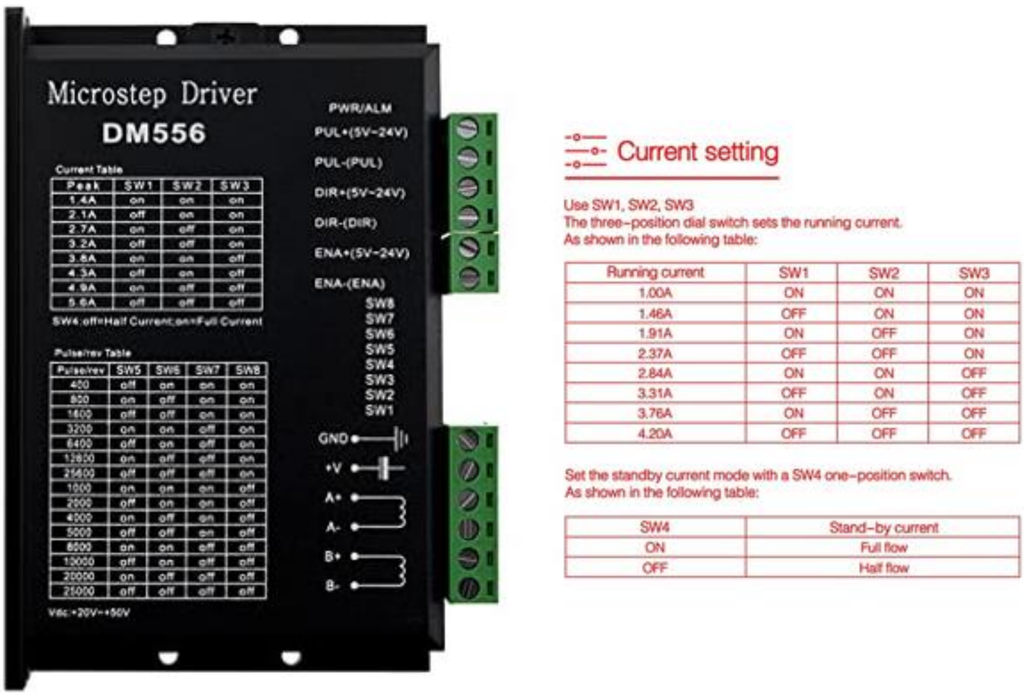


Figure 45: DM556 Stepper motor driver for Nema 23 (Twotrees 2021)

So, in order to control the stepper motor, the connections are to be made as shown in Figure 46 with the micro-controller. The direction pin allows to control the direction of rotation of the stepper motor i.e., by setting the pin high the motor spins in one direction and setting the pin low, the motor spins in the other direction. The pulse signal pin is to be connected with the micro-controller which helps in running the motor.

Figure 46: Wiring reference of Dm556 stepper motor driver (Twotrees 2021)

5.1.2 12V POWER SUPPLY

The 12V power supply as seen in Figure 47 is used to power the Nema 17 stepper motor which is used to actuate Arm 2 and for the base rotation of the robotic arm. It also acts as a power source for the 6V supply. Therefore, 2 stepper motor drivers are used for controlling the stepper motor, TB6600 as seen in Figure 48.

Figure 47: 12V power supply adapter (LEDLUX Store 2021) and Nema 17 Stepper motor (Usongshine 2020)

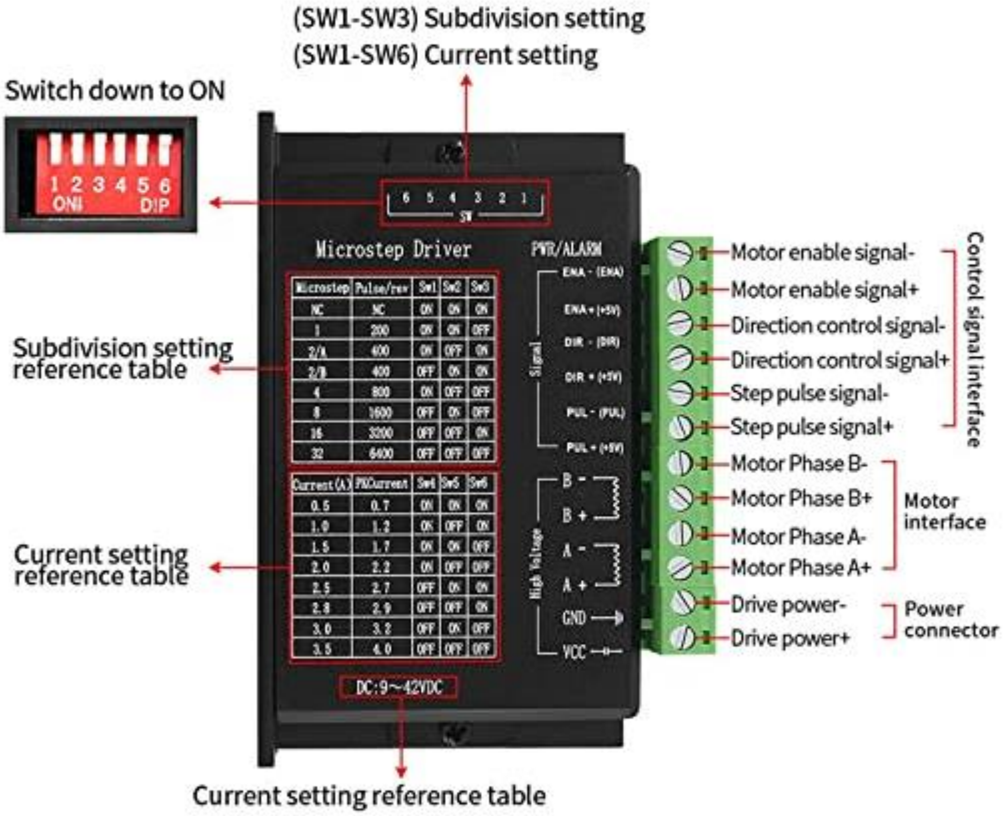


Figure 48: TB6600 stepper driver wiring connection for Nema 17 stepper motor (OUYZGIA 2021)

Similar to the DM556, the connections for the TB6600 are made as shown in the Figure 48

5.1.3 6V POWER SUPPLY

The 6V supply is used to power the Arduino. So, a buck converter chip used to step down the voltage from 12V to 6V. LM2596 as seen in Figure 49 is the DC-DC converter that steps down the voltage and powers the Arduino.

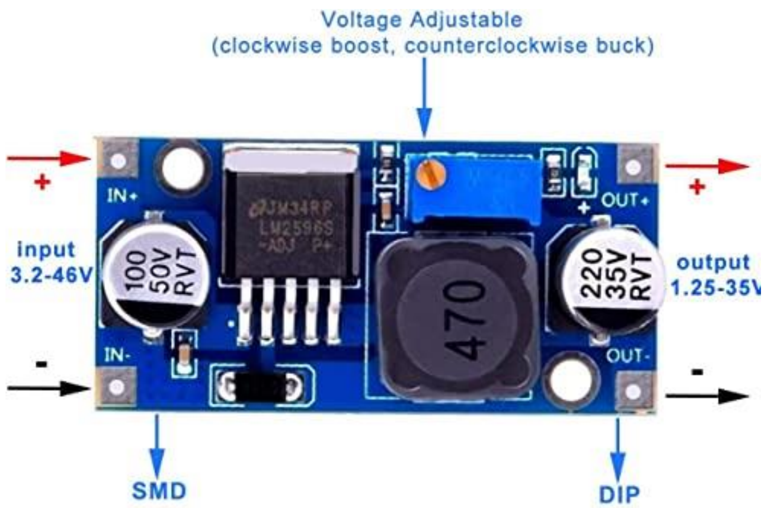


Figure 49: LM2596 step down buck converter (Innovateking-EU 2019)

5.1.4 5V POWER SUPPLY

The 5V power supply is used to power the Servo motors and the multiplexer. So, a 5V bus is created to power all these modules.

The AS5600 as seen in Figure 53 uses I2C for communication. The value from the sensor can be read only by referring to the address of the device. The problem is that all these sensors have the same address so when 2 or more sensors are used, it is difficult to get values since all the AS5600 has the same address. In order to counteract this problem, a multiplexer is used. The TCA9548A as seen in Figure 50 device has eight bidirectional translating switches that can be controlled through the I2C bus.

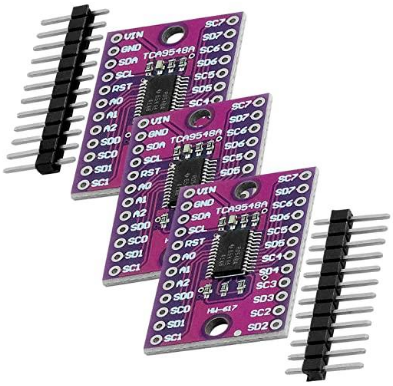


Figure 50: TCA9548A I2C multiplexer (AZDelivery 2020)

Figure 51: MG995 Servo motor with servo horns (AZDelivery store 2018)

The servo motors MG995 as seen in Figure 51 is used to actuate Arm 3

The servo motor SG90 9G as seen in Figure 52 is used to actuate the gripper.

Model	SG 90 Servo	Weight	10g±5%
Size	22.4*12.5*22.8mm	Dead Brand	7us
Quiescent Current	5mA	Output Shaft	20T (4.8mm)
No-load Current	90mA	Stall Current	750mA
Pulse Signal PWM	50Hz/0.5- -2.5ms		
No-load Speed	0.09S/60 degree@4.8V		
Operating Voltage Range	4.8V~ 6.0V		
Operating Temperature Range	-25° C~ 70° C		

Figure 52: SG90 servo motor with motor specifications (RUIZHI 2021)

5.1.5 3.3V POWER SUPPLY

A contactless sensor, AS5600 as seen in Figure 53 is fixed next to the robotic arm to get the angle feedback of the robotic arm. It’s an absolute sensor and it works based on Hall effect principle. So, a neodymium magnet is fixed to the worm shaft using a screw to get the angle readings from the sensor.

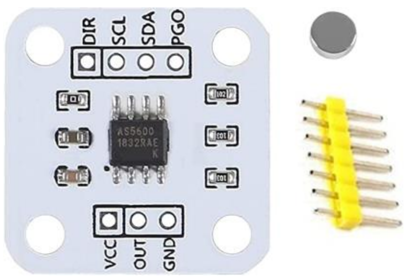


Figure 53: AS5600 sensor (Bzocio 2022)

5.2 CIRCUIT DIAGRAM

Figure 54 shows the wiring connections that are to be made for the Robotic arm. The controller that is used in this project is Arduino Mega 2560. According to (Arduino 2009), The Arduino Mega 2560 is a microcontroller board based on the ATmega2560. It has 54 digital input/output pins (of which 15 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. As it can be seen that there are still many pins left unused which could be used in the future for more advanced versions of the Robotic Arm.

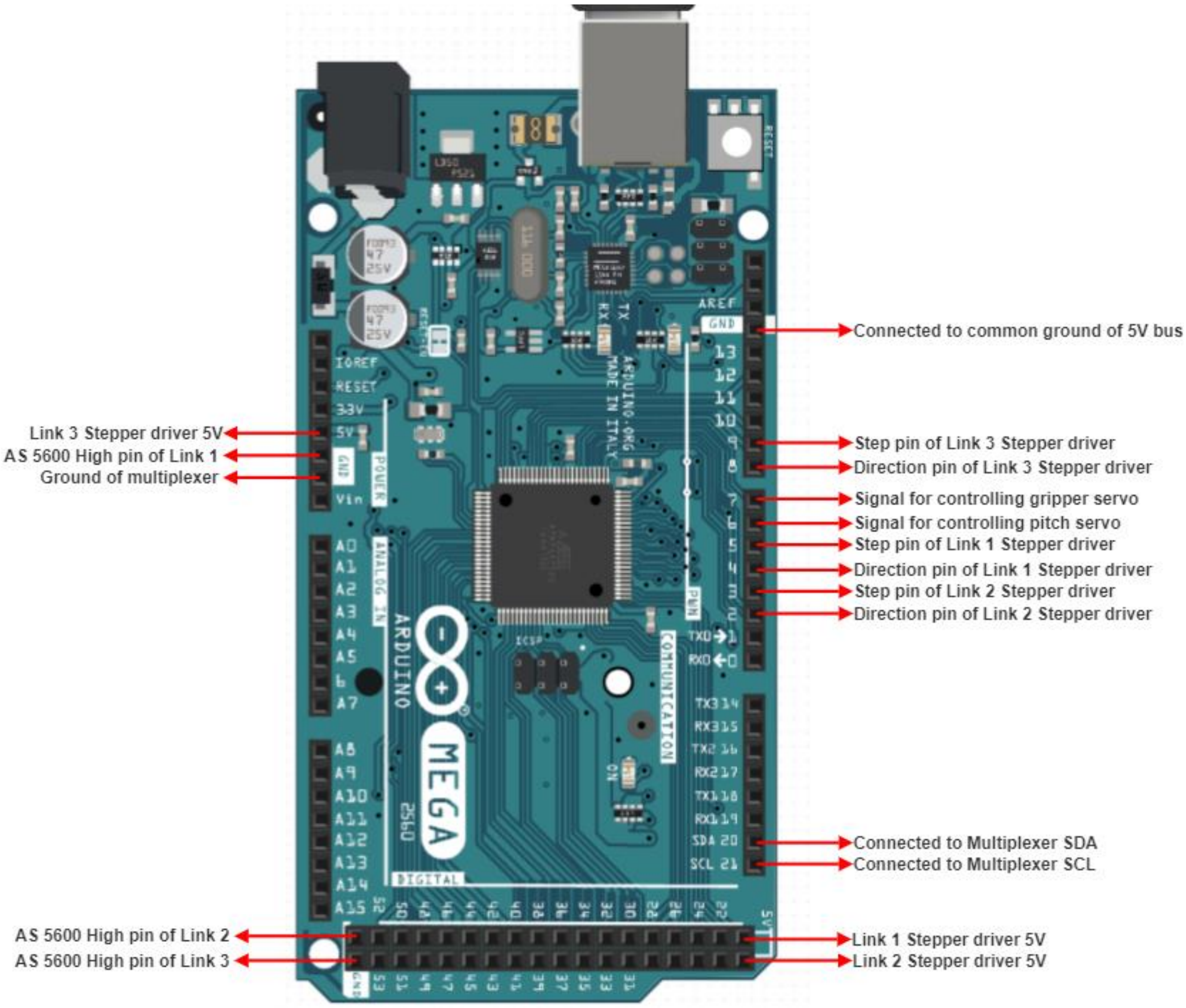
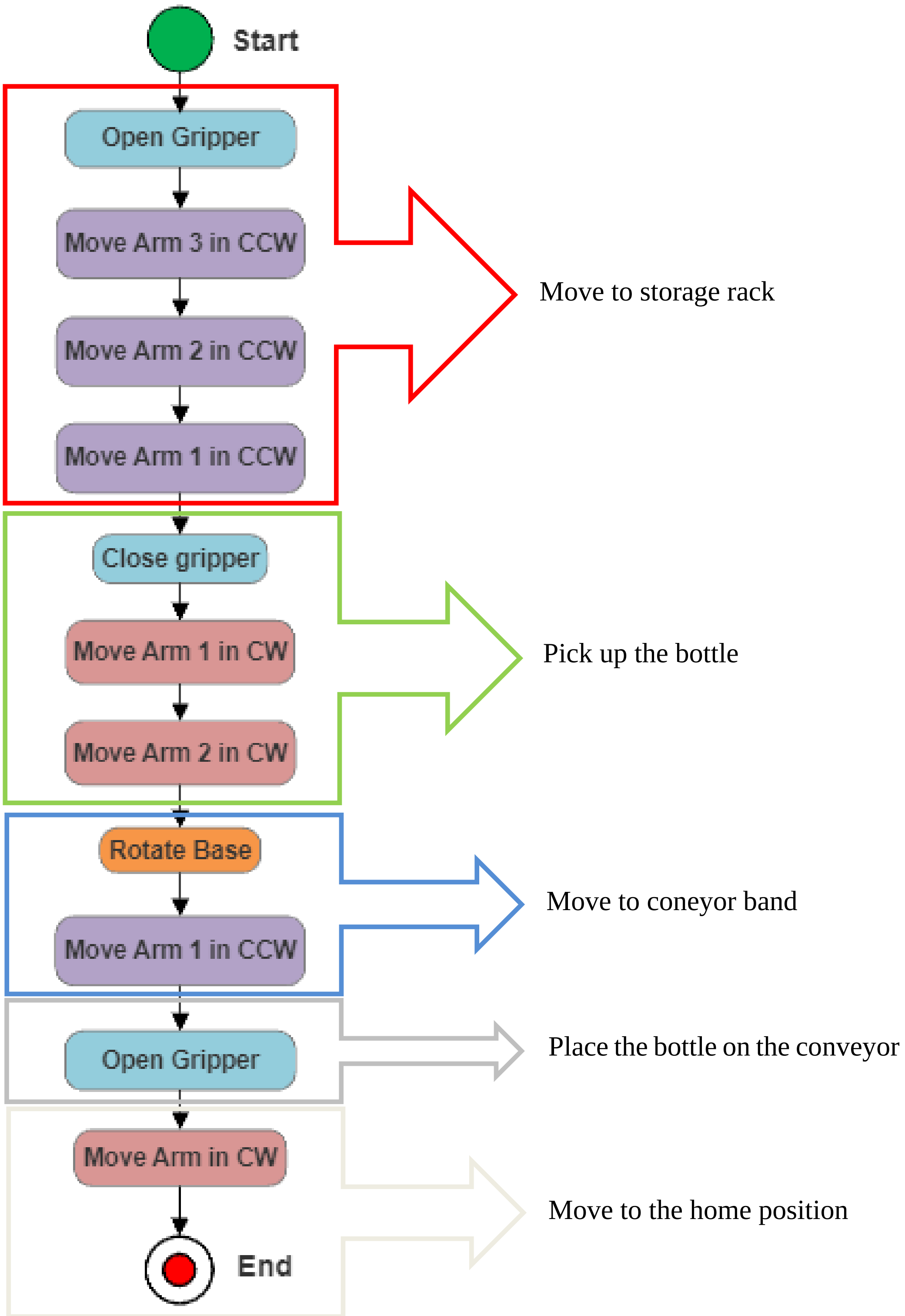


Figure 54: Robotic arm wiring connections in Arduino Mega 2560

6 PROGRAMMING

Arduino Mega 2560 was the controller that was used to control the robotic arm and the programming was done in the Arduino IDE. The program is as follows,

6.1 PROGRAM FLOW DIAGRAM



6.2 ARDUINO CODE

```
//Including the stepper library
#include <Stepper.h>

// Number of steps per output rotation
const int stepsPerRevolution = 100;

// Define stepper motor connections and steps per revolution:
// for link 1

#define dirPin 4
#define stepPin 5
#define stepsPerRevolution1 1600

// for link 2

#define dirPin1 2
#define stepPin1 3
#define stepsPerRevolution2 3200

// base rotation
#define dirPin2 40
#define stepPin2 38
#define stepsPerRevolution3 3200
// for servo Pitch movement and Gripper

#include <Servo.h>
Servo servog; // Servo for gripper
Servo servop; // Servo for pitch

void setup()
{

// for link 1
  pinMode(stepPin, OUTPUT);
  pinMode(dirPin, OUTPUT);

// for link 2
  pinMode(stepPin1, OUTPUT);
  pinMode(dirPin1, OUTPUT);

// servo pitch
servop.attach(6);


// servo gripper
servog.attach(7);

// Stepper Base rotation setup
// set the speed at 5 rpm:
// myStepper.setSpeed(5);
```

```
}

void loop()
{

servog.write(20);
delay(1000);
servop.write(0);
delay(1000);
servop.write(20);
delay(1000);
servop.write(0);
delay(1000);

// Link 2 to pick up the bottle
   // Set the spinning direction clockwise:
  digitalWrite(dirPin1, HIGH);

  // Spin the stepper motor 1 revolution slowly:
  for (int i = 0; i < 1000; i++) {
    // These four lines result in 1 step:
    digitalWrite(stepPin1, HIGH);
    delayMicroseconds(2000);
    digitalWrite(stepPin1, LOW);
    delayMicroseconds(2000);
  }

  delay(1000);

// Link 1 to pick up the bottle

 // Set the spinning direction clockwise:
  digitalWrite(dirPin, LOW);

  // Spin the stepper motor 1 revolution slowly:
  for (int i = 0; i < 5000; i++) {
    // These four lines result in 1 step:
    digitalWrite(stepPin, HIGH);
    delayMicroseconds(2000);
    digitalWrite(stepPin, LOW);
    delayMicroseconds(2000);
  }

  delay(1000);

// Gripper to close so that the bottle is picked up

servog.write(0);
delay(1000);
```

```
// Link 1 to home position

// Set the spinning direction anti-clockwise:
  digitalWrite(dirPin, HIGH);

  // Spin the stepper motor 1 revolution slowly:
  for (int i = 0; i < 5000; i++) {
    // These four lines result in 1 step:
    digitalWrite(stepPin, HIGH);
    delayMicroseconds(2000);
    digitalWrite(stepPin, LOW);
    delayMicroseconds(2000);
  }

  delay(1000);

// Link 2 to home position

 // Set the spinning direction clockwise:
  digitalWrite(dirPin1, LOW);

  // Spin the stepper motor 1 revolution slowly:
  for (int i = 0; i < 1000; i++) {
    // These four lines result in 1 step:
    digitalWrite(stepPin1, HIGH);
    delayMicroseconds(2000);
    digitalWrite(stepPin1, LOW);
    delayMicroseconds(2000);
  }

  delay(1000);

//

//Base rotation
// Step half revolution in clockwise direction
//myStepper.step(-stepsPerRevolution);
 // delay(500);

/////// Robot base is rotated and the bottle is to be place on to the conveyor

 // Set the spinning direction clockwise:
  digitalWrite(dirPin2, LOW);

  // Spin the stepper motor 1 revolution slowly:
  for (int i = 0; i < 5000; i++) {
    // These four lines result in 1 step:
    digitalWrite(stepPin2, HIGH);
    delayMicroseconds(2000);
    digitalWrite(stepPin2, LOW);
    delayMicroseconds(2000);
```

```
  }

  delay(1000);

// The gripper is to be loosened to place the bottle on the conveyor

servog.write(20);
delay(1000);

//The robot returns back to its home position
// Set the spinning direction clockwise:
  digitalWrite(dirPin, HIGH);

  // Spin the stepper motor 1 revolution slowly:
  for (int i = 0; i < 5000; i++) {
    // These four lines result in 1 step:
    digitalWrite(stepPin, HIGH);
    delayMicroseconds(2000);
    digitalWrite(stepPin, LOW);
    delayMicroseconds(2000);
  }

  delay(1000);

// The robot comes back to its original state where it picked the bottle
//Base rotation
// Step half revolution in clockwise direction
//myStepper.step(stepsPerRevolution);
 //delay(500);

//End of the program

}
```

7 CONCLUSION

The 4 DOF robotic arm is a wonderful mechatronics system that covers all the aspects of mechanical, electrical and computer science. From an educational stand point of view this project would be possible to easily implement by anyone and also to understand the concepts of the mechatronics subject with a practical approach. The total estimated cost of this robotic arm is around 500 Euros. Figure 55 shows the final version of the 4DOF Robotic arm.

Figure 55: 4DOF Robotic Arm

The future scope of this robotic arm would be to make it as a closed loop control using inverse kinematic concepts i.e., the robot should be capable of determining the joint angles on its own when given the world co-ordinates of the points where it has to move.

By this way the robot could perfectly be suitable for an Industry 4.0 plant where it can automatically move to pick up and place an object within the plant.

The further advancement of this project would also be to drive the robot joints through vision feedback. Through the concept of visual servoing the robot would be able to move itself closer to a identified object by placing a camera at the TCP of the robotic arm. Through this technique the robot would be able to pick and place an object irrespective of a fixed location in the world co-ordinate.

In addition, it is also planned to control the robotic arm using a tablet which would act as a teach pendant.

8 REFERENCES

1. ACT Motor store. 2016. https://amzn.eu/d/9IdwYFm (accessed 2022).
2. Arduino . 2009. https://store.arduino.cc/products/arduino-mega-2560-rev3 (accessed 2022).
3. AZDelivery. 2020. https://amzn.eu/d/3cyoxk5 (accessed 2022).
4. AZDelivery store. 2018. https://amzn.eu/d/i3MscLg (accessed 2022).
5. Bzocio. *Amazon.de.* 2022. https://amzn.eu/d/7HVBDkm (accessed 2022).
6. Docooler. 2016. https://amzn.eu/d/gH12kuj (accessed 2022).
7. Dragulescu, Doina and Perdereau, Veronique and Drouin, Michel and STANCIU, Loredana and Menyhardt, Karoly. "3D active workspace of human hand anatomical model." *Biomedical engineering online,* 06 2007: 15.
8. Framo Morat. 2014. https://framo-morat.com/products/worm-gear-sets/worm-gear-sets-a17/ (accessed 2022).
9. Innovateking-EU. 2019. https://amzn.eu/d/h4rfHR1 (accessed 2022).
10. Jadeshay Store. 2018. https://amzn.eu/d/gP3oxPd (accessed 2022).
11. LEDLUX Store. 2021. https://amzn.eu/d/boR6anm (accessed 2022).
12. M, Saif. 2022. https://www.theengineerspost.com/types-of-gears/ (accessed 2022).
13. OUYZGIA. 2021. https://amzn.eu/d/0bx1TkI (accessed 2022).
14. ROBU.in. *ROBU.in.* 2018. https://robu.in/product/8mm-inner-diameter-zinc-alloy-pillow-block-flange-bearing-kfl08/ (accessed 2022).
15. RS Online. 1937. https://au.rs-online.com/web/p/bearing-units/7508762 (accessed 2022).
16. —. 1983. https://de.rs-online.com/web/p/lagergehause/3112724 (accessed 2022).
17. RUIZHI. *Amazon.* 2021. https://amzn.eu/d/9YpgJYZ (accessed 2022).
18. Spectral Engines. 2 26, 2018. https://www.spectralengines.com/articles/industry-4-0-and-how-smart-sensors-make-the-difference (accessed 2022).
19. Twotrees. 2021. https://amzn.eu/d/4U4RCGt (accessed 2022).
20. Usongshine. 2020. https://amzn.eu/d/hiiTFgV (accessed 2022).
21. Wikipedia. 2007. https://en.wikipedia.org/wiki/Robotic_arm (accessed 2022).
22. Woernle, Prof. Dr.- Ing. habil. Christoph. *Universität Rostock.* 2019. https://www.igp.fraunhofer.de/content/dam/agp/de/documents/Lehre/Skripte/Robotertechnik/RTWoernle_PW_18-19.pdf.