Design and Development of 5 link 2-D Pantograph Parallel Robot

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THESIS SUBMITTED TO

DEPARTMENT OF MECHANICAL ENGINEERING INDIAN INSTITUTE OF TECHNOLOGY (ISM), DHANBAD – 826004

16 May 2023

For the award of the degree of **BACHELOR OF TECHNOLOGY**

Supervisor: Prof. Arun Udai

CERTIFICATE

This is to certify that the thesis titled "Design and Development of 5 link 2-D Pantograph Parallel Robot" being submitted by Mr. Ninad Reshim Nakade (Admission no: 19JE0574) and Mr. Abhishek Aman (Admission no: 19JE0024) for the award of the degree of Bachelor of Technology in the Department of Mechanical Engineering of Indian Institute of Technology (Indian School of Mines), Dhanbad is a record of bonafide research work carried out by him/her under my supervision. In my opinion, the thesis is worthy of consideration for the award of the degree of Bachelor of Technology in accordance with the regulations of the institute. The results presented in the thesis have not been submitted to any other university or institute for the award of any degree.

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Date: 16-May-2023

DECLARATION

I hereby declare that the work which is being presented in this dissertation entitled "Design and Development of 5 link 2-D Pantograph Parallel Robot" in partial fulfillment of the requirements for the award of the degree of B.Tech in is an authentic record of my own work carried out during the period from June 2022 to May 2023 under the supervision of Prof. Arun Udai Department of Mechanical Engineering, Indian Institute of Technology (ISM) Dhanbad, Jharkhand, India.

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I further declare that no portion of the dissertation or its data will be published without the Institute's or Guide's permission. I have not previously applied for any other degree or award using the topics and findings described in my dissertation.

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ACKNOWLEDGEMENTS

We would like to convey our appreciation to all whom have played a role for completion of his/her B. Tech thesis work. We would like to thank our supervisor Prof Arun Udai who has provided us with crucial components of the work like motors, SBC, carbon fibre rods, helpful guidance among many other useful things. We would like to thank head of the department Prof Amit Dixit for granting us permission for 3D printing all the necessary components. We would like to thank 3D printing lab in-charge Mr.Gopalji for assisting us and helping us to 3D print all necessary components. We would also like to thank Robotics and Automation Lab research scholars Mr. Himanshu Varshney and Mr. Ashish Sidharth for helping us in our work.

Ninad Reshim Nakade
Abhishek Aman

Date:16-May-2023

ABSTRACT

The paper describes the process of Design and Development of 5 link 2-D Pantograph Parallel Robot for vision-based pick and place operations. Mechanical design, manufacturing of components and development of the control software, consisting of image segmentation using HSV thresholding to extract the object coordinates and implement the Inverse kinematics to get the actuator output angles have been discussed.

Contents

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Chapter 1

Introduction

The Pantograph is a kind of mechanism or more specifically a linkage which has only lower joints, consists of 5 links and 5 revolute joints. It is a planer 2D linkage. From Kutzbach criterion, it can be seen that it has 2 degrees of freedom, which means that the mechanism can defined by 2 parameters.The 2 parameters are the angles of 2 links attached to 2 motors which are fixed on frame.The next two links are connected together at a point, forming a closed chain, parallel robot. This is the end point that are we trying to control to traverse the 2D plane to pick and place magnetic objects with help of a linear actuator and an electromagnet working as end effector. The position input will be provided by a camera which will locate the object to be picked and placed.

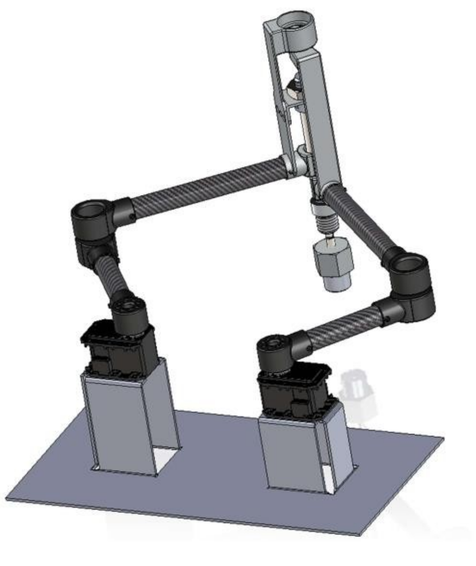


Figure 1.1: CAD Design of 2-DOF, Pantograph Robot.

Chapter 2

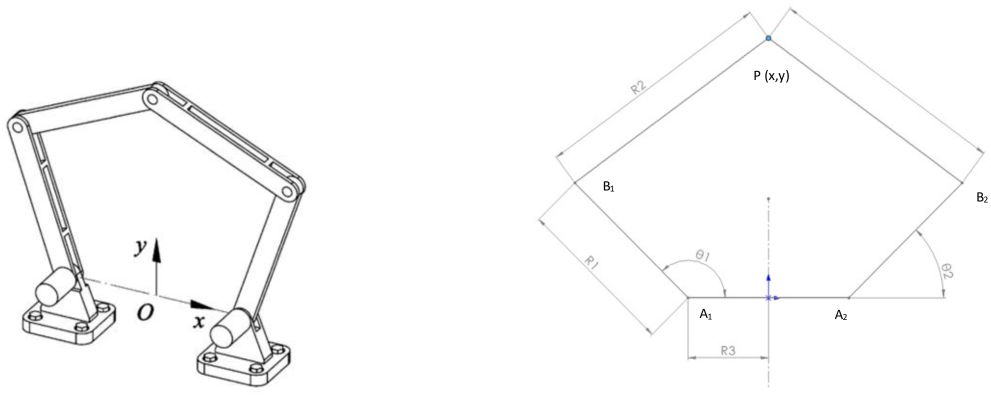
Review of Literature

2.1 Determination of Link Lengths and Dimensions

The choice of link length is one of the core features of this study. [1] and [2] papers are in continuation where first paper discusses identification of range of link length ratios and singularities associated with it. Paper [2] discusses various performance indexes through performance atlases in design space associated with link lengths for optimal link length.

2.1.1 Kinematics

For kinematics, refer to section 4.1.



(a) Pantograph (b) Coordinate System

Figure 2.1: The planar 5R parallel mechanism.

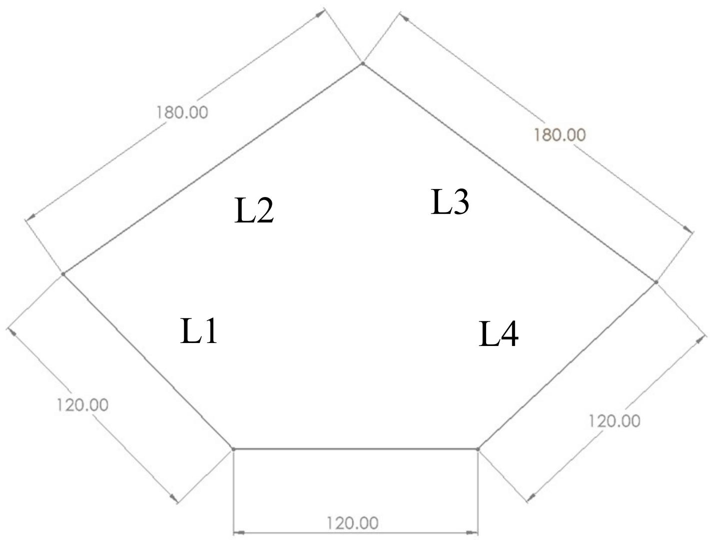


Figure 2.2: Line Diagram of Link Lengths

2.1.2 Theoretical workspace

Theoretical workspace is the area bound where the end effector can reach.

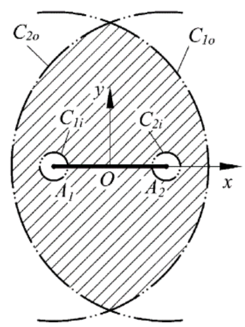


Figure 2.3: Theoretical workspace

Curve C_{2o} is formed when link L1 and L2 are parallel hence fully extended. Similarly curve C_{1o} is formed by L3 and L4.

Curve C_{2i} is formed when link L1 and L2 are anti-parallel hence fully retracted. Similarly curve C_{1i} is formed by L3 and L4.

2.1.3 Jacobian Matrix

The Jacobian Matrix relates joint angle velocities to end effector velocity.

From section 4.1, equations 6) and 7) can be differentiated to with respect to time to obtain velocity equations.

A d**θ**/dt =B d**v**/dt

Jacobian Matrix of mechanism can then be written as

J=A^{-1} B

2.1.4 Singularites

Singularities are conditions when

1. Workspace Boundary is reached.
2. Jacobian becomes singular. In that case the DOF mechanism changes instantaneously. It can arise when either A or B or both becomes singular.

The paper further discusses study of link length ratios and maps of theoretical workspace along with associated singularities.

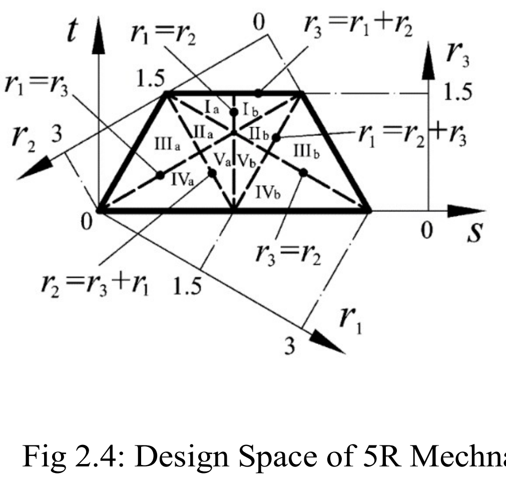


Fig 2.4: Design Space of 5R Mechnaism

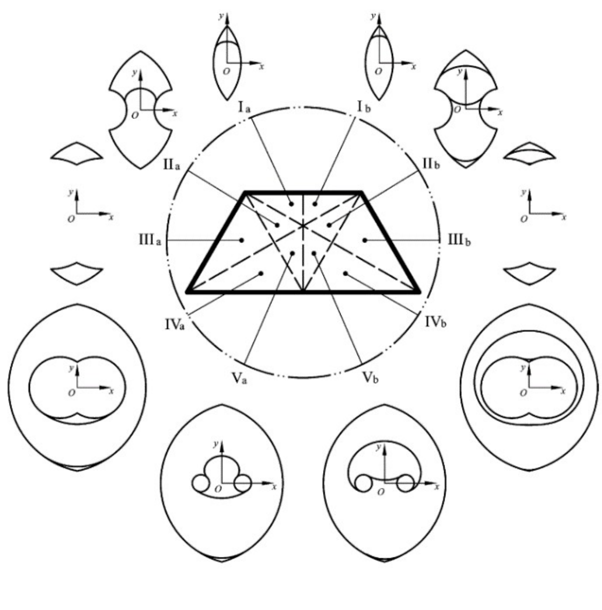


Fig 2.5: Workspace with Singularity in +-

Work Area can be doubled condition $r_2=r_3+r_1$.
From figure 2.4, it can be seen that region IVa and Va divided by $r_2=r_3+r_1$ has sufficient workspace free from singularity. We tried to stay on line $r_2=r_3+r_1$.

Chapter 3

Methodology for Designing

3.1 Design and Manufacturing of Components

The Pantograph Robot is designed in the Solidworks 2022 program and has two degrees of freedom. The goal of design is to cover an area on plane as discussed in the literature which is taken as 450mmx350mm.

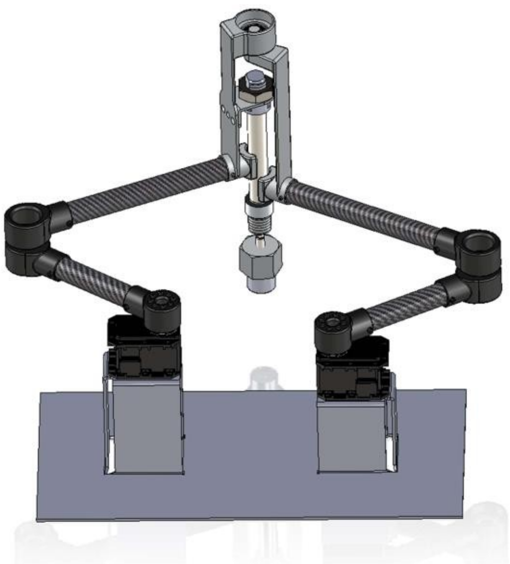


Figure 3.1: Model of Pantograph Robot in Solidworks

3.1.1 Coupler

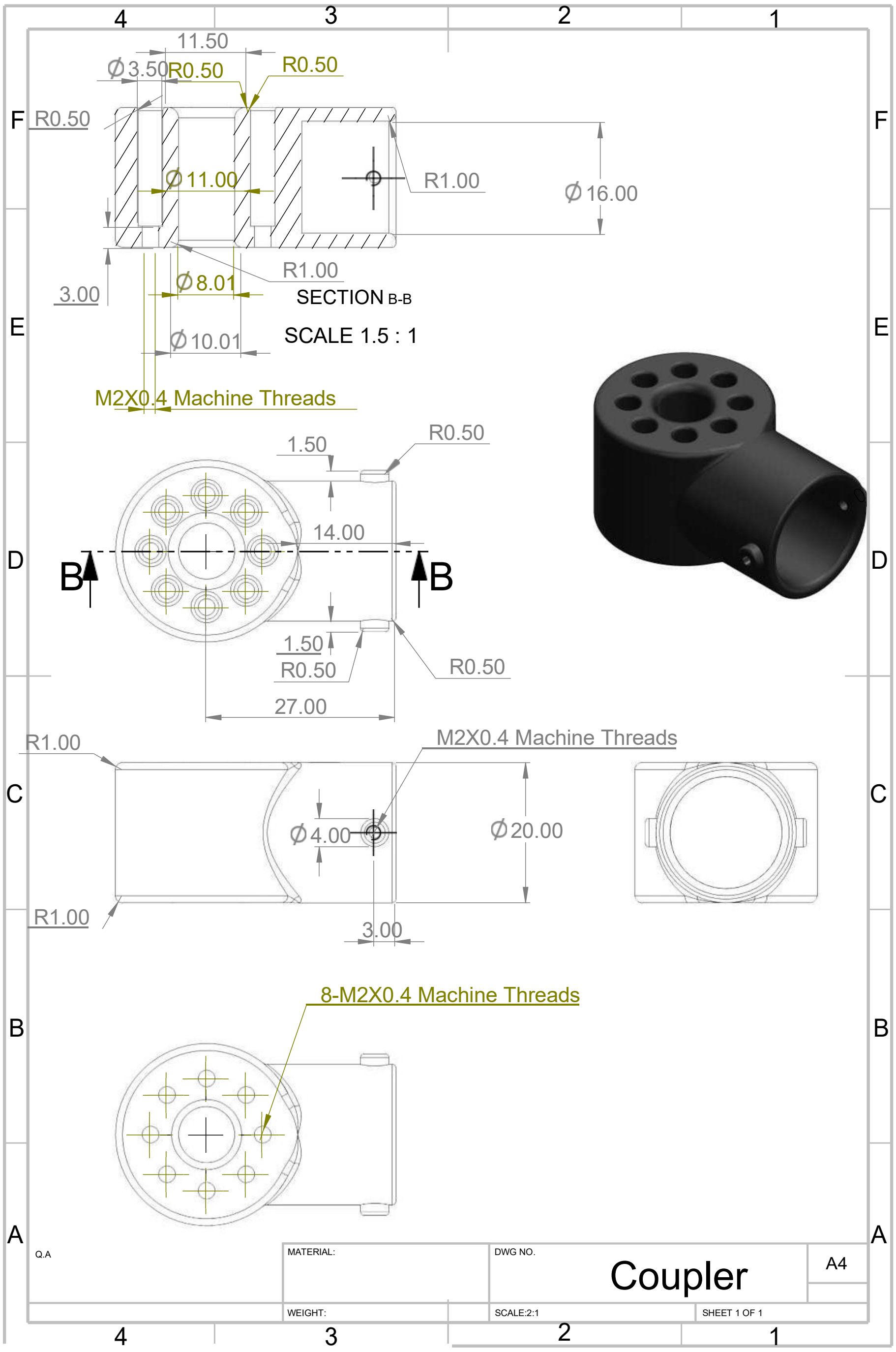


Figure 3.2: Coupler

In a 2D pantograph mechanism, the coupler connects link L1 and L4 to motors. This part was printed with the 3D-printing process using (ABS). We fastened coupler with motor through screw M2*6.

3.1.2 Lower Joint

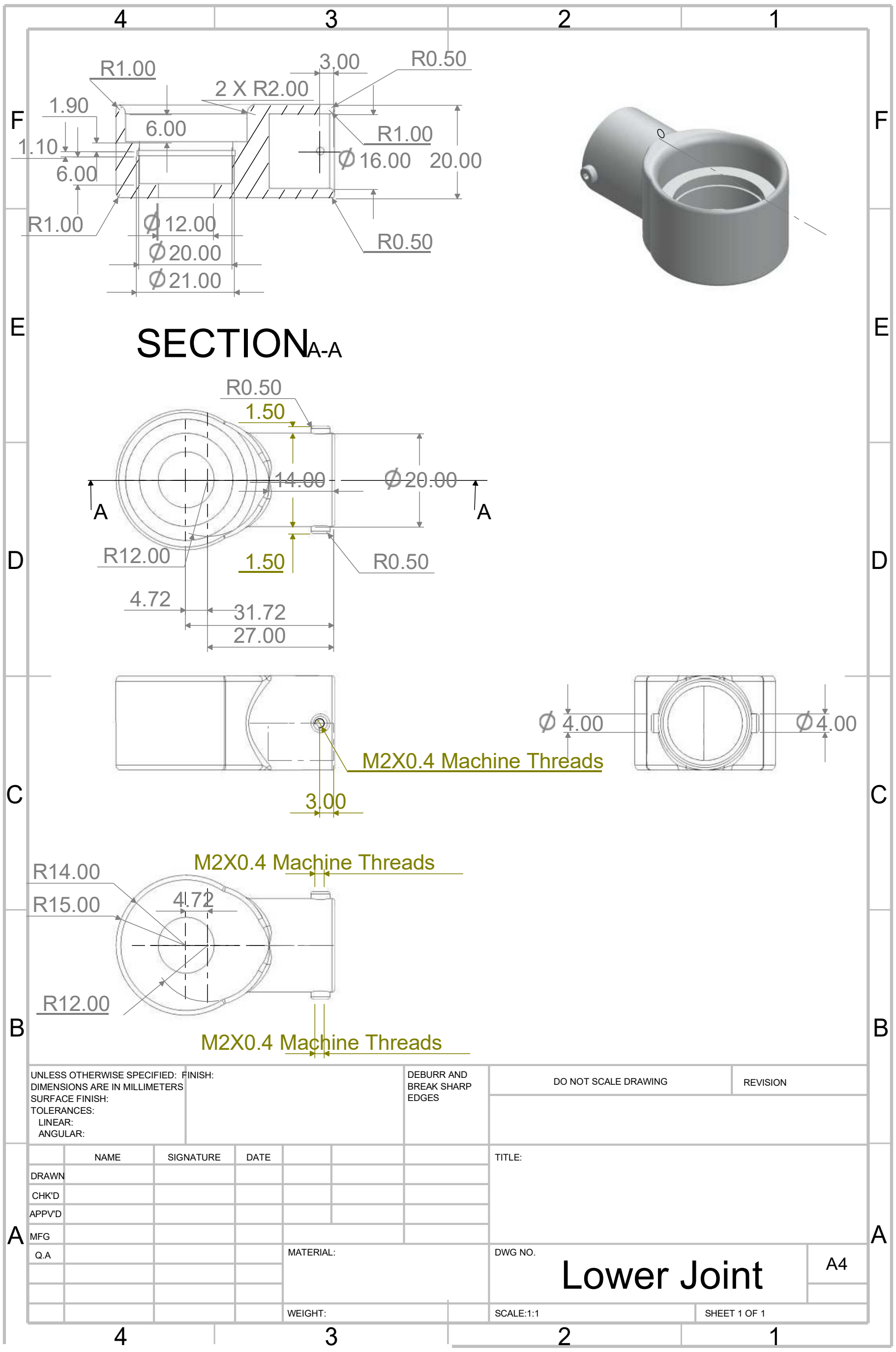


Figure 3.3: Lower Joint

Lower Joint is made up of ABS. It will connect links L1 and L4 to links L2 and L3 respectively. It contains housing for bearing and retention ring to hold the bearing in place. For connecting to upper joint, a hole is provided which can allow upper joint's shaft to connect to the bearing.

3.1.3 Upper Joint

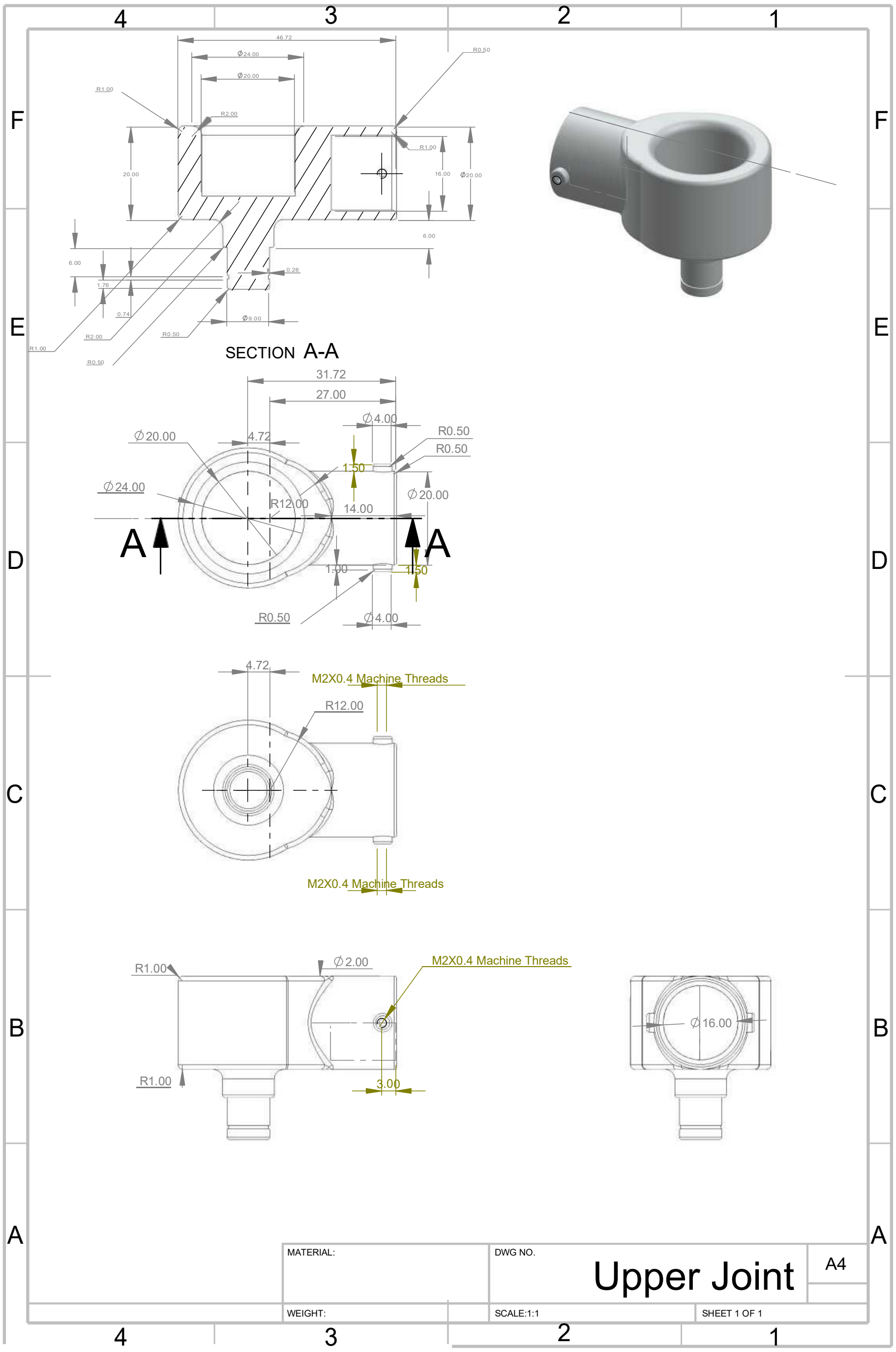


Figure 3.4: Upper Joint

Upper Joint is made up of ABS. It will connect links L1 and L4 to links L2 and L3 respectively. It contains shaft for bearing and retention ring to hold to the bearing. For reducing the weight, some material is extrude cut from it in cup form.

3.1.4 Upper End Joint

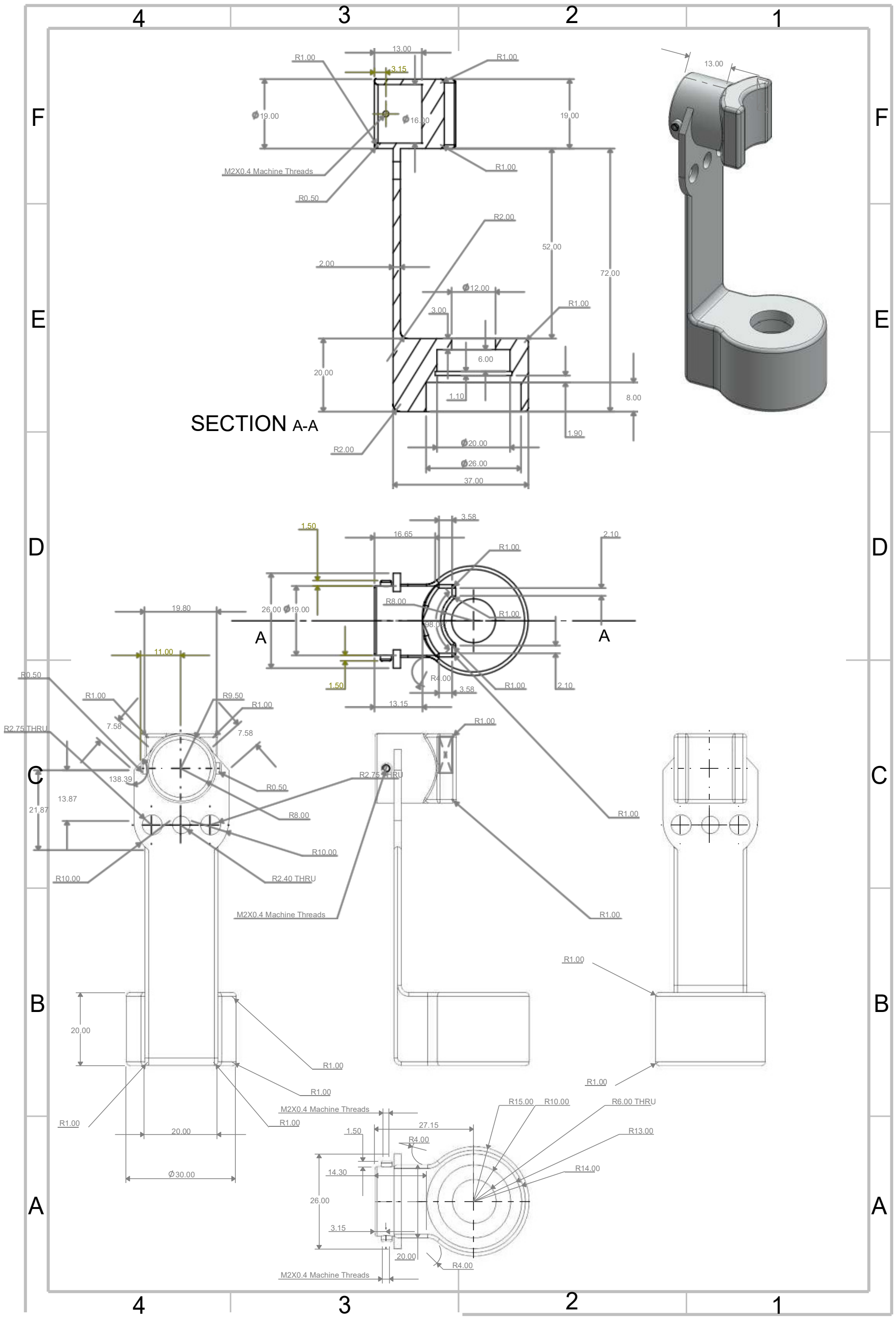


Figure 3.5: Upper End Joint

Upper End Joint Connects link L2 to end effector. To complete the closed loop, revolute joint with help of bearing is integrated in this part. It contains housing for bearing and retaining ring. It is also designed to support pneumatic actuator with help of a special foot bracket. More details about actuator are discussed in section 5.2.

3.1.5 Lower End Joint

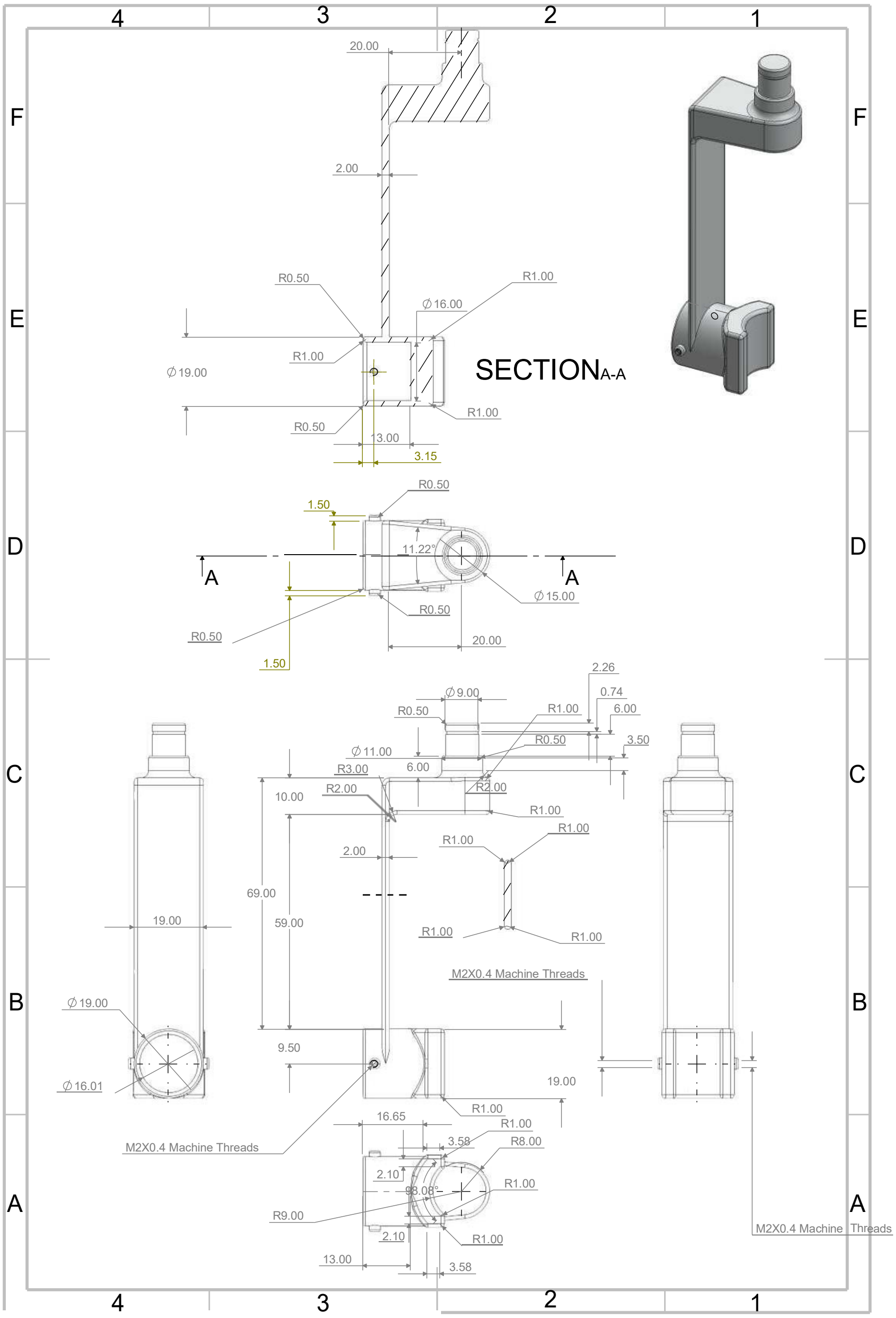
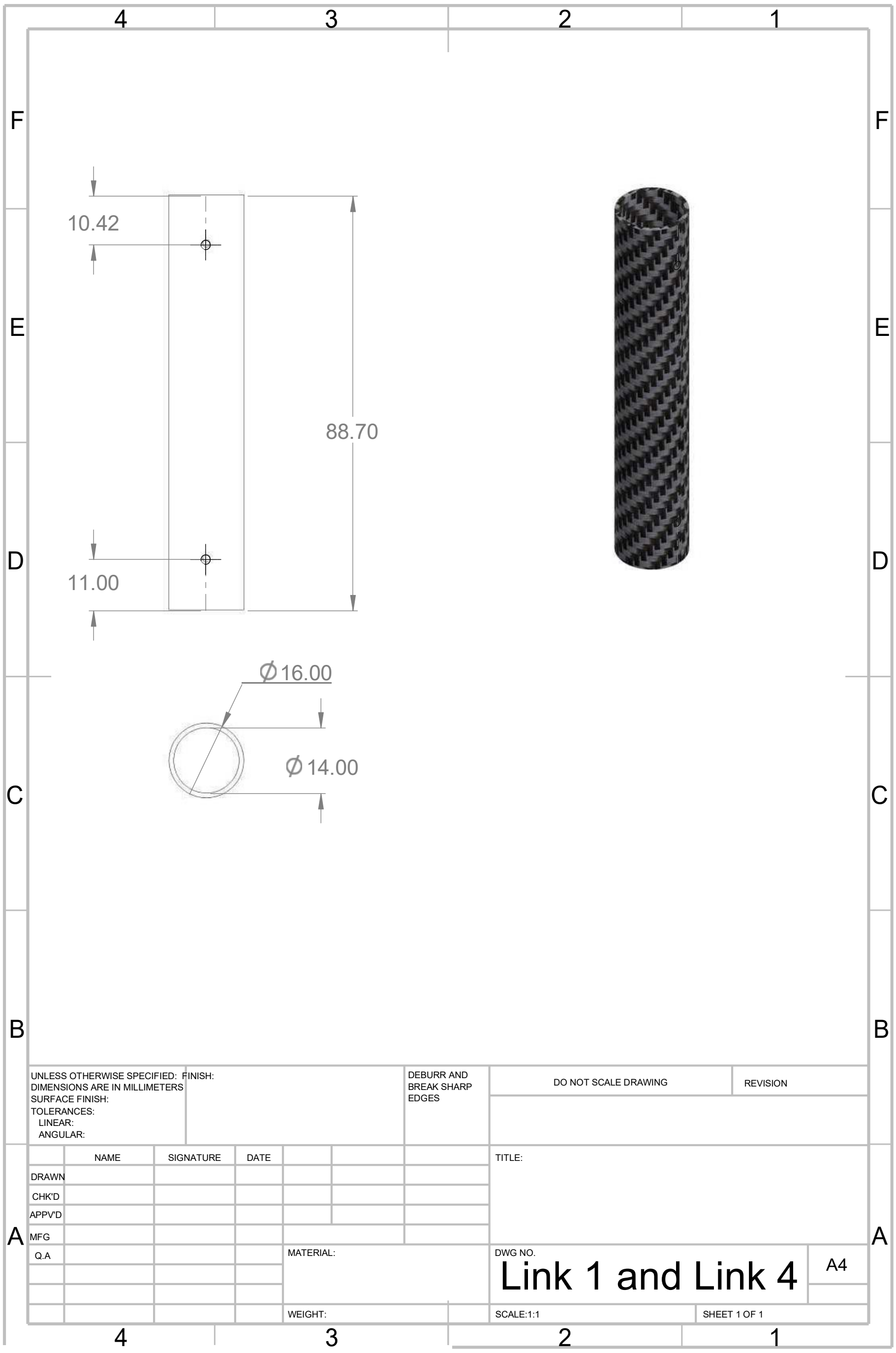


Figure 3.6: Lower End Joint

Lower End Joint Connects link L3 to end effector. To complete the closed loop, revolute joint with help of shaft connecting to the bearing in upper end joint.



3.1.6 Link 1 and Link 4

Figure 3.7: Link 1 and Link 4

Link 1 and Link 4 are similar in length due to symmetric design of the pantograph. Both are approximately 88 mm long. The links are made up of carbon fibre rods which provide good strength and are great at resisting deformation under load. The length of these links in addition to offsets provided by joints provide overall length of link L1 and L4 which are used in the design of pantograph.

3.1.7 Link 2 and 5

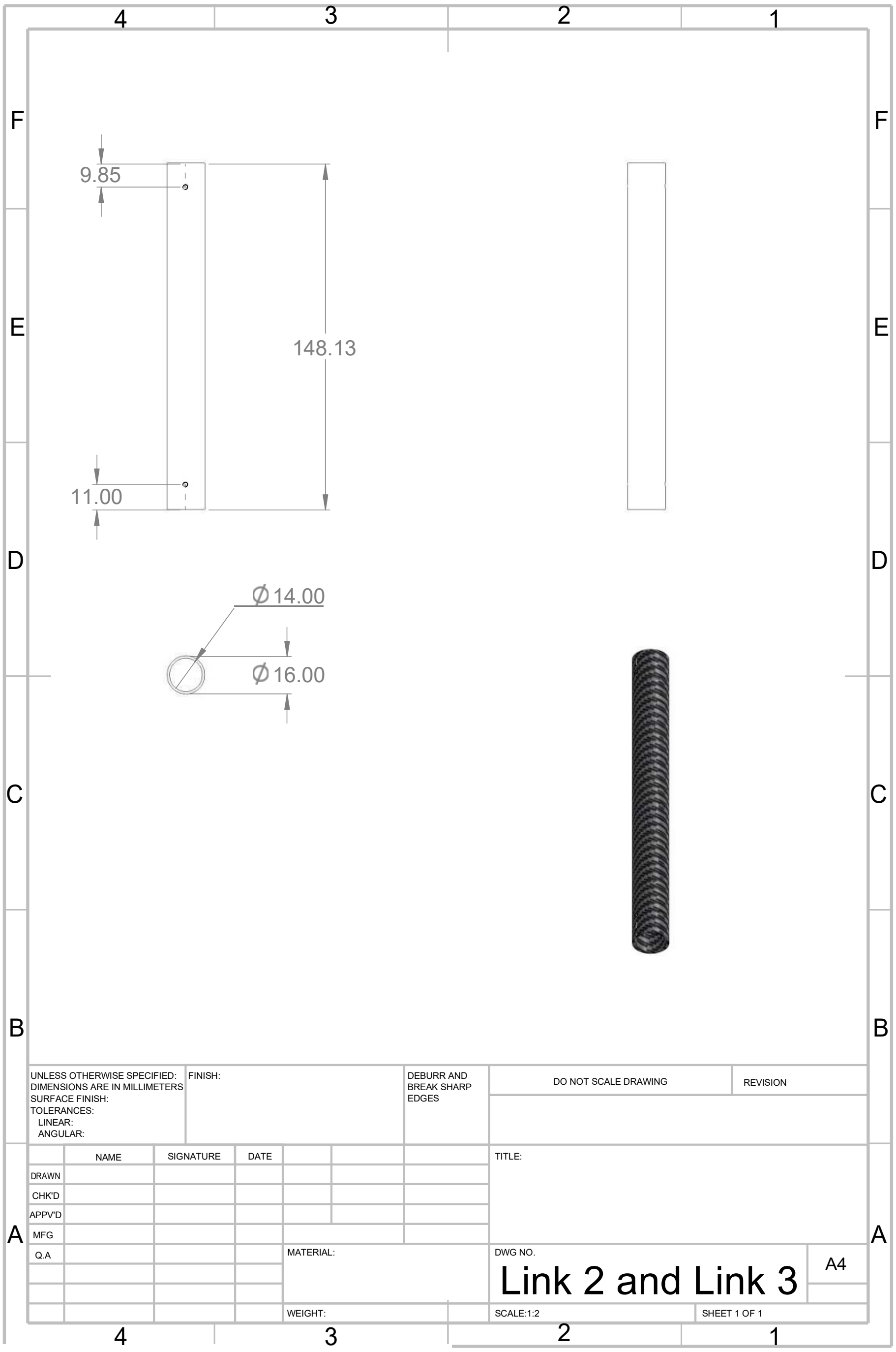


Figure 3.8: Link 2 and Link 3

Link 2 and Link 3 are also similar in length. Both are approximately 148 mm long. The links are made up of also made up of carbon fibre.

3.2 Assembly

All the components were bought or manufactured; assembly of the structure was performed. For the base platform, 6 mm thick plywood was used which gives freedom to modify it more easily than metal frame for attaching other components. For providing motion, we are using Dynamixel MX-28 motors. The motors have sufficiently high torque. The simulations of simple oscillating motion show that the maximum torque (170 Nmm) occurring in motion is fulfilled by the motor.

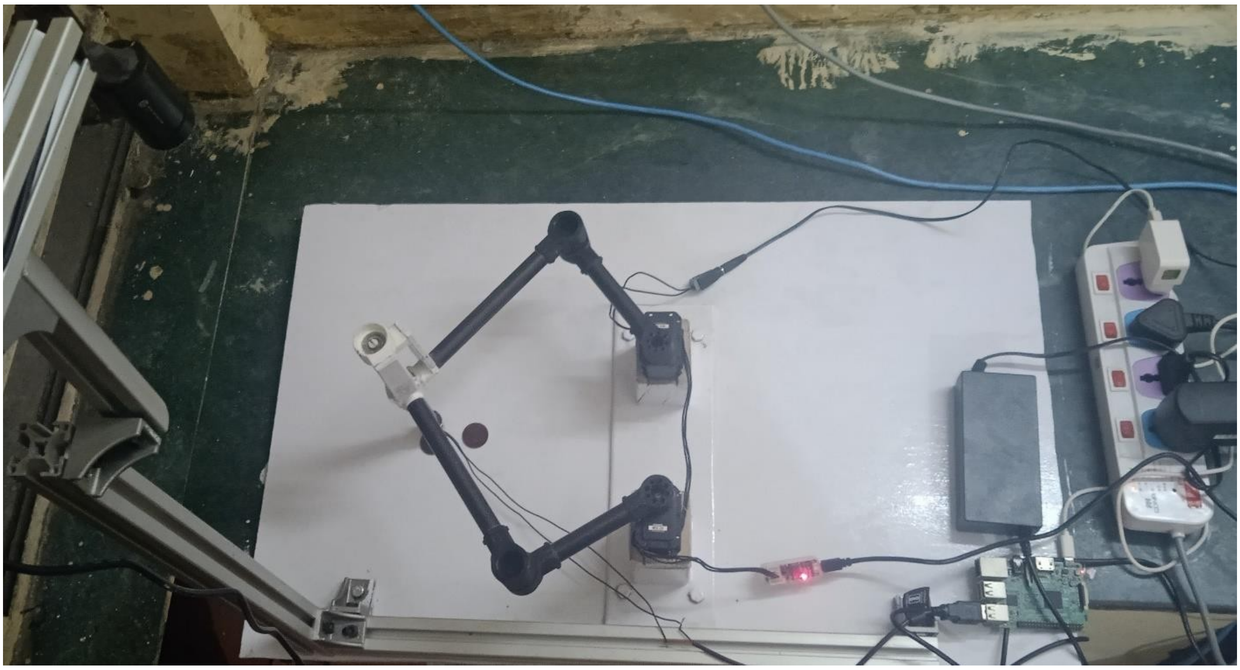


Figure 3.9 Assembly

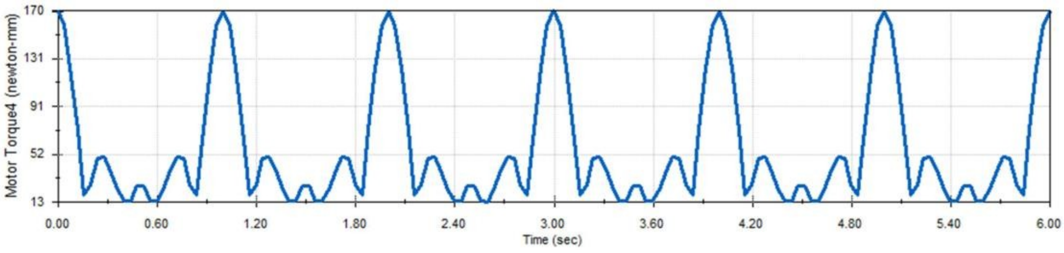


Figure 3.10: Oscillating motion between limits of workspace with 1 Hz frequency

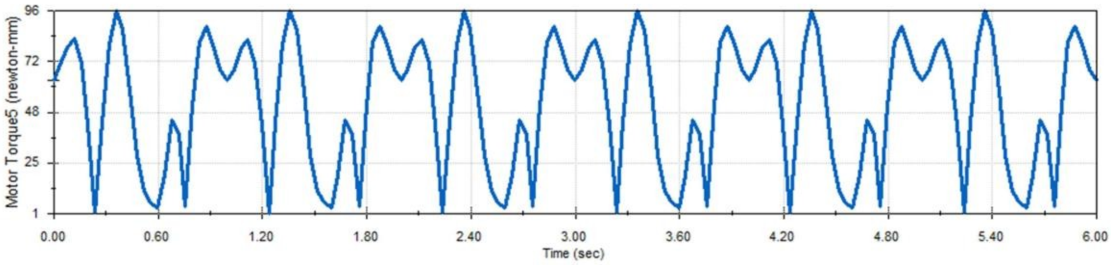


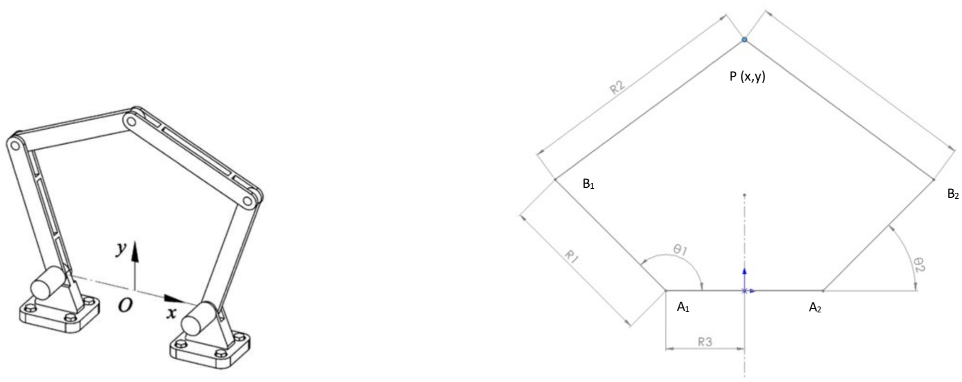
Figure 3.11: Oscillating motion between limits of workspace with 1 Hz frequency and 90° phase difference

Chapter 4

Kinematics and Control Procedure

To interact with hardware to perform the required task of moving to the location of the object, control is necessary. Kinematics is required to establish relation between Cartesian Coordinates of end effector and rotation angles of the motors.

4.1 Inverse Kinematics



(a) Pantograph (b) Coordinate System

Figure 4.1: The planar 5R parallel mechanism.

Position of point P that is end effector is given by vector p is given as

$$p= (x, y)^{T} \quad 3)$$

Positions of points B_1 and B_2 are given as

$B_1 = (r_1 \cos\theta_1 \ -r_1\sin\theta_2)^T$

and

$B_2 = (r_1 \cos\theta_1 \ -r_1\sin\theta_2)^T$ 4)

Distance between P and B is given by.

$|PB_i|=r_2$ i=1 and 2 5)

In another form it can be written as

$(x-r_1\cos\theta_1+r_3)^2 + (y-r_1\sin\theta_1)^2= r_2^2$ 6)

$(x-r_1\cos\theta_1+r_3)^2 + (y-r_1\sin\theta_1)^2= r_2^2$ 7)

Input position can be obtained as

$\theta_i=2\tan^{-1}(z_i)$ i=1,2 8)

here

$$z_i = \frac{-b_i+k_i\sqrt[2]{b_i^2-4a_ic_i}}{2a_i} \qquad 9)$$

where

$k_i = 1$ or -1

$a_1=r_1^2 + y^2 +(x+r_3)^2-r_2^2-2(x+r_3) r_1$

$b_1=-4yr_1$

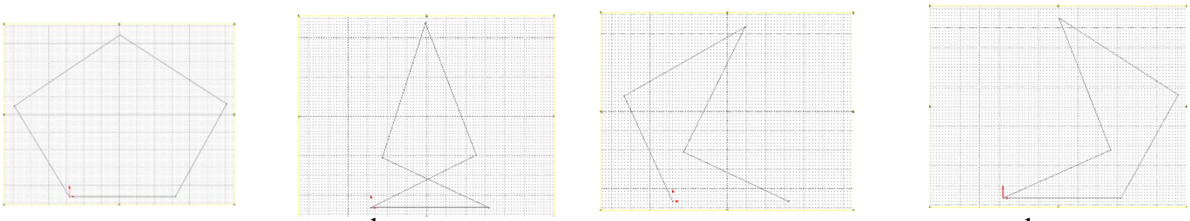
$c_1=r_1^2 + y^2 +(x+r_3)^2-r_2^2-2 (x+r_3) r_1$

$a_2=r_1^2 + y^2 +(x-r_3)^2-r_2^2-2 (x-r_3) r_1$

$b_2=-4yr_1$

$c_2=r_1^2 + y^2 +(x-r_3)^2- r_2^2-2(x-r_3) r_1$

There are solutions we will use for this, we by putting $k_{i=}$ 1 or -1 and i=1 or 2 for a, b, c. The solutions are denoted as “++”, “+-”, “-+” and “--”. Out of these, we will be sticking to “+- mode.



a. +-   b. - +   c. + +   d. - -

Figure 4.2: Solutions of inverse kinematics.

In addition to inverse kinematics, forward kinematics also have 2 solutions- up configuration and down configuration. Paper [1] is based on up and “+-” configuration. We are following it as well.

a. Up   b. Down

Figure 4.3: Solutions of Forward kinematics

Due to physical limitations of the joints of end effector, the angle between the links (α) should be greater than 55°. Vector dot product of the vector of two links can be used to calculate
the angle.

$$\cos^{-1}\frac{(PB_1)*(B_2P)}{|PB_1||B_2P|} = \alpha \qquad 10)$$

As PB1 and PB2 have magnitude equal to r2, we can write

$$\cos^{-1}\frac{(PB_1)*(B_2P)}{r_2^2} = \alpha \qquad 11)$$

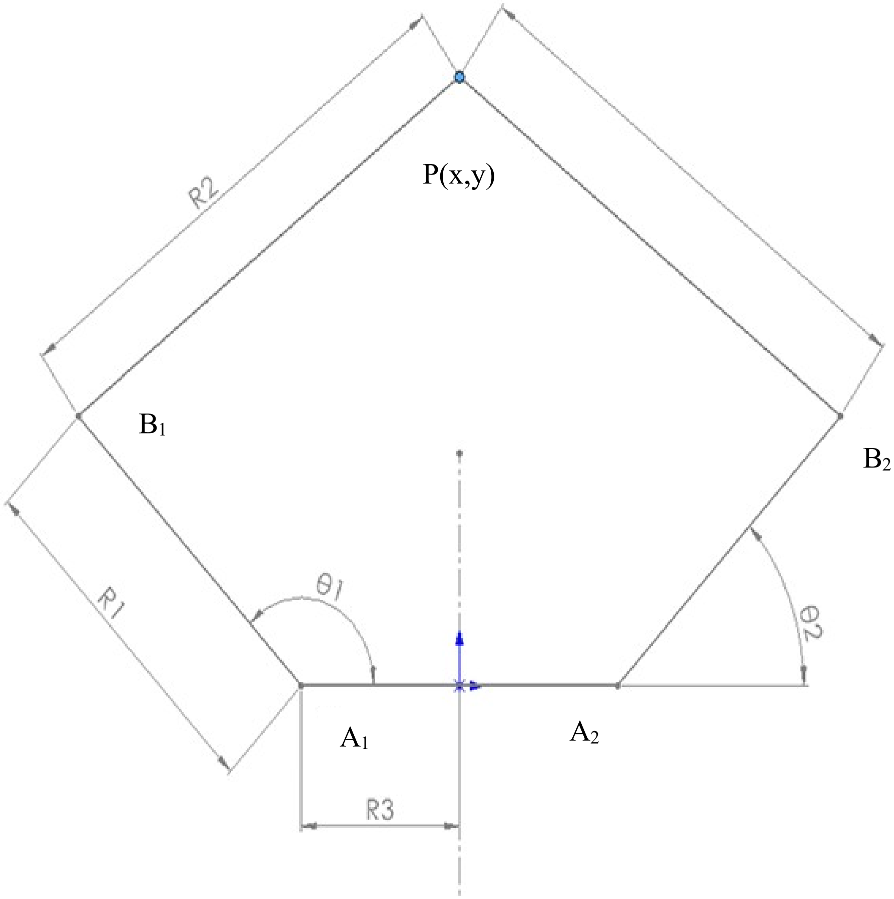


Figure 4.4: Diagram of Pantograph with Coordinate system

4.2 Image Processing using Hue Saturation Value

A USB webcam was mounted on the frame of the robot. The coordinate of centroid of the image is determined. HSV thresholding or binary masking was used to extract the object from the background. HSV separates colour information from intensity or lighting. As value is separated, rules for thresholding can be easily framed using only hue and saturation

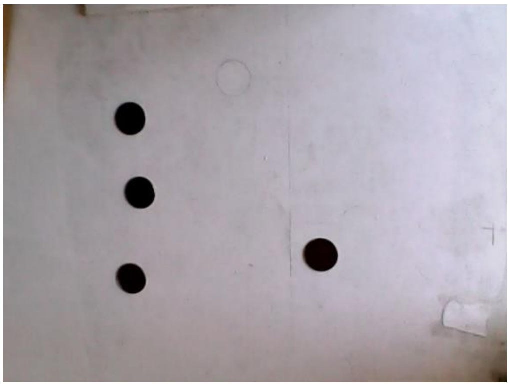


Figure 4.5: Image from USB Webcam

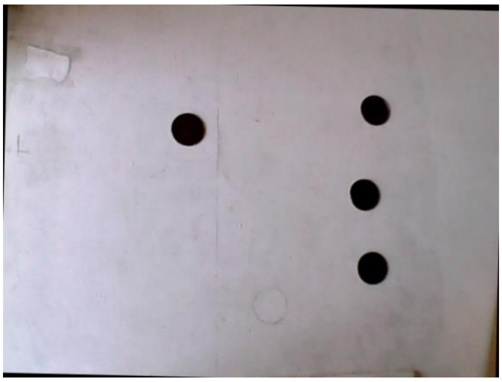


Figure 4.6: Rotated Image

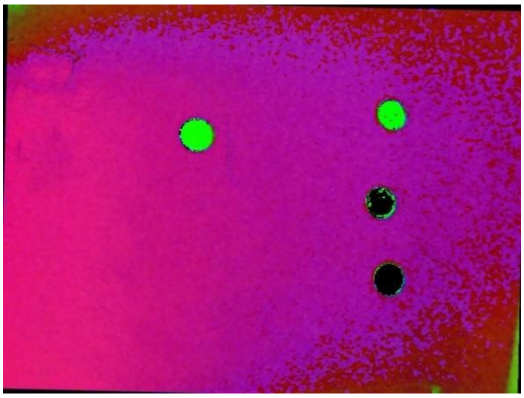


Figure 4.7: Conversion to hsv

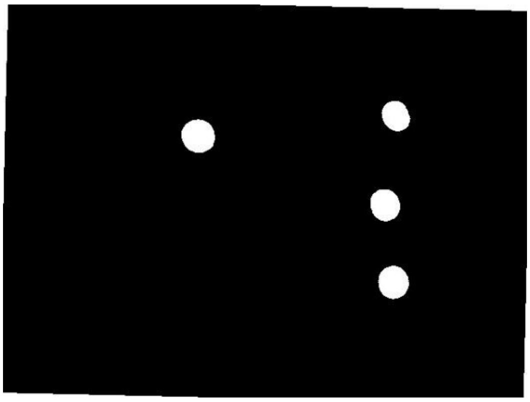


Figure 4.8: Applying hsv thresholding

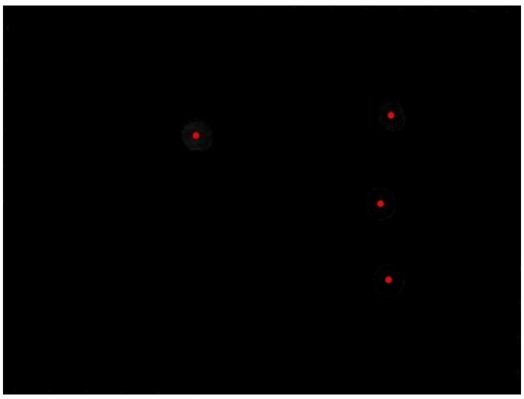


Figure 4.9: Pixel Coordinates of Centers

4.3 Pixel to Cartesian Coordinates

The pixel center of the object obtained from hsv algorithm is then transformed into Cartesian coordinates with respect to base frame. For this purpose, the pixel to image scale, rotation and offsets is calculated from experimentation. The image is rotated, scaled and offsets are ad8ded to get Cartesian coordinates

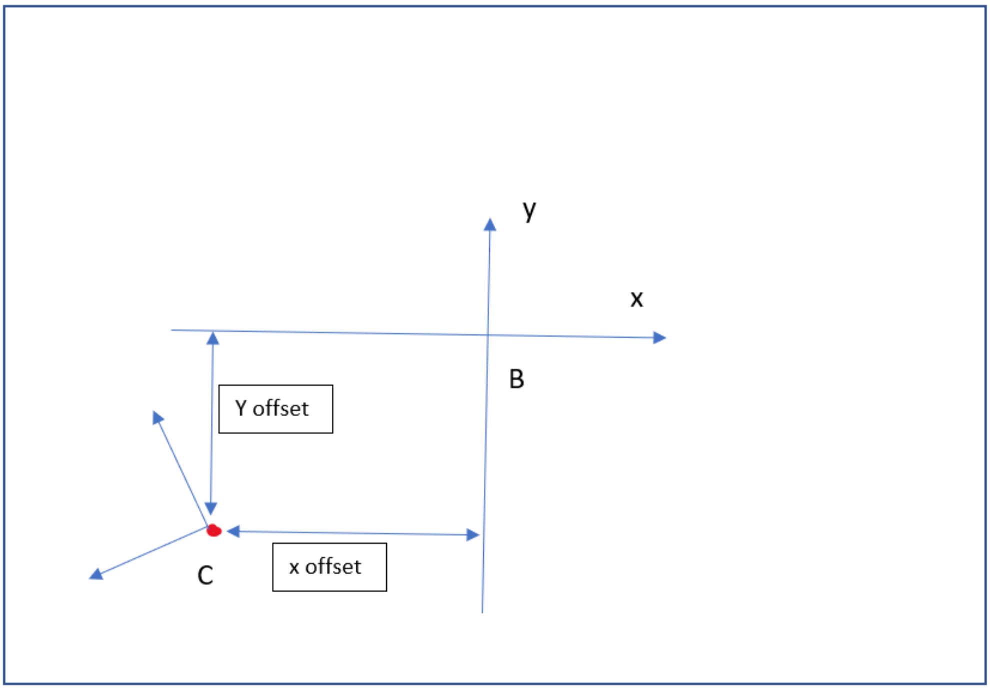


Figure 4.10: Pixel to Cartesian Transformation

B: Fixed Base Cartesian Frame

C: Camera pixel frame

4.4 Flow Chart of Function Calls

Figure 4.11: WorkFlow

The function prints pixel coordinates of points detected then prints converted cartesian coordinates, then gives motor angles for valid points and then passes the angles to the motors.

```
enter any key to continue or 'q' to quit:

(480, 640, 3)
x: 531 y: 356
x: 515 y: 255
x: 263 y: 182
x: 525 y: 135
No. of objects detected: 4
[458.5 232. ]
Cartesian
x: 168.59999999999997 y: 145.72
x: 159.0 y: 209.35
x: 7.799999999999983 y: 255.34
x: 165.0 y: 284.95
Point (165.0, 284.95) is out of reach1
(71.10886227425276, -23.063481317704127)
(64.0031303006811, 7.66016098756602)
(117.71037549667581, 57.42520004641742)
```

Figure 4.12: Executing Program

Chapter 5

Results and Future Work

5.1 Results and Conclusion

The paper presents the design and development of Pantograph robot. The chosen link lengths and motor specifications are based on the required workspace and the required degree of resolution of the end-effector. The components of this structure were designed in Solidworks 2022, after which they were manufactured using 3D printing technology. In 3D printing FDM (Fused Deposition Method) based printers were used.

After manufacturing and purchasing the components, the robot has been assembled and integrated with a python code to identify coloured objects in its workspace and pick from its home position to the target location. The pick and place task of objects ha been successfully performed.

5.2 Future Work

For picking magnetic objects, the single acting pneumatic actuator is proposed to be attached to the end effector of the pantograph robot, which will help in picking objects lying down with help of electromagnet. The single acting model proposed is from Janatics. The actuator has stroke of 5 cm.

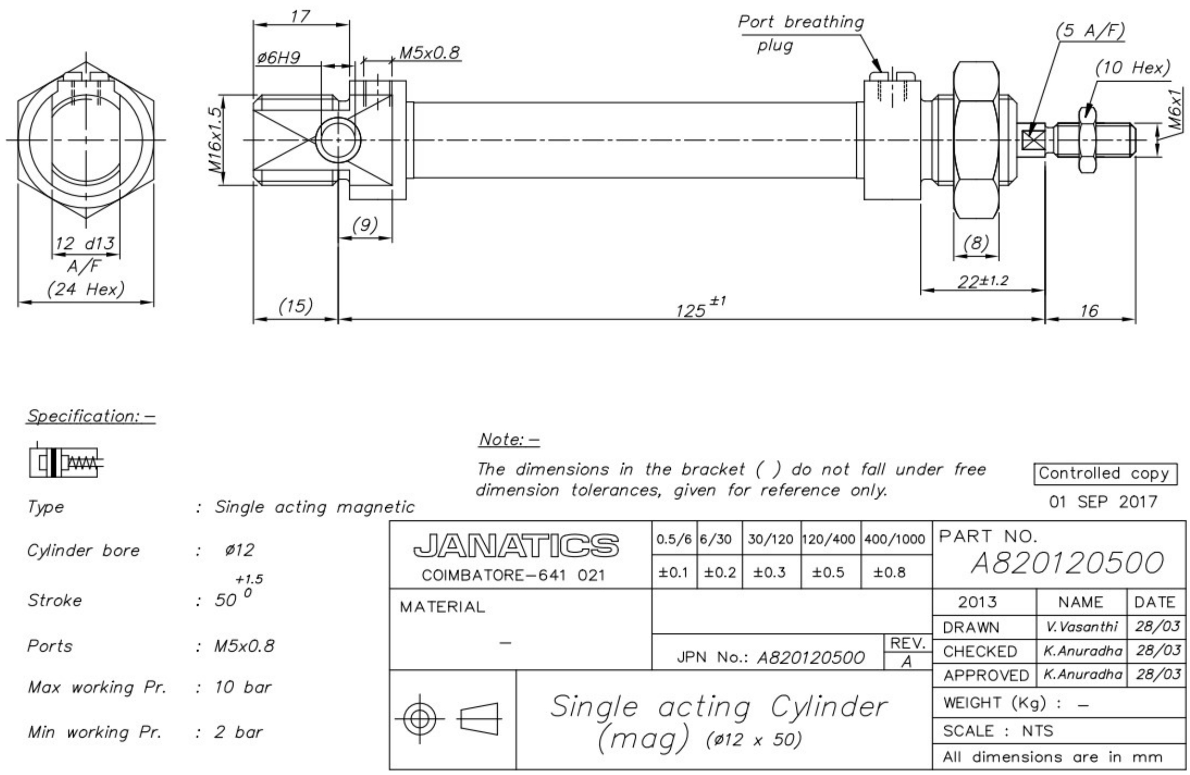


Figure 5.1: Single Acting Pneumatic Actuator

Appendix A

A.1 Python Code for Pick and Place Operation

To get the python code visit: https://github.com/ProtiumPower/Pantograph-Robot/blob/main/python/tests/protocol1_0/My/M.py

A.2 CAD Model

Cad model is available here: https://github.com/ProtiumPower/Pantograph-Robot/tree/main/Assembly

Bibliography

[1] Kinematics, singularity and workspace of planar 5R symmetrical parallel mechanisms http://dx.doi.org/10.1016/j.mechmachtheory.2005.05.004

[2] Performance atlases and optimum design of planar 5R symmetrical parallel mechanisms http://dx.doi.org/10.1016/j.mechmachtheory.2005.05.003

[3] Guidance for Pantograph Development Methodology https://www.redalyc.org/jatsRepo/614/61465285005/

[4] [Robotis, 2022] Robotis (2022)