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Design and Construction of 3 DOF Prototype Delta Parallel Robot

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Abstract: The design and construction of a prototype delta robot to utilize for upper secondary educational institutes is presented. The focus is on leveraging 3D printing technology in AutoCAD for component fabrication, detailing electrical schematics, and integrating Arduino for its intuitive User Interface (UI). The project's objective is to construct a delta robot prototype equipped with essential features to serve as an educational tool for teaching fundamental robotics principles. Additionally, the design allows for customization of specific robot parts in future iterations to adapt it to various applications as needed.
Keywords: Delta Robot, 3 DOF, Design, CAD, 3D Printing, Inverse Kinematics, Arduino

I. INTRODUCTION

A. Overview

Today the manufacturing industry is evolving rapidly, heavily around the automatization of manufacturing processes that require high performance and low cost. Due to the low moment of inertia of the end effector, the delta robot can achieve high-speed movement and while retaining high precision. Resulting in being a highly desired robot in the food, electrical, and pharmaceutical industry where fast pick-and-place is required [1]. Therefore, this project is designed to be used as a learning tool exploiting the bright future of the robotics industry. The robot will mainly be designed from 3D printed parts in polylactic acid (PLA) plastic, designed in AutoCAD software. The selected open-source single-board microcontroller is an Arduino Uno R3. A highly versatile open-source microcontroller that allows for the connection of external accessories and includes an easy-to-use Integrated Development Environment (IDE) [2]. It is in the IDE the user will be able to access the User Interface (UI) and manipulate the movement of the robot. This includes being able to set up an automated trajectory, with speed and time control, and a mode where coordinates can be inputted through the UI, and calibration of the robot. A series of questions will be asked in the serial monitor located in the IDE, which will allow the user to make their input and program the robot. In sequel, the Arduino will send the information to a driver controlling the position of the stepper motor. A gripper will be mounted to the moving platform as the end effector, powered by a 5g servo motor. Implementing the inverse kinematics of the robot in the Arduino code will allow the user to input the desired coordinate of the end effector down to millimeter precision. This will allow the user to explore robotics concepts such as work envelope, maxima speed, sensory feedback, and computer system for control.

B. Motivation for Design

This project evolved as part of a Senior Design Project, reflecting the lead author's keen interest in robotics and career aspirations. Through designing and building a robot, the lead author gained insights into delta robots' challenges and potentials, fostering a deeper appreciation for the diverse opportunities within the robotics field. This hands-on experience provided valuable exposure to practical complexities while laying a solid groundwork for future pursuits in robotics.

C. Objectives

The objective for this project was to firstly design and construct a functioning 3DOF delta robot, while gaining and applying knowledge to produce a best possible product. Secondly, to allow for customizability of the robot by taking use of 3D printing technology, in a manner that opens up the possibility to make the robot fit any desired application.

II. KINEMATIC DESIGN

A. 3 DOF Delta Robot

Parallel robots with 3 degrees of freedom consist of a base and an end effector linked together by three open kinematics chains. In a Delta parallel robot, the three identical open kinematics chains are powered by one rotary actuator each. Connecting the end effector with two links creates a parallelogram and locks the orientation horizontal at all times [3].

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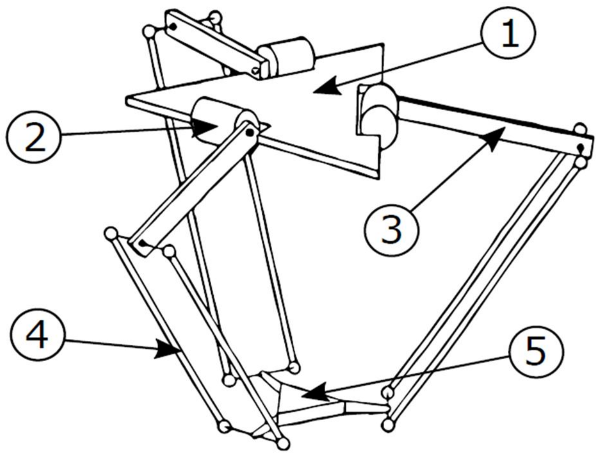

Figure 1- Typical 3-DOF Parallel Robot. 1-Fixed base, 2-Actuator, 3-Active Arm, 4- Passive Arm, 5-End Effector **[4].**

B. Forward and Inverse Kinematics

Forward kinematics involves calculating the position of the end effector in a 3D space given the angles of the three motors for the active arms. Inverse kinematics, on the other hand, is the reverse process: determining the motor angles required for the end effector to reach a desired position in 3D space [5].

The calculations are based on formula collected online [6] and shown below in figure 2 and 3. Coordinates of end effector E_0 is given as X_0, Y_0, Z_0 and returns motor angle *theta1, theta2, theta3.* The robot can be represented as two equilateral triangles: the base triangle which holds the motors, and the end effector. The side of the base triangle *f* and the side of the end effector triangle *e*, length of active arm *rf*, and the length of the passive arm *re*. These are the dimensions of the robot and depends on your design. The origin of the cartesian coordinate system is at the center of the base triangle resulting in the *z* value of the end effector coordinate to always be negative. The motor joint are represented as F_1, F_2, F_3, and the joint connecting the passive and active arm J_1, J_2, J_3.

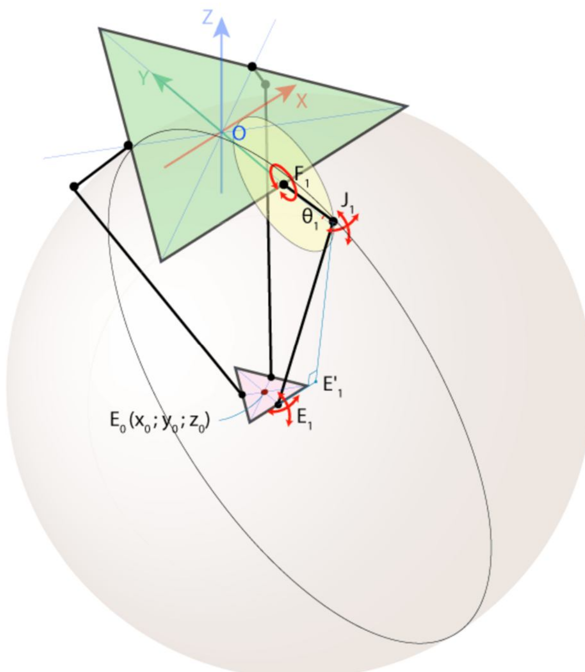

Fig. 2 Representation of delta robot illustrating variables used for inverse kinematics

$$E(x_0, y_0, z_0)$$

$$EE_1 = \frac{e}{2}\tan 30^\circ = \frac{e}{2\sqrt{3}}$$

$$E_1(x_0, y_0 - \frac{e}{2\sqrt{3}}, z_0) \Rightarrow E'_1(0, y_0 - \frac{e}{2\sqrt{3}}, z_0)$$

$$E_1E'_1 = x_0 \Rightarrow E'_1J_1 = \sqrt{E_1J_1^{\,2} - E_1E'^{\,2}_1} = \sqrt{r_e^2 - x_0^2}$$

$$F_1(0, -\frac{f}{2\sqrt{3}}, 0)$$

$$\begin{cases} (y_{J1} - y_{F1})^2 + (z_{J1} - z_{F1})^2 = r_f^2 \\ (y_{J1} - y_{E'1})^2 + (z_{J1} - z_{E'1})^2 = r_e^2 - x_0^2 \end{cases} \Rightarrow \begin{cases} (y_{J1} + \frac{f}{2\sqrt{3}})^2 + z_{J1}^{\,2} = r_f^2 \\ (y_{J1} - y_0 + \frac{e}{2\sqrt{3}})^2 + (z_{J1} - z_0)^2 = r_e^2 - x_0^2 \end{cases} \Rightarrow J_1(0, y_{J1}, z_{J1})$$

$$\theta_1 = \arctan\left(\frac{z_{J1}}{y_{F1} - y_{J1}}\right)$$

Fig. 3 Inverse kinematics for 3-DOF delta robot

Figure 4 presents a MATLAB Simulink simulation of forward and inverse kinematics for this robot with a desired input coordinate [7]. We can observe that the z value will always be negative, and that positive angles for the motor joints are angles below the horizontal plane.

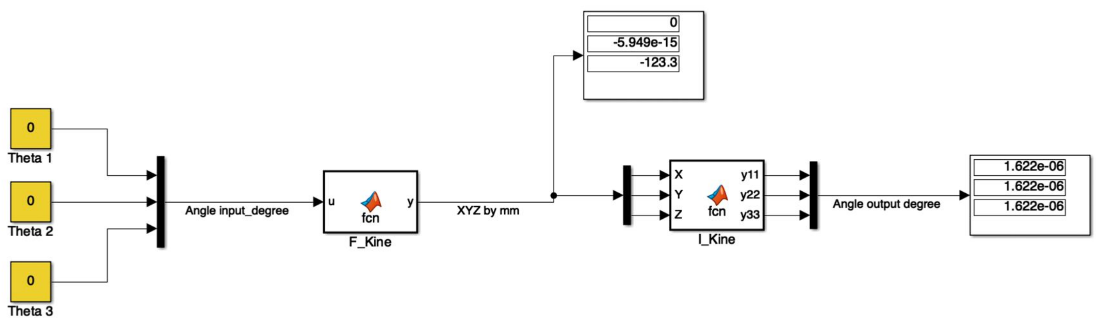

Fig 4. Simulink model of forward and inverse kinematics for delta robot.

Figure 5 shows a MATLAB Simulink simulation of the forward kinematics with a ramp input changing the input angle of each stepper motor. This clearly shows the movement of the end effector position as the motor angle changes.

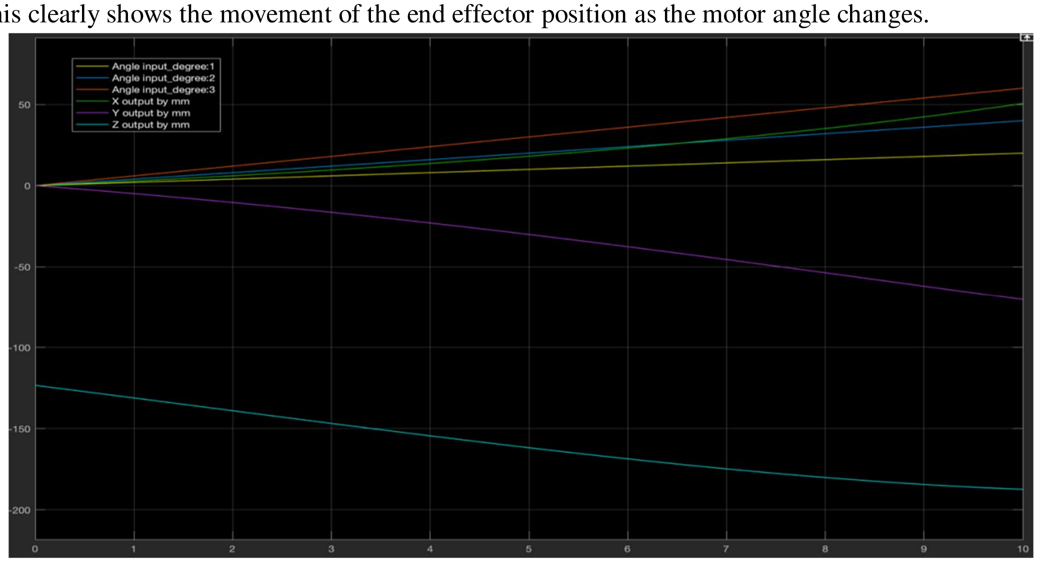

Fig 5. Forward kinematics

Figure 6 shows a MATLAB Simulink simulation of the inverse kinematics of the robot. By changing the desired position of the end effector, we can easily observe how the angle of each stepper motor changes.

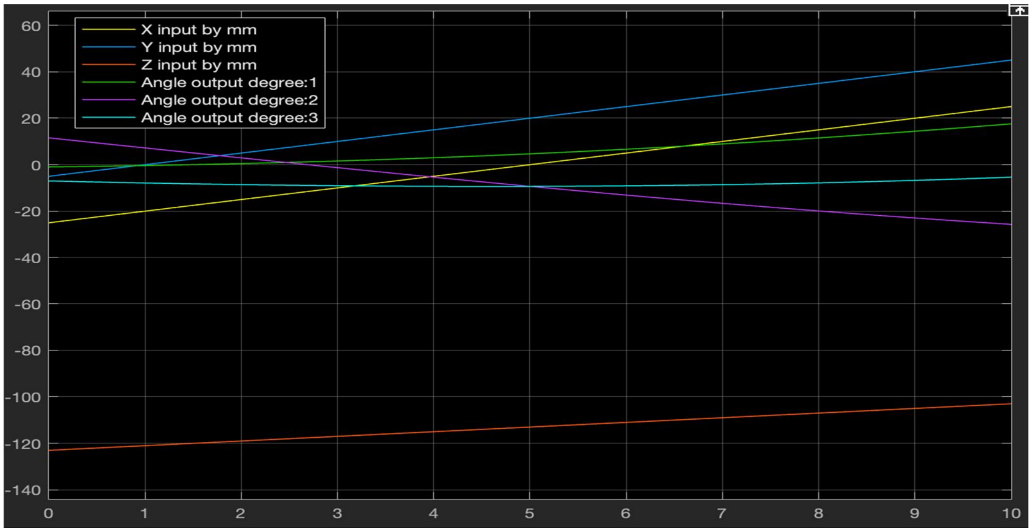

Fig. 6 Inverse kinematics

III.MECHANICAL CONSTRUCTION

The robot consists of six main components (frame, base, active arm, passive arm, end effector, electronic casing) whereas four of them are designed in AutoCAD and 3D printed. The remaining two components are composed of metal parts that have been procured in the desired dimensions. A delta robot works by manipulating the active arms with the use of revolute actuators. The active arms are rotated 120 degrees from each other, in the horizontal plane, and are mounted to the base. The robot relies heavily around the principle of using 2 passive arms creating a parallelogram, resulting in end effector orientation being maintained [8].

A. Frame

The frame serves the purpose of providing a rigid mounting point for the base. A delta robot has its work envelope below the base, hence why a frame is needed, as opposed to other robot types that have their work envelope above the base. The frame is composed of eight extruded aluminum bars, following these dimensions: 300mm x 20mm x 20mm, creating a sufficient 300mm x 300mm x 300mm workspace below for the robot. The extruded aluminum bars are all joined together via corner bracket connectors.

B. Base

The base is designed to attach to the frame and hold the actuators and ensuring that they are mounted with a 120-degree offset from each other. 3D printed in PLA plastic.

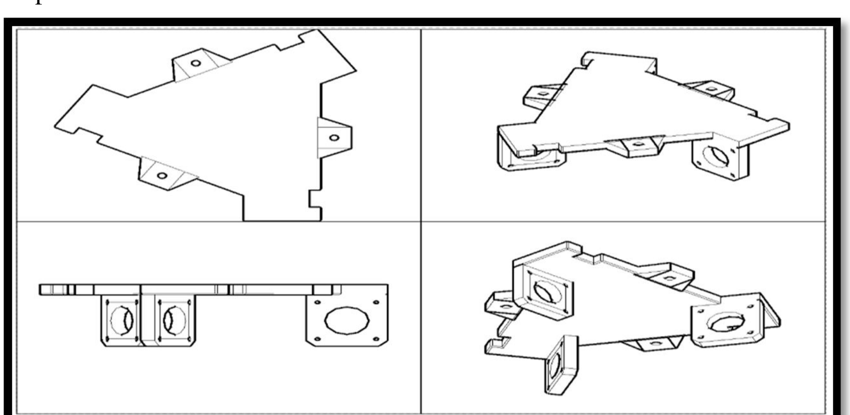

Fig. 7 CAD drawing of base

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C. Active Arm

The active arm attaches to the output shaft of the stepper motor via a flange shaft coupling. The 3D-printed part contains four holes with a hexagonal nut trap on the backside. The coupling and the 3D-printed arm can be fixed together using screws. The same nut trap principle is used on the other side of the active arm as well, to attach to the passive arms. The arm provides an effective active arm length of 110mm.

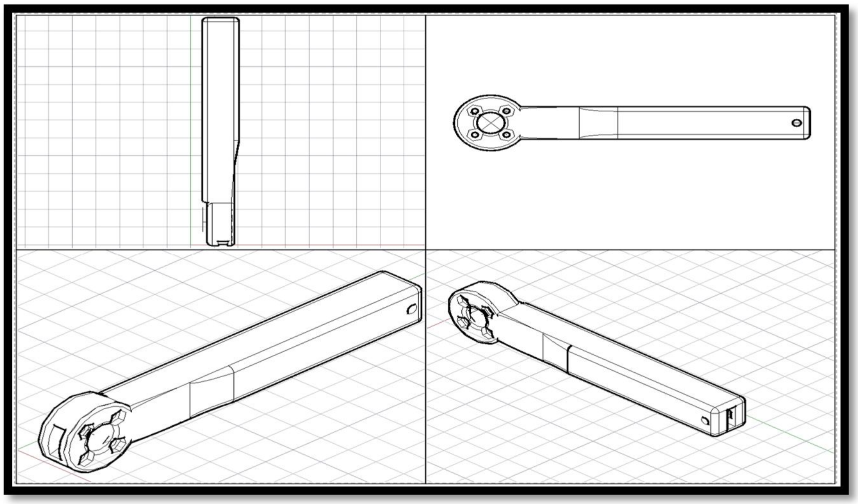

Fig. 8 CAD drawing of active arm

D. Passive Arm

The passive arm is made up of two 150mm fully threaded M4 rod bars. At each end, an M4 metal head ball joint is attached. The opening of the ball joint is 3mm allowing for an M3 screw to pass through and attach to the active arm and the end effector.

E. End Effector

The end effector consists of two parts: a moving platform and a gripper. Both parts have been designed in AutoCAD and 3D printed. The moving platform, in 7, connects at the bottom of all the passive arms and serves as a mounting point for the gripper. The gripper is made up of two arms that interact with each other via a set of gears, shown in figure 10. When one of them is moved by the servo, the other will move equal in the opposite direction.

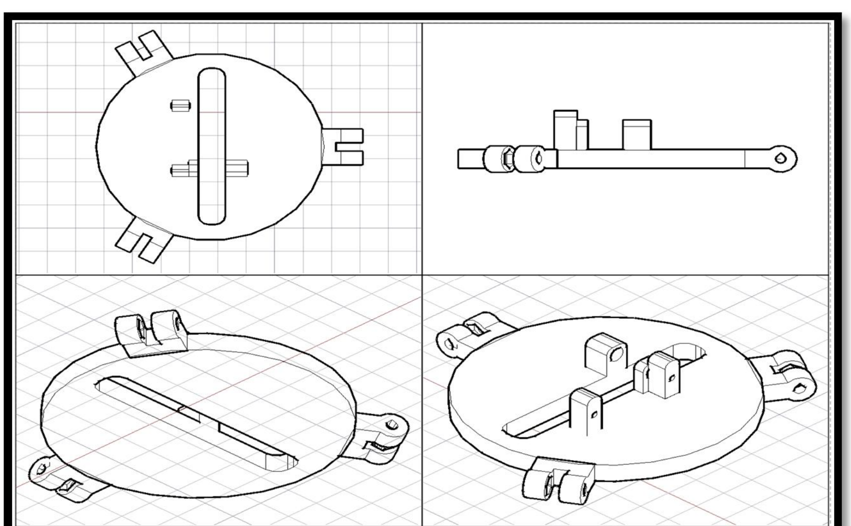

Fig. 9 CAD drawing of end effector

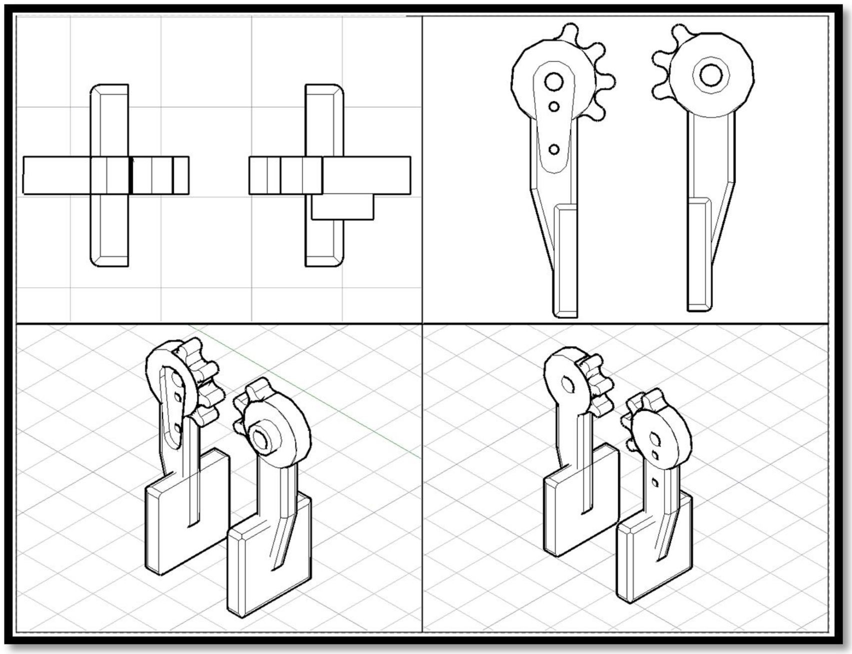

Fig. 10 CAD drawing of Gripper

F. Electronic Casing

The electronic casing provides a rigid fixture base and protection for all electrical components. As well as providing sufficient cooling for the drivers with the use of forced airflow and venting holes.

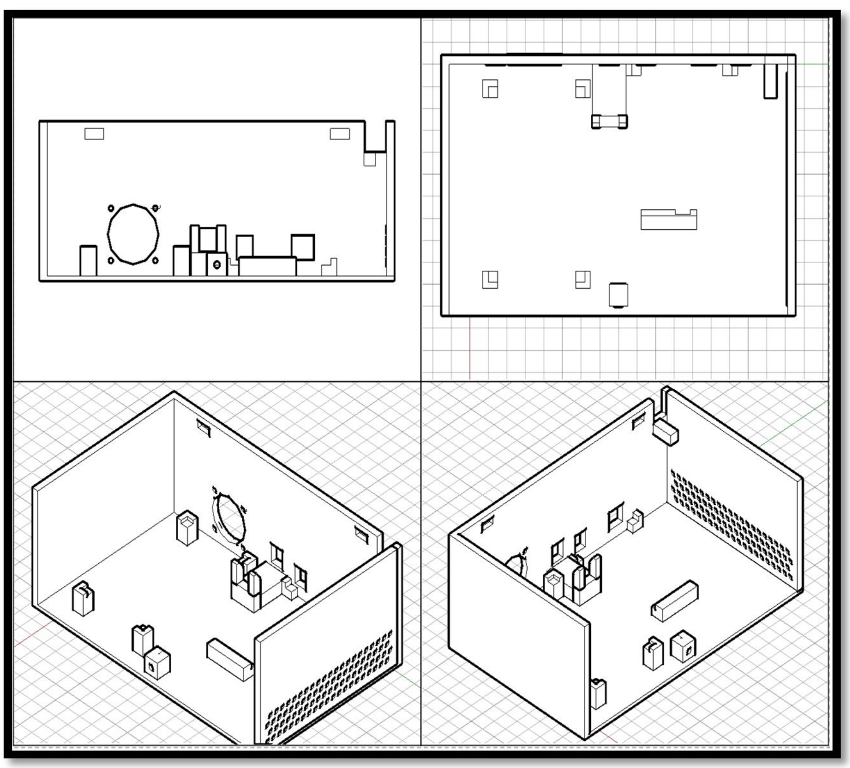

Fig. 11 CAD drawing of Electronic casing

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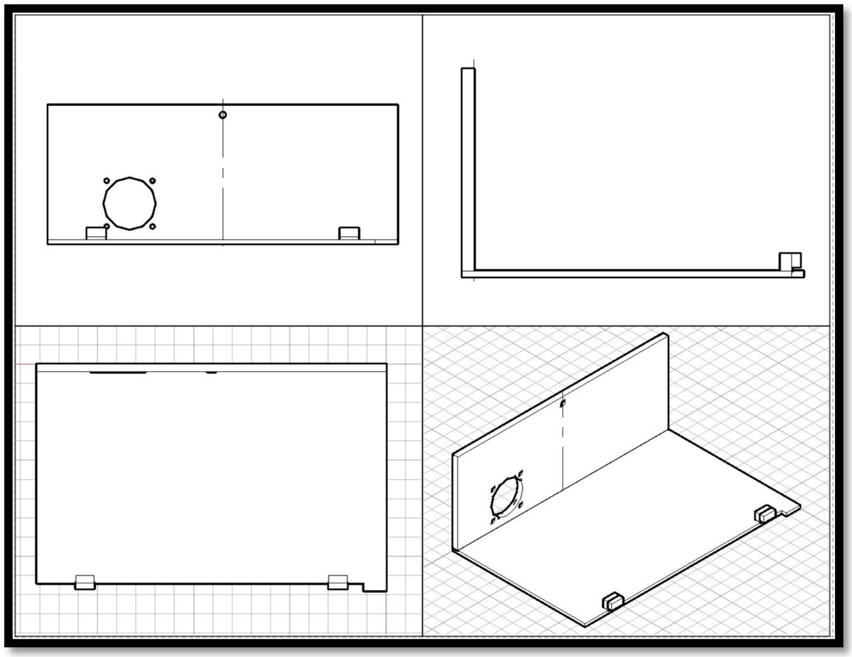

Fig. 12 CAD drawing of lid for the electronic casing

IV. ELECTRICAL AND CONTROL SYSTEM

A. *Arduino*

Arduino is a versatile open-source platform built around the ATmega328P microcontroller, offering a wide array of features and capabilities for electronics projects. The board boasts 6 analog input pins and 14 digital input/output pins, with 6 of them supporting Pulse Width Modulation (PWM) functionality, providing users with extensive flexibility for interfacing with sensors, actuators, and other peripheral devices [2]. Operating at a voltage of 5 volts, the ATmega328P microcontroller is renowned for its reliability and efficiency in handling a variety of tasks.

One notable feature of the ATmega328P microcontroller is its 1 KB Electrically Erasable Programmable Read-Only Memory (EEPROM), which allows it to retain stored information even when power is removed, owing to its non-volatile properties [9]. This capability ensures that crucial data or program settings are preserved across power cycles, enhancing the reliability and stability of Arduino-based projects.

Programming Arduino is facilitated through an intuitive development environment that is derived from the C++ programming language. This environment simplifies the process of writing and uploading code to the Arduino board, making it accessible to both beginners and experienced developers alike. Additionally, Arduino's vast online community provides a wealth of resources, tutorials, and libraries, further easing the learning curve and enabling users to quickly bring their ideas to fruition.

B. *Nema 17 HE15-1504S*

The Nema 17 stepper motor, renowned for its reliability and performance, exhibits specific electrical characteristics crucial for its operation. With a coil current rating of 1.5 Amperes and an internal resistance of 2.3 Ohms, it is optimized to deliver consistent and efficient power distribution [10]. To ensure reliable operation and accommodate potential fluctuations in power requirements, a 45-watt Power Supply Unit (PSU) is deemed sufficient, incorporating a 50 percent safety margin within the 12-24v range.

Beyond its electrical specifications, the stepper motor's mechanical capabilities contribute significantly to its functionality. In its base configuration, the motor offers 200 steps per revolution, providing a foundational level of precision for various applications. However, by leveraging the micro-step function, users can achieve finer granularity in motion control. Enabling a 1/16th step increases the steps per revolution to an impressive 3200, significantly enhancing the motor's precision and resolution.

The implementation of micro-stepping allows for a reduction in the motor's step angle to 0.1125 degrees, thereby augmenting the robot's ability to execute intricate movements with utmost accuracy. This substantial increase in resolution translates to a remarkable improvement in positioning precision, reducing the margin of error from +/- 2.81mm to an exceptional +/- 0.17mm.

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Despite the evident benefits of micro-stepping in enhancing precision, it is essential to acknowledge the trade-offs involved. One notable drawback is the considerable loss of holding torque, amounting to approximately 90% in this configuration [11]. While this reduction in torque may pose limitations in certain applications requiring high holding torque, the significant gains in precision and resolution render micro-stepping a compelling choice for tasks prioritizing accuracy.

C. Driver

The A4988 IC driver stands out for its advanced features, including variable current limitation and built-in protection against overheating. With a maximum current output of two amperes per coil with additional cooling, and one ampere without cooling, it ensures versatility in various operating conditions. For this project, the current limiter will be adjusted to 1.5 amperes to optimize performance, necessitating the addition of a heat sink, and forced airflow to the driver [12]. In the context of this project, the integration of micro-stepping technology offers enhanced precision and control, contributing to the overall success and effectiveness of the robotic system.

V. INTEGRATION AND TESTING

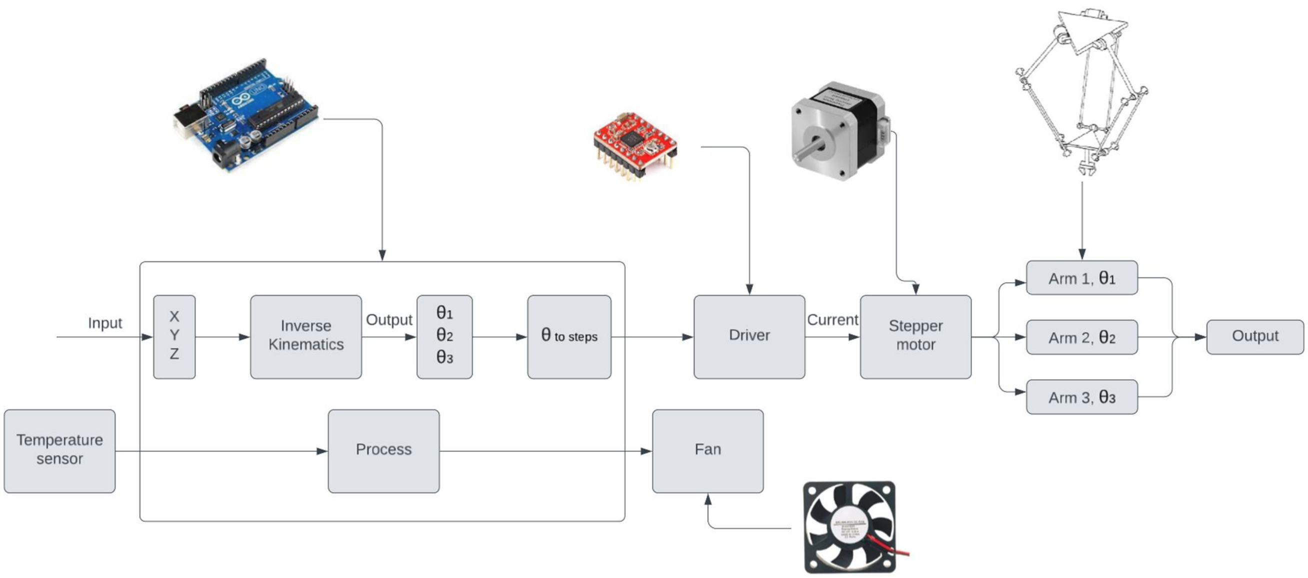

Fig. 13 Delta Robot Block Diagram

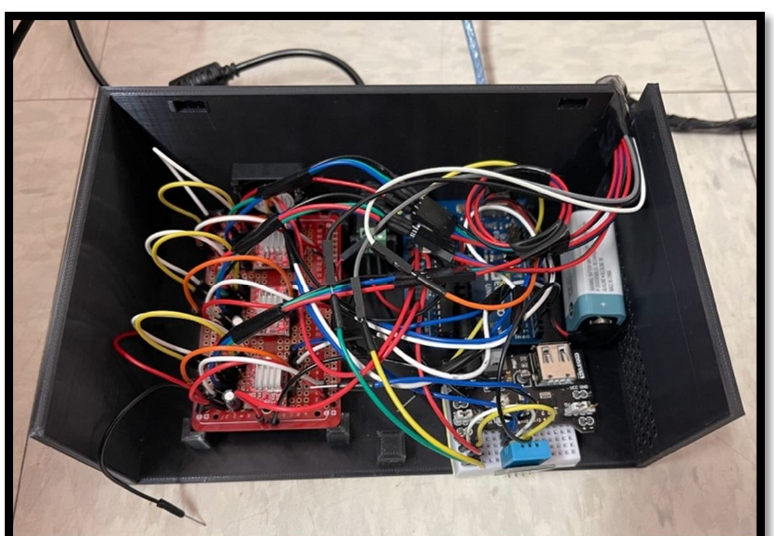

Fig. 14 Electronic casing

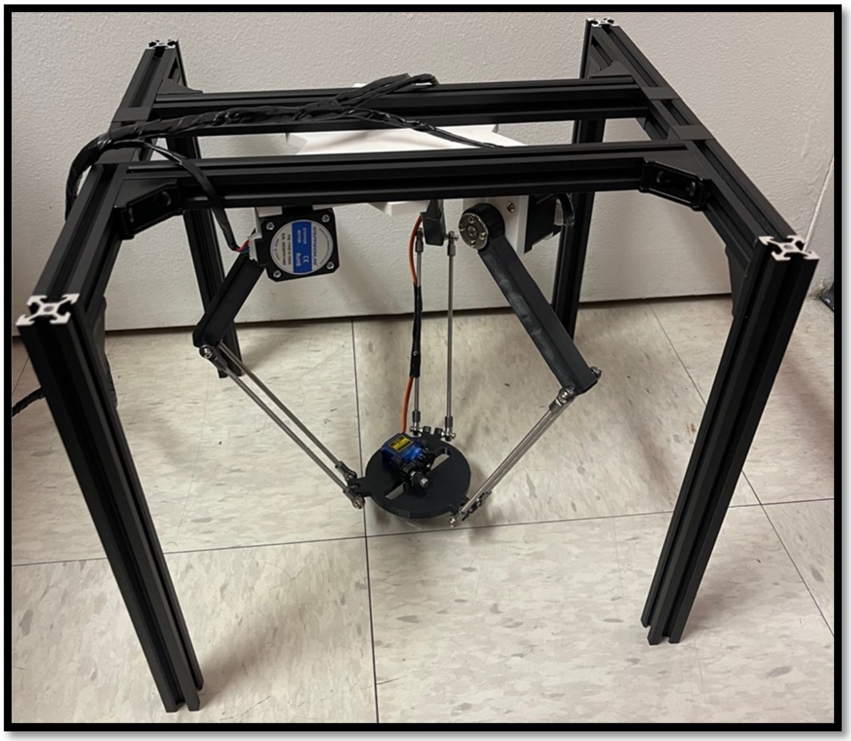

Fig. 15 Final complete product

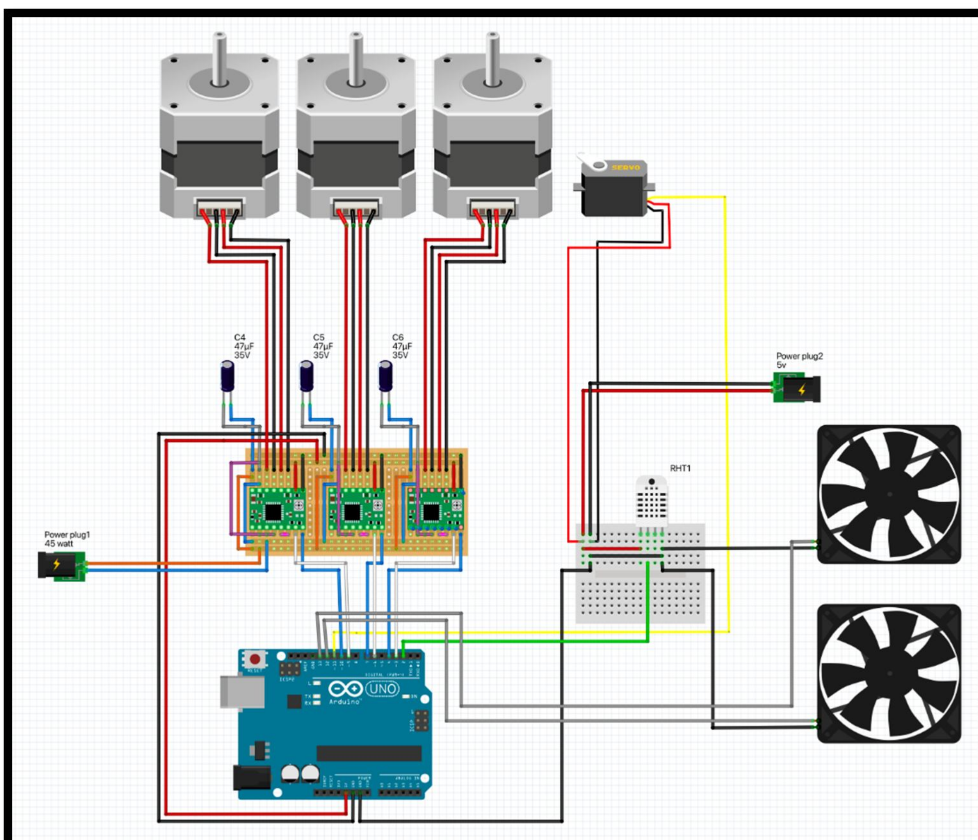

Fig. 16 Schematic

Each driver's current limiter must be set to the desired value. In this project the target is 1.5 Ampere to attain peak torque from the motor, consequently to the torque loss due to the micro stepping function.

TABLE I
OUTPUT CURRENT FROM DRIVER

Driver #	Actual Current (Ampere)
1	1.48
2	1.42
3	1.46

Table 2 describes the motor characteristics of the robot in this project. The table is only valid with 1/16th micro stepping enabled and the "AccelStepper" library [13] installed as the dynamics can change with different software. Speed outside of these parameters can result in inconsistent accuracy & precision, as well as step losses.

TABLE II
MOTOR CHARACTERISTICS

Actual Nema 17 HE15-1504S Characteristics		
MOTOR SPEED (STEPS/S)	MAX. SPEED	1000
	MIN. SPEED	400
DELAY TIME (MS)	MIN. DELAY	50
ANGULAR RESOLUTION (DEGREES)		0.1125

The robot´s work envelope is limited due to restricted movement in the ball joints. As a result, the shape of the work envelope is changed. The theoretical work envelope, shown in figure 17, will be larger than stated below in table 3 if the maxima points is considered. Theoretical work envelope is origins from equations collected at Trossen Robotics [6] and is calculated as a rectangular cuboid work envelope. Due to the true work envelope not being exactly cylindrical, but close enough for it to be considered as one, the diameter is calculated as the average diameter of 9 measurements. Figure 17 shows a MATLAB simulation of the work envelope for the robot [14].

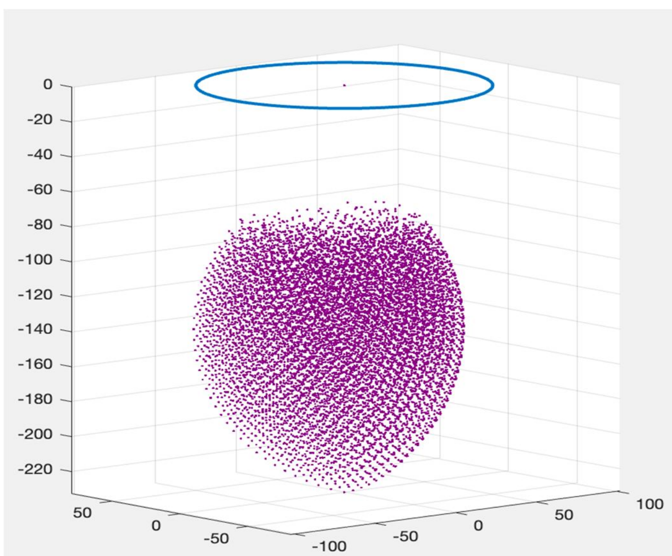

Fig. 17 Work envelope

TABLE III
ROBOT CHARACTERISTICS

ROBOT DIMENSIONS (MM)	BASE RADIUS (F)	70
	END EFFECTOR RADIUS (E)	98
	ACTIVE ARM (RF)	110
	PASSIVE ARM (RE)	160
WORK ENVELOPE (MM)	THEORETICAL (RECTANGULAR CUBOID) (X, Y, Z)	145.8 x 145.8 x146
	ACTUAL (CYLINDER) (D, H)	139.7 x 101
RESOLUTION (MM)		+/- 0.17

VI. CHALLENGES AND SOLUTIONS

A servo motor was initially settled on for this project, due to its easy position control and high torque. However, a major drawback with the servo motor was the lack of speed control and angular resolution, resulting in poor control of the end effector [15]. Therefore, a stepper motor was decided on to replace the servo motor with its microstep function and speed control. The downside is the huge lack of torque, but due to the light weight of the end effector, the torque offered from the stepper motor will still be sufficient for this application.

A core principle that was considered during this project was Design for Manufacturability (DFM). Because 3D printing works by printing layer by layer, a vertical hole results in the printer having to print an overhang. This means that it will print over the edge of the layer below and into free air. IN certain instances when this overhang becomes too large, the hole loses its dimensions. A solution to this is to shape the holes into water droplets to reduce the overhang [16], as well as carefully considering the orientation of the product during the printing process. I experienced some shrinkage of the parts, meaning that the finished product tended to be slightly smaller than in the design, consequently I would have to design every dimension slightly larger to account for this shrinkage.

VII. CONCLUSION

In conclusion, the robot operates effectively without any significant flaws or limitations. Its adaptable design facilitates effortless modification and reconfiguration to suit diverse applications. Fulfilling the primary objective of the project, the robot serves as a valuable educational tool for students to explore robotics concepts. The user-friendly interface facilitates hands-on learning of robot programming. Moreover, the robot's components are highly customizable, empowering students to design and integrate their own modifications. This flexibility enables adjustments to the work envelope, precision, speed, and end effector, fostering creativity and innovation in robotics education.

VIII. ACKNOWLEDGEMENT

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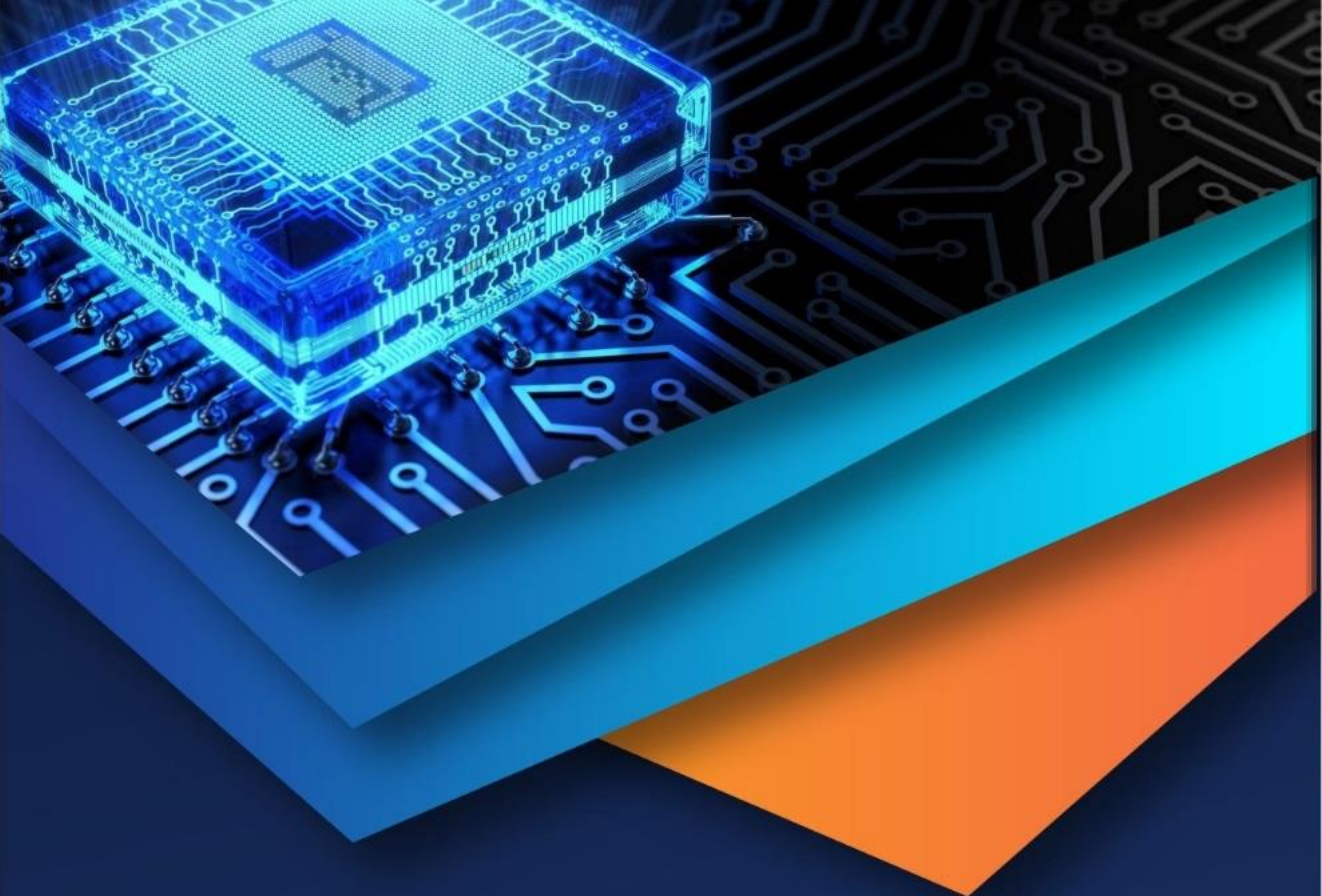

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