Schmalkalden University of Applied Sciences

Project Report on

XY- Pen Plotter

In partial fulfilment of the requirements for the degree of

Master of Engineering in
Mechatronics and Robotics

Under the subject of:

Workshop Mechatronics

Submitted By:

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CERTIFICATE

This is to certify that the project titled "**XY Pen plotter**" submitted by **Choudhary Prithviraj**, **Gangiredla Varun Kumar**, **Khule Nitin**, **Pandaraboyana Dheeraj Kumar**, **Rao Parul Vivek Sunder**; to the Mechanical Engineering Department of Schmalkalden University of Applied Sciences, in partial fulfilment of the requirements for the award of the degree of Master of Engineering in Mechatronics and Robotics is a record of our own work.

To the best of my knowledge, this report has not been submitted to any other University or Institute for award of any degree.

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This is to certify that the statements made by the candidate are correct to the best of our knowledge and belief. It is further understood that by this certificate the undersigned do not endorse or approve any statement made, opinion expressed or conclusion drawn herein, but approve the report only for the purpose for which it is submitted.

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1. INTRODUCTION

1.1 Objectives

We take great pleasure in presenting the comprehensive project report documenting our group's remarkable achievement in the development of a pen plotter. Our endeavour was dedicated to the creation of a sophisticated pen plotter capable of producing intricate drawings, with a specific emphasis on the renowned Nikolaus Haus. This project report meticulously details our journey, providing an exhaustive account of the design process, implementation strategies, testing protocols, and the successful realization of our pen plotter project.

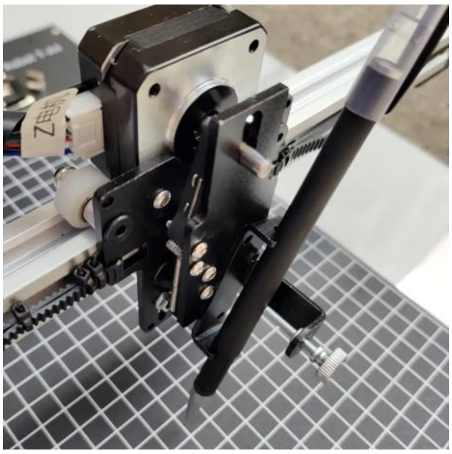

Figure 1.1 Pen Plotter

The Nikolaus Haus, renowned for its complex architectural details and artistic significance, posed a compelling challenge. Our sole objective was to engineer a pen plotter capable of faithfully reproducing the intricate features of the Nikolaus Haus.

The design phase involved a thorough exploration of hardware, software, and mechanical components. We meticulously selected motors, sensors, and control mechanisms to ensure optimal accuracy and control. Our software development efforts focused on designing and implementing sophisticated algorithms capable of interpreting drawing sequences and translating them into precise pen movements.

Testing and evaluation played a pivotal role in validating the performance of our pen plotter. Rigorous tests were conducted to measure accuracy, speed, and overall capability in recreating the Nikolaus Haus. Through detailed analysis of test results and iterative improvements, we ensured that our pen plotter consistently delivered exceptional results, capturing the essence of the Nikolaus Haus in each stroke.

This project report offers an in-depth narrative of our journey, elucidating the design process, implementation strategies, testing methodologies, and the final outcome of our pen plotter project. It stands as a testament to our commitment to innovation, precision, and admiration for architectural marvels that serve as sources of inspiration. We aspire for our work not only to contribute to the advancement of pen plotting but also to ignite further exploration and creativity in the realms of architectural representation and artistic expression.

2. PROJECT GOALS AND PROJECT PLANNING

2.1 Project Goals and Objectives

The main goal of this project is to construct and advance a pen plotter by integrating various components responsible for governing pen movement and ensuring precise plotting on paper. The project team will engage in tasks such as designing, fabricating, and assembling the pen plotter, programming the control system, and establishing a user-friendly interface. The key activities encompass:

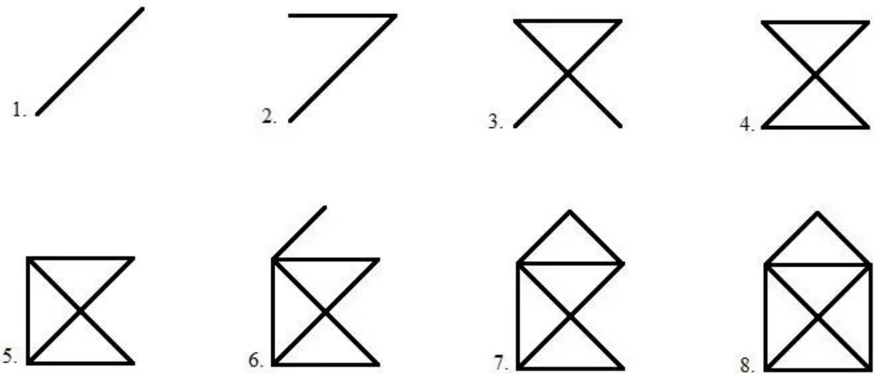

Figure 2.1 Nikolaus Haus

- Identifying user requirements and subsequently formulating technical and design specifications.
- Executing hardware, software, electrical, and mechanical CAD designs.
- Creating a user interface to manage pen movement.
- Conducting thorough testing and calibration of the pen plotter to achieve optimal performance.
- Demonstrating the pen plotter's functionality and showcasing its output through plotted designs, with a specific focus on Nikolaus Haus.

2.2 ORGANISATION CHART

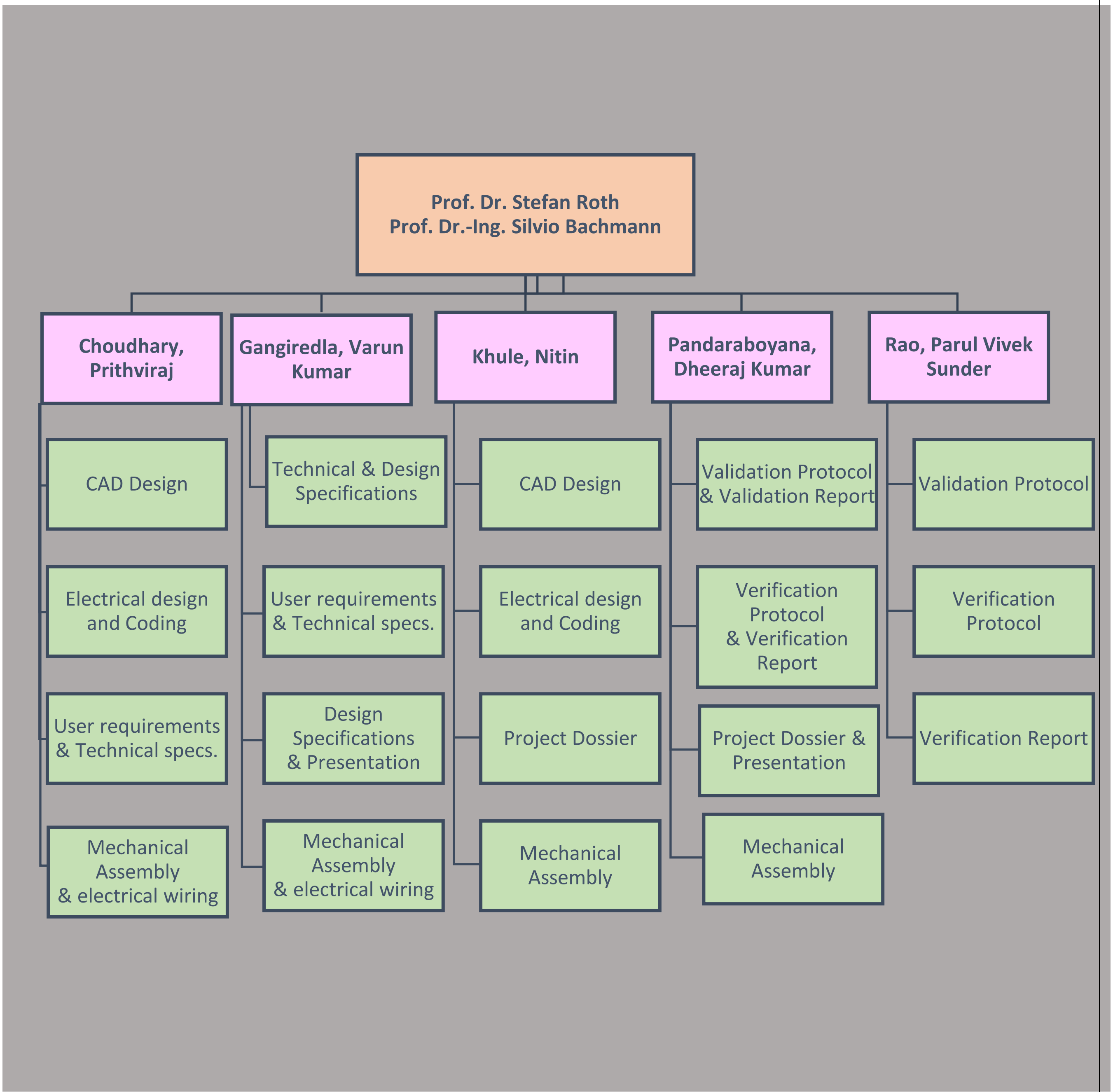

Figure 2.2 Organisation Chart

2.3 PROJECT TIMELINE

The project timeline for the pen plotter is structured into several phases, encompassing research and design, component acquisition, prototyping, testing, and final implementation.

Table 2.1 Project Timeline

Phase	Tasks	Days	Start Date
Idea Phase		7	17.04.23
	Conduct market research	2	
	Benchmark models of seniors in the lab	1	
	Brainstorm for the integration of new features	3	
	Set user requirements	1	
	Completion of the idea phase with the deliverable of user requirements	0	
Project Planning		6	24.04.23
	Budget and Resource Planning	1	
	Set-Up Project Team	1	
	Develop technical specifications	2	
	Formulate design specifications	2	
	Completion of the project planning phase	0	
Development Phase		34	02.05.23
	Concept Development	2	
	Electrical Design	2	
	Software Design	18	
	Mechanical / CAD Design	12	
	Completion of CAD model and electrical circuit diagram	0	
Prototyping & Fabrication		14	03.09.23
	3D printing of test piece for fitment	2	
	Test piece printing and checking	1	
	3D printing of plastic parts	6	
	Assembly	2	
	Electrical Wiring	3	
	Completion of the prototype	0	
Testing and calibration		17	17.09.23
	Programming and Troubleshooting	6	
	X and Y Axis calibration	3	
	Testing drawing performance and tuning PID	4	
	Formulation of verification protocol and report	2	
	Formulation of validation protocol and report	2	
	Completion of testing and calibration	0	
Documentation		5	04.10.23
	Project Presentation	5	
	Project Dossier	5	
	Bill of material	1	
	Completion of documentation	0	

2.4 DEVELOPMENT OF DOCUMENTATION ACCORDING TO V-MODEL

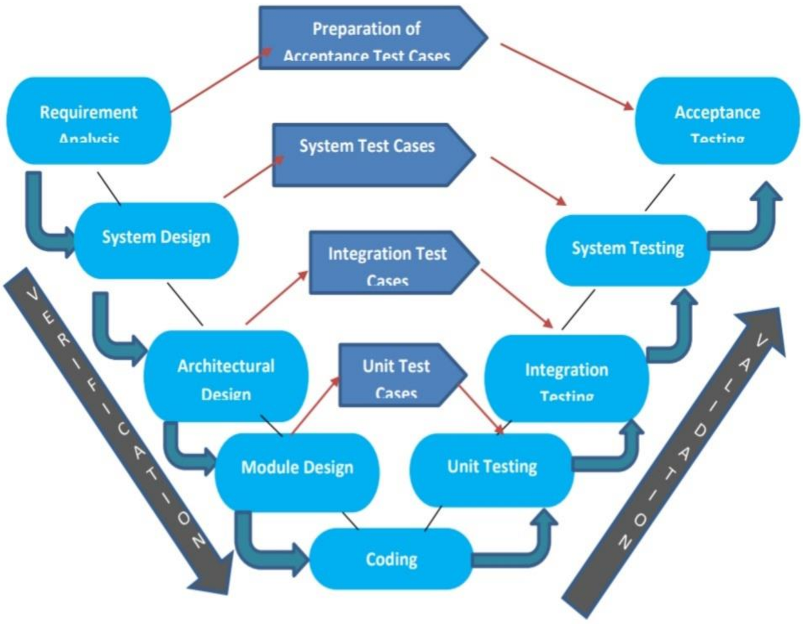

Figure 2.3 V-Model

The V-model for the pen plotter project offers a comprehensive framework, ensuring a systematic and structured development process. Commencing with the User Requirement stage, specific needs and expectations are gathered and documented, laying the groundwork for subsequent phases. The Technical Specification stage defines detailed specifications, covering size, resolution, speed, and accuracy. Software Requirements identify necessary functionalities, user interface design, and programming needs.

Mechanical Requirements specify components, materials, and design considerations for the pen plotter's physical structure. The Electrical Requirements stage determines electrical components, circuitry, and power requirements.

Moving into the Implementation stage, the pen plotter system is built, involving the assembly of mechanical and electrical components, integration of control systems, and software development. In the System Integration stage, individual subsystems are combined and tested for proper interaction and functionality.

The Verification of Design stage includes rigorous testing to ensure the pen plotter design aligns with specified requirements. System Testing validates overall performance, functionality, and reliability under various conditions. The Test Report documents results and findings from system testing, including encountered issues and resolutions.

Ultimately, the completed and tested XY Pen Plotter is ready for deployment and use. Adhering to the V-model ensures a systematic and thorough development approach, resulting in a reliable and high-quality pen plotter system.

2.5 MORPHOLOGICAL CHART:

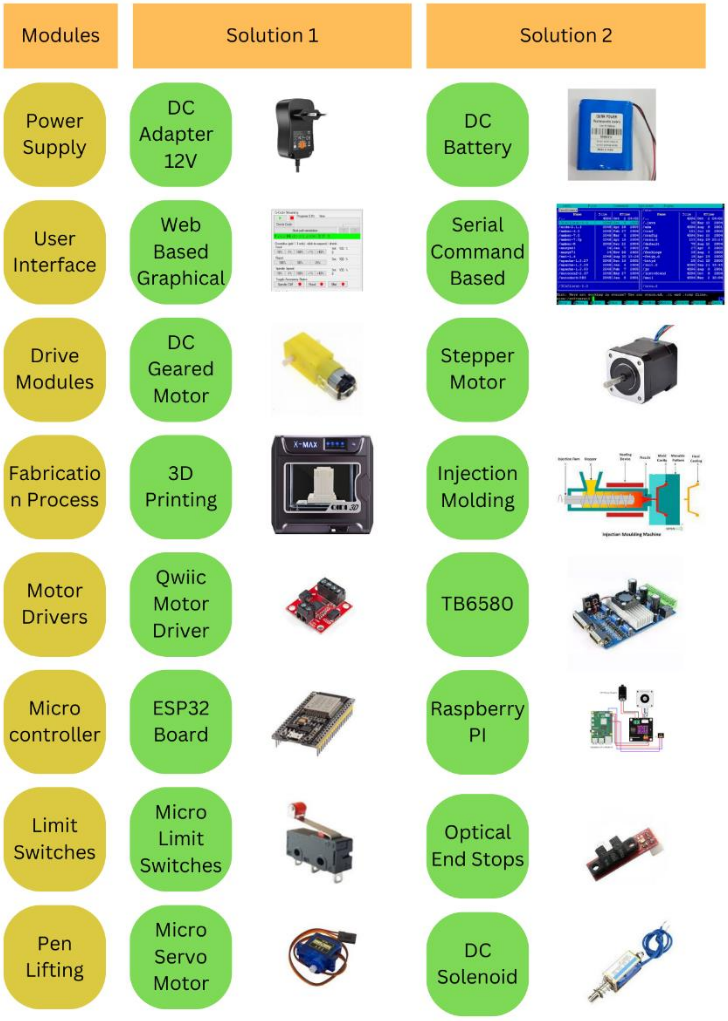

Figure 2.4 V-Model

The morphological chart for the pen plotter project is a visual tool that presents various design options and their corresponding features. It helps in systematically exploring and selecting components such as motors, controllers, sensors, pens, and user interface elements.

Through pairwise comparison, each design concept underwent systematic evaluations against others. As per the given set of components and best suitable components as per design requirements, we had opted for the design with **Solution 2.**

3. DESIGN STAGE

3.1 COMPONENT SELECTION

1- D.C. Motor: Two DC motors play a crucial role in a pen plotter project by providing precise rotary motion. This controlled movement of the motors allows for accurate pen positioning, facilitating precise plotting and drawing on a variety of surfaces.

Figure 3.1 D.C. Motor

2-ESP32 Board: ESP32 board used in pen plotter project versatile microcontroller with built-in Wi-Fi and Bluetooth, providing wireless connectivity and control for precise pen plotting and automation.

Figure 3.2 ESP32 Board

3-L298N Motor: The L298N Motor Driver is employed in a pen plotter project as a dual H-bridge module, responsible for regulating both motor speed and direction. This utilization ensures accurate control over the movement and positioning of the pen within the plotter, contributing to precise plotting and drawing outcomes.

Figure 3.3 L298N Motor Driver

4- Linear Ball Bearings: Linear ball bearings are implemented in the pen plotter project as rolling element bearings. These components facilitate smooth and low-friction linear motion, guaranteeing the precise and stable movement of the plotter carriage along the rails.

Figure 3.4 Linear Ball Bearing

5- Geared Pulley: In the pen plotter project, a pulley serves as a mechanical component with grooves, enabling the smooth and controlled rotation of belts or cables. This functionality ensures accurate pen positioning and movement within the plotter system.

Figure 3.5 Pulley

6-Adapter 12V (DC Power): The 12V DC Adapter employed in the pen plotter project serves as a power source, delivering regulated power to the plotter system. This ensures the stable and reliable operation of the various components and motors within the system.

Figure 3.6 Adapter

7-GT2 Driver Belt: In the pen plotter project, the GT2 driver belt is utilized as a high-quality toothed belt. This component plays a crucial role in enabling precise and synchronized movement by transferring rotational motion to linear motion with minimal backlash.

Figure 3.7 GT2 Belt

8-Screws and Fasteners: In the pen plotter project, screws and fasteners play a vital role by securely fastening components. This ensures the structural integrity of the system and precise alignment, contributing to stable and accurate operation of the plotter.

Figure 3.8   Fastener

9-Micro Limit Switch: The Micro Limit Switch incorporated into the pen plotter project is a small, mechanical switch with precise actuation. This component plays a key role in providing accurate end stop detection, contributing to precise pen movement control and ensuring accurate positioning in the plotter system.

Figure 3.9 Limit Switch

10-MOSFET Switch: MOSFET Switch used in pen plotter project electronic switch with high switching speed and low power dissipation, enabling efficient control of motor and other high-current devices in the plotter system.

Figure 3.10 MOSFET Switch

11-49E Hall Sensor: 49E Hall sensor used in pen plotter project magnetic field sensor detecting changes in magnetic field intensity, providing feedback for precise position sensing and control in the plotter system.

Figure 3.11   Hall Sensor

12-DC-DC Voltage Converter: DC-DC voltage converter used in pen plotter project converts input voltage to desired output voltage, providing power flexibility and stability for various components in the plotter system.

Figure 3.12 DC-DC Voltage Converter

13-Push Button: Push button (kill switch) used in pen plotter project emergency stop button for immediate system shutdown, ensuring operator safety and preventing potential accidents during operation.

Figure 3.13 Kill Switch

3.2 Electrical Design

The electrical schematic diagram illustrates the well-structured design of a pen plotter project, showcasing the efficient interconnection of key components. At the heart of the circuit is the ESP32 microcontroller, functioning as the main controller to independently manage X and Y axis motors through L298N motor drivers. These drivers ensure precise motor control, facilitating smooth and accurate pen movements for precise drawings.

For vertical pen motion control, a 12V DC solenoid with a 5N force is integrated. Activated selectively by the microcontroller, the solenoid accurately raises or lowers the pen onto the plotting surface, allowing precise positioning for drawing or lifting to prevent unintended marks.

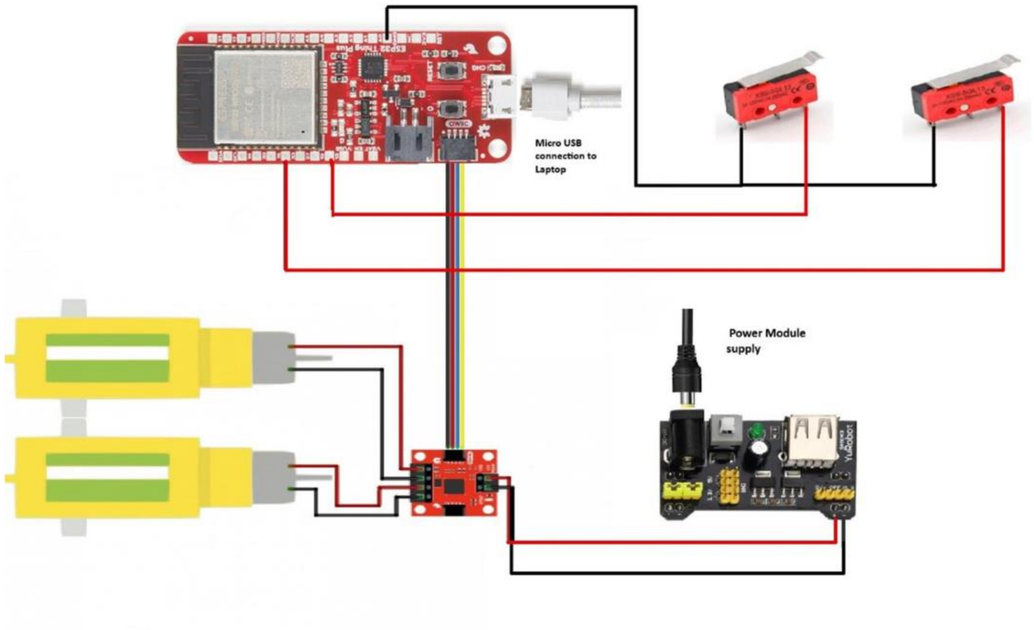

Figure 3.14 Electric Circuit Diagram

To provide operational feedback, a 0.96-inch OLED display is incorporated, offering a clear interface for real-time updates on drawing progress, error messages, and user prompts. Enhancing the user experience, the display facilitates interaction with the plotter.

The inclusion of four Hall sensors serves as encoders, providing precise position feedback by detecting and measuring magnetic fields. This feedback loop ensures accurate plotting, enabling the creation of intricate designs.

For safety and boundary enforcement, strategically placed limit switches in the X-Y plane halt the pen plotter's movement upon reaching predefined limits. These switches trigger the microcontroller, adding an extra layer of safety to prevent damage.

Unlike a breadboard, the circuit is constructed on a perf-board, eliminating signal noise risks from loose connections. This choice ensures the reliable and stable operation of the pen plotter, providing a secure platform for component assembly and contributing to the overall robustness of the system.

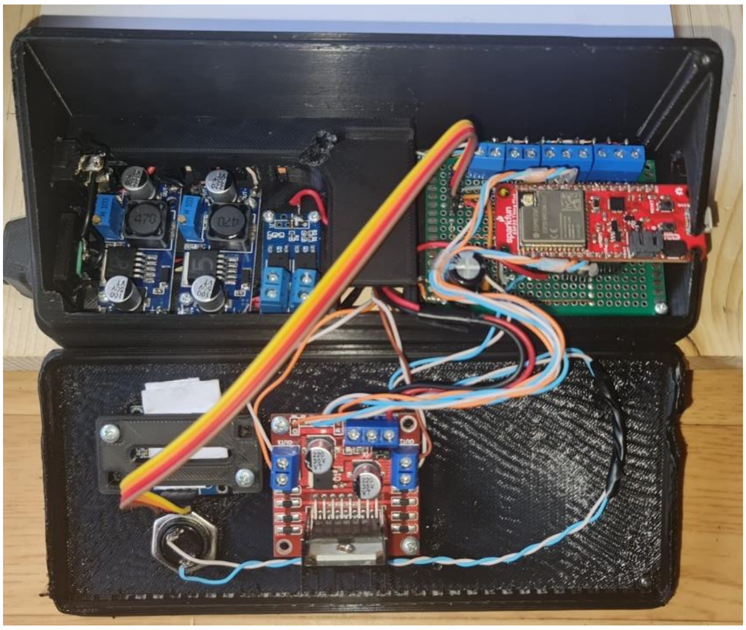

Figure 3.15 Electronic Enclosure

In summary, the electrical schematic diagram offers a comprehensive configuration for a pen plotter project, leveraging the integration of key components to enable precise control, accurate plotting, and improved reliability. This results in the creation of intricate and high-quality drawings.

3.3 MECHANICAL CAD DESIGN

As per requirements, the planning phase regarding the design was done and the below procedure was followed: Initially, the following components were designed accurately by using DSS SolidWorks:

a) Frame and Structure

b) Carriage and Slides

c) Pulley and its fixtures

d) Pen Holder

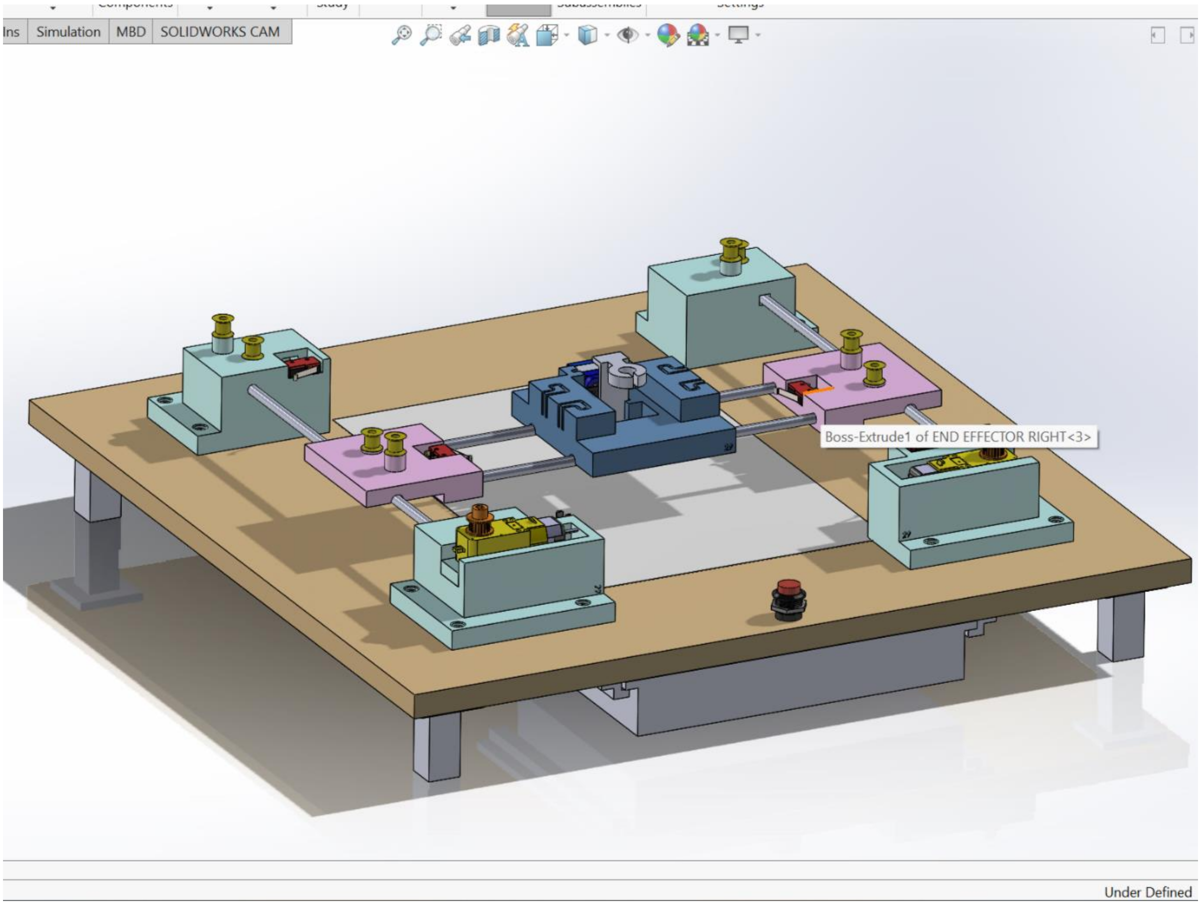

Figure 3.16 CAD Design

1-Pen holder: It is a mechanical component designed to securely hold the pen, enabling controlled and precise movement during plotting. It accommodates different pen sizes, allows for quick pen changes, and ensures consistent pen pressure for accurate and smooth drawings.

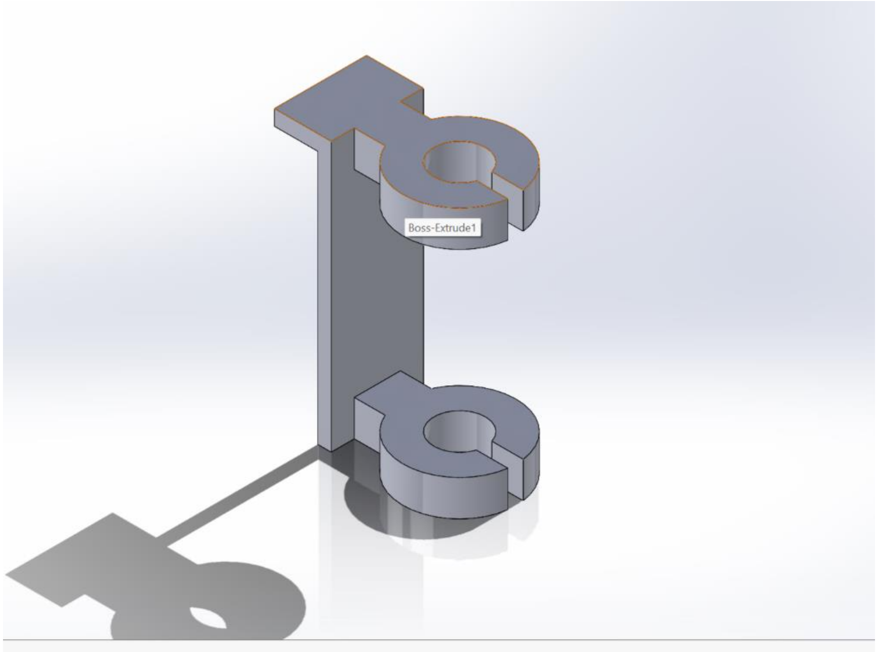

Figure 3.17 CAD Design

2-End Effector: The pen plotter's end effector should securely hold adjustable pens, maintain precise positioning, adapt to various drawing surfaces, be lightweight for efficient movement, integrate seamlessly with the plotter frame, include a reliable pen lifting mechanism, and offer a feedback system for improved control. Prioritize ease of maintenance and part replacement.

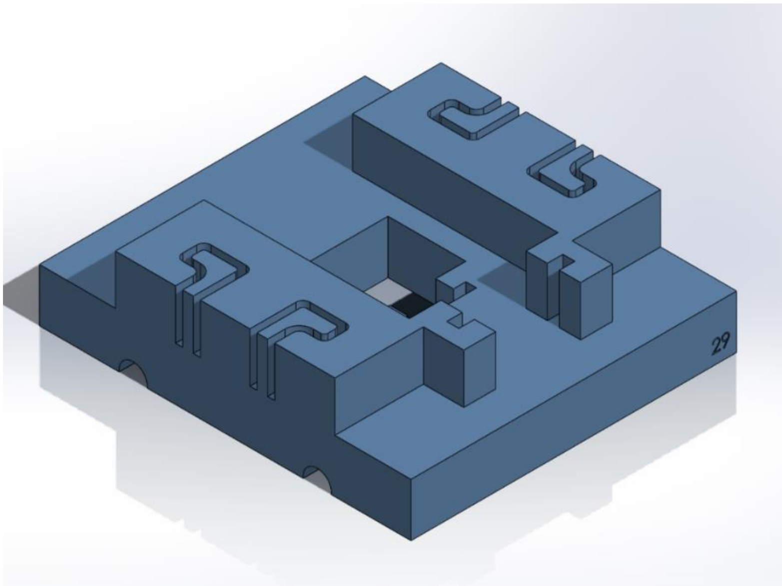

Figure 3.18 End Effector

3-Foot: The foot design in a pen plotter ensures stability, vibration damping, and non-slip properties. It should be compatible with the plotter frame, allow for adjustable height, and be easy to install. Durable materials contribute to longevity, and considerations for portability may also be relevant.

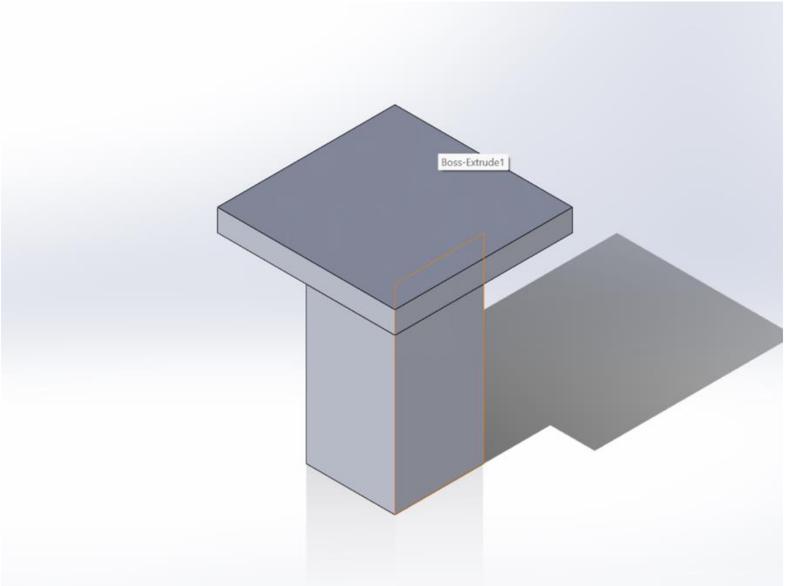

Figure 3.19 Foot Design

4-DC Motor Mount: The DC motor mount in a pen plotter design secures the motor in place, ensuring stable and precise movements. It is typically engineered to integrate seamlessly with the plotter structure, providing reliability and facilitating ease of assembly. The design should consider factors such as vibration reduction, adjustability, and compatibility with the overall plotter framework.

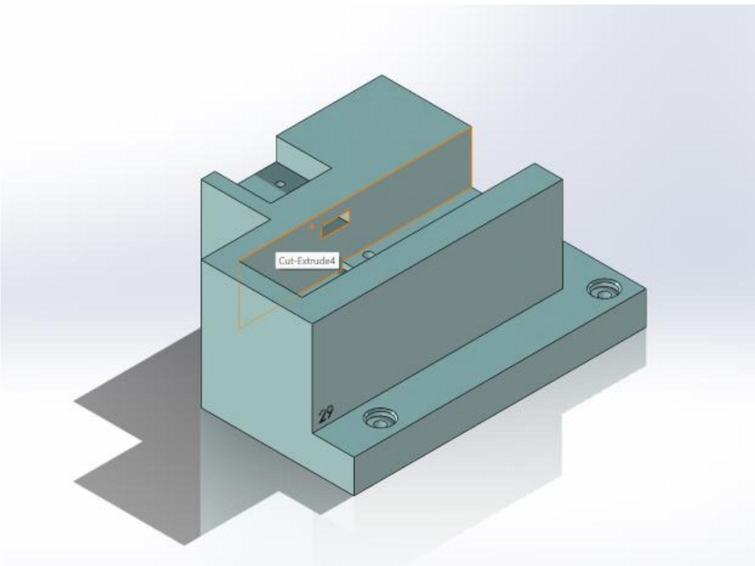

Figure 3.20 DC Motor Mount

5-Pully Mount: The pulley mount in a pen plotter design securely positions the pulleys for smooth and controlled movement. It is engineered for stability, compatibility with the plotter structure, and efficient power transmission. The design emphasizes precision, minimizing play, and ensuring optimal alignment for accurate plotting.

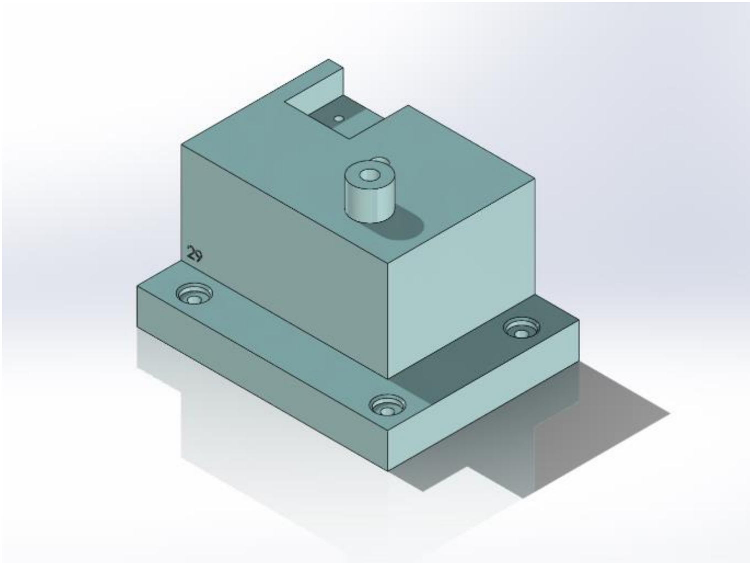

Figure 3.21 Pully Mount

6-Sliding pully Mount: The sliding pulley mount in a pen plotter design enables movement solely in the Y-direction. This specialized mount houses pulleys that guide the plotter mechanism, ensuring smooth and accurate motion along the vertical axis. The design prioritizes precision, minimizing play, and facilitating efficient power transmission for reliable plotting performance.

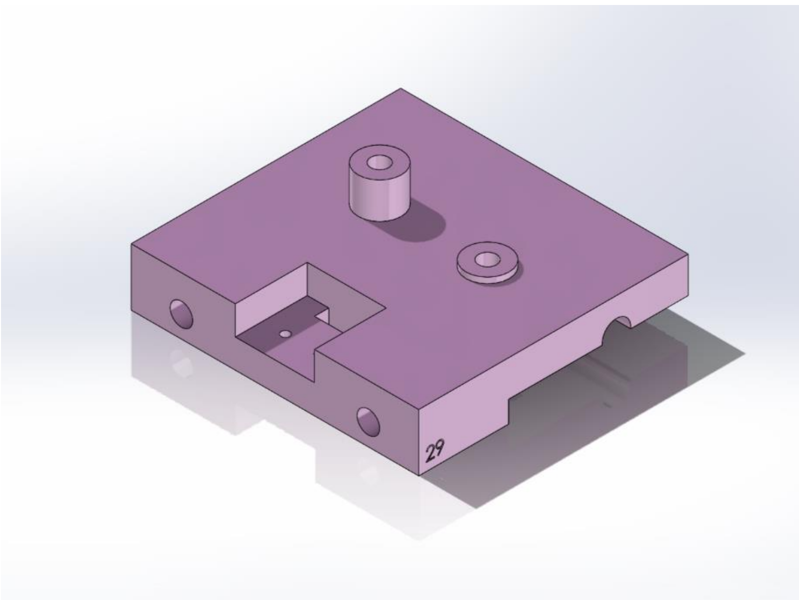

Figure 3.22 Sliding Pully Mount

7-Storage Compartments: The storage compartments in the XY pen plotter design house various electrical components, ensuring organized and accessible placement. These compartments are strategically integrated into the plotter structure, providing a space-efficient solution for storing components such as controllers, drivers, and wiring. The design prioritizes accessibility, allowing for convenient maintenance and troubleshooting when needed.

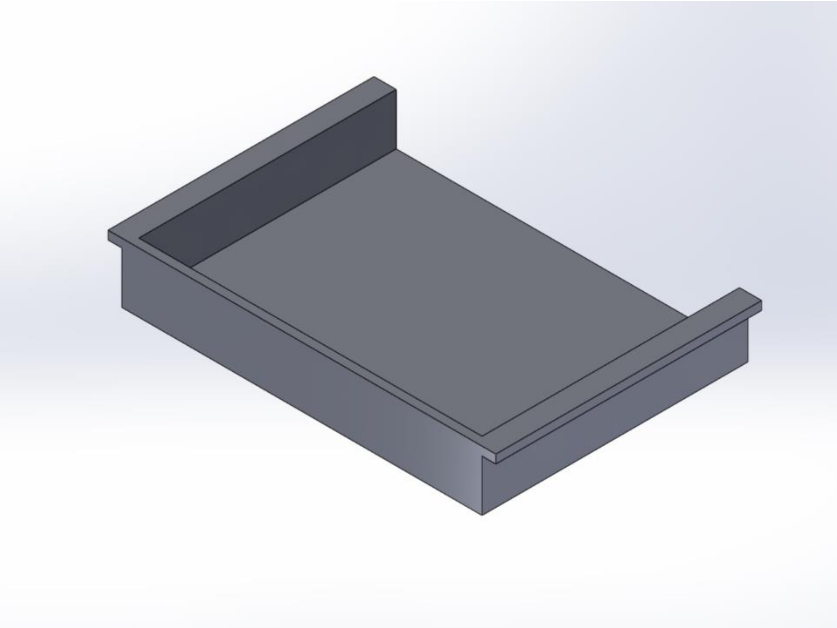

Figure 3.23 Storage Compartment

Base Plate: The base plate in a pen plotter project serves as the foundational chassis on which the entire assembly is mounted. Typically made of wood, it provides stability and support to the various components, ensuring a rigid structure for accurate and reliable pen plotting operations.

It provides a convenient and organized arrangement, securing and protecting these components, simplifying the wiring connections, and facilitating easy access for control and operation of the pen plotter system.

4. DEVELOPMENT AND FABRICATION STAGE

4.1 PROCESS USED TO DEVELOP THE PEN PLOTTER

The creation and construction phase of the pen plotter encompass the conversion of the initial concept into a fully operational device. This entails the formulation of the mechanical framework, the careful selection and incorporation of components, the production and assembly of physical elements, the thorough testing of the system to ensure functionality and accuracy, and the documentation of the entire process for future reference and enhancement.

4.2 SELECTION OF MATERIALS

PLA (Polylactic Acid) stands out as the ideal filament for beginners in the typical FDM printing procedure, owing to several key attributes. It has been selected because of its:

1. Excellent printability
2. Reduced distortion (warping) throughout the printing process.
3. User-friendly nature
4. Cost-effectiveness
5. Compatibility with 3D printing technology
6. Environmentally friendly characteristics
7. All the 3D designed components were printed using the "QIDI TECH X-MAX 3D Printer" located in the AKT lab, Haus D.

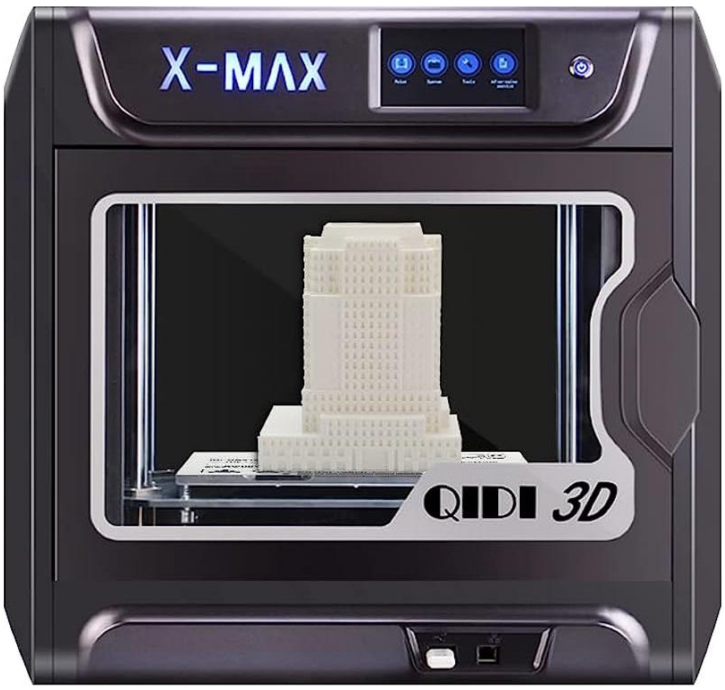

Figure 4.1 3D Printer

4.3 APPLICATION OF TEST PIECE

Incorporating a test piece in the 3D printing process enables the assessment of print quality, detection of potential issues, and fine-tuning of printing parameters to achieve precise tolerance and fitment before proceeding with the final part production. This practice enhances the assurance of accuracy, functionality, and compatibility, ultimately reducing errors and minimizing material and time wastage.

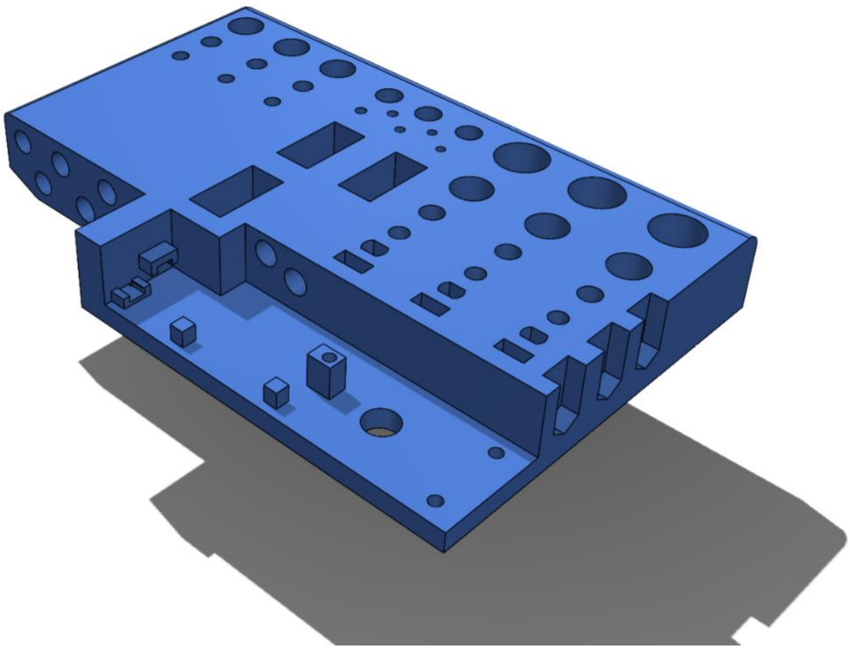

Figure 4.2 Application test piece

4.4 CHALLENGES FACED DURING DEVELOPMENT STAGE:

4.4.1 Challenges Regarding Wire Routing

Within electronic design, a pivotal aspect involves concealing the wiring network to elevate the visual appeal of the product. Exposed wires not only result in a disorderly and unappealing aesthetic but also compromise the overall design and professionalism of the product. Additionally, the susceptibility of exposed wires to snagging, bending, or unintentional interference can lead to electrical malfunctions or even the complete failure of the device. To address these issues, we've developed an enclosure featuring a built-in wire routing channel that adeptly accommodates all wiring connections and electronic components. The incorporation of plastic cable ribbons facilitates the organized routing of wires to the X and Y carriages, ensuring a tidy internal structure for enhanced functionality and reliability.

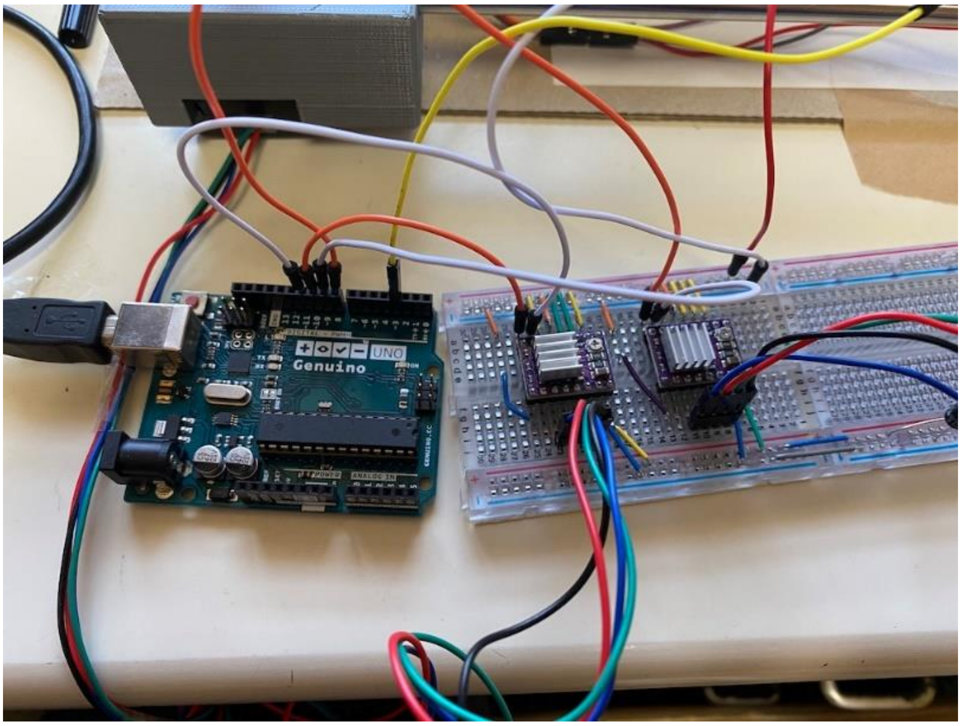

Figure 4.3 Wires and Cables

4.4.2 Issue associated with noise in sensor output signals poses

In our design, we have integrated Hall sensors along with a magnetic encoder disk to detect rotational changes in the magnetic field. The encoder disk features alternating magnetic poles positioned uniformly around its circumference. As these magnetic poles pass the Hall sensors, they induce voltage through the Hall effect, allowing microcontrollers to interpret position and movement. Unfortunately, the presence of noise in the sensor output signals led to inconsistencies in position sensing, resulting in inaccuracies in plot path tracking.

To address this issue, we implemented effective wiring techniques, such as using twisted pair cables, to minimize ground loops and reduce noise coupling. Additionally, the incorporation of a digital Butterworth filter, a signal filtering method, proved instrumental in significantly reducing high-frequency noise components. Furthermore, we took measures to shield all wires using a Silver-Plated Copper Braid, providing protection against external electromagnetic interference. These enhancements collectively contribute to a more reliable and accurate performance of the system.

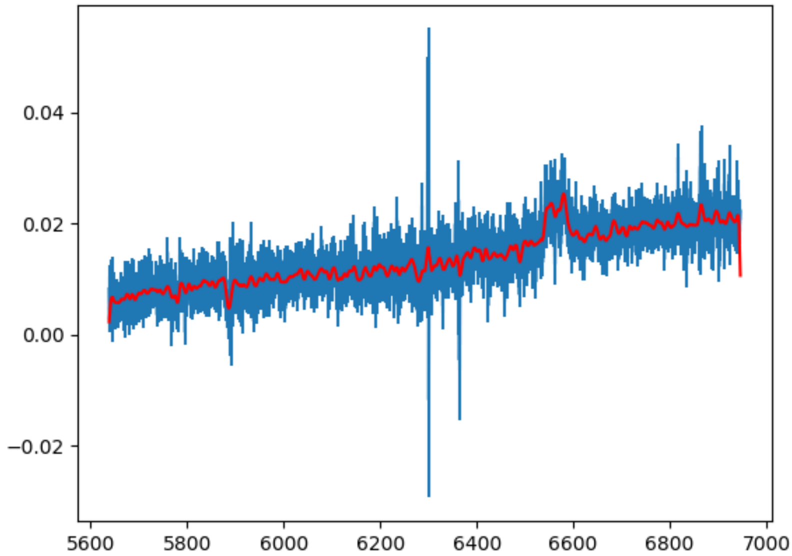

Figure 4.4 Raw v/s Filtered Data

5. TESTING AND ITERATION

The phase of testing and iteration in the development of a pen plotter project entails a comprehensive assessment of the system's functionality, performance, and reliability. This encompasses the evaluation of motion control, pen actuation, and plotter coordination. The goal is to identify any issues or limitations and implement iterative refinements to enhance the overall performance and accuracy of the project.

5.1 TESTING PROCEDURE

- **Restricted Color Range:** Pen plotters typically employ a single color of pen or marker, restricting the artistic use of color to monochrome or a narrow spectrum. Working solely with pen plotters may pose challenges in creating vibrant and diverse color combinations.

- **Slower Speed:** In comparison to alternative printing technologies, pen plotters operate at relatively slower speeds. The mechanical nature of the device, coupled with the precision required for accurate charting, constrains their efficiency for large-scale or time-sensitive tasks. This limitation can result in extended processing and plotting durations.

- **Positional Accuracy:** Pen plotters can utilize both DC geared motors and stepper motors. However, when employing micro-stepping, stepper motors offer superior positional accuracy compared to DC geared motors.

- **Limited Media Compatibility:** Pen plotters perform optimally on flat materials such as paper or cardstock. Challenges may arise when attempting to plot on unconventional or uneven surfaces. The restricted compatibility with various artistic mediums may impede experimentation and exploration.

5.2 DESIGN ITERATION

The CAD design of the pen plotter project incorporates meticulously planned cable routing paths to ensure effective cable management, thereby reducing the likelihood of cable entanglement or obstruction during operation.

The objective is to uphold a neat and organized layout while enabling the smooth movement of the plotter. Through the strategic planning of cable routes, potential issues such as interference with moving parts, signal disruptions, and overall system reliability are proactively addressed. Factors like cable length, flexibility, and secure attachment points receive careful attention to ensure optimal performance and minimize the risk of malfunctions related to cables. The design considerations underscore the significance of cable management in maintaining a streamlined and efficient operation of the pen plotter.

Table 5.1 Verification Test Protocol

Verification Protocol					
VerP #	**ref to TS #**	**Test procedure (description of routine)**	**Verification Criterion**	**Ref. # (i.e. test protocol, etc)**	**Domain (HW/SW/ME/ALL)**
Application					
VerP1	TS5	Setup pen plotter on a stable surface. Then draw Nikolaus house 10 times.	10 Nikolaus Haus drawn	Group 29_Technical Specification.xlsb	ALL
General Functions					
VerP2	TS1	Put the pen plotter into a box of 56x42x39 cm provided by Uni Lab.	Fits in box with lid closed	Group 29_Technical Specification.xlsb	HW
VerP3	TS1	Place the pen plotter assembly on a measuring scale with an accuracy of ± 1gm. Take 3 readings and find out their mean value.	Mean of three weight measurement is well below 3500gm	Group 29_Technical Specification.xlsb	HW
VerP4	TS1	Run the Pen Plotter continuously across the paper for 30 min.	Continuous drawing upto 30 min at a time.	Group 29_Technical Specification.xlsb	ALL
VerP5	TS1	Start stopwatch, activate plotter with button, run stopwatch concurrently. Stop timer after drawing completion. Take 3 readings and find out their mean value.	Average Time taken <40 seconds	Group 29_Technical Specification.xlsb	ALL
VerP6	TS1	Move the Pen from point A (0,0) to Point B (100,100) 10 times and measure the error at Point B for each cycle.	Average error <= ± 0.24mm	Group 29_Technical Specification.xlsb	ALL

General Functions					
VerP7	TS1	Start the pen plotter and take noise level measurement by sound level meter. Take 5 readings and find out their mean value.	Mean of three noise measurement is <=60 dBA	Group 29_Technical Specification.xlsb	HW/ME
Module Motor Controller Electronics and Wiring					
VerP8	TS8	Confirm switch functionality, halt plotter movement when contacted by levers, preventing overtravel and ensuring accurate and safe plotting. Check 10 times.	Overtravel prevention, accurate and safe plotting.	Group 29_Technical Specification.xlsb	HW
Module Base Plate					
VerP9	TS8	Align the plotter for accurate plotting within the maximum A4 size. Perform 10 test plot using an A4-sized drawing media.	Maximum size of drawing media = A4.	Group 29_Technical Specification.xlsb	HW
Module Pen Holder / Carriage					
VerP10	TS8	Gather pens, position them and measure the diameter by Vernier callipers. Record the measurement results for each pen.	The diameter is less than 15mm	Group 29_Technical Specification.xlsb	ME
VerP11	TS8	Drawing media is positioned correctly, and maximum thickness of drawing media (wood base, etc) 3cm.	Maximum thickness of drawing media = 3cm.	Group 29_Technical Specification.xlsb	HW/ME

Module Coding, Control & User Interface					
VerP12	TS8	Power on, calibrate for accuracy (repeat 5 times), test emergency stop. Establish reliable starting point, align X and Y axis, move to specific point & check error.	Calibration (5 times), X and Y alignment, move to point, check error and usage of emergency stop.	Group 29_Technical Specification.xlsb	SW

Table 5.2 Verification Test Report

Verification Report								
VerR #	**ref. to VerP #**	**Test function (to be copied from verification protocol)**	**verification criterion, the target value**	**Actual value**	**Criterion passed/ failed**	**remark**	**ref. # (i.e. test report, etc)**	**Domain (HW/SW /ME/AL L)**
Application								
VerR1	VerP1	To draw Nikolaus Haus until failure or more than 10 times.	10 drawings without error	All the 20 houses are drawn correctly.	Passed		Group 29_Technical Specification.xlsb	ALL
General Functions								
VerR2	VerP2	To put the pen plotter into a box of 56x42x39 cm^3 provided by Uni Lab.	Fits in box with lid closed	Fits perfectly	Passed		Group 29_Technical Specification.xlsb	HW
VerR3	VerP3	To ensure that pen plotter assembly weighs less than 3.5 kgs.	Weight <= 3.5kg	2.8kg	Passed		Group 29_Technical Specification.xlsb	HW
Module Base Plate								
VerR9	VerP9	Align the plotter for accurate plotting within the maximum A4 size. Perform 10 test plot using an A4-sized drawing media.	Drawing media size = A4.	A4	Passed		Group 29_Technical Specification.xlsb	HW

Module Pen Holder / Carriage								
VerR10	VerP10	Maximum pen diameter used is less than or equal to 15mm	Diameter <=15mm	13mm	Passed		Group 29_Technical Specification.xlsb	ME
VerR11	VerP11	Determine the max. Permissible Drawing media thickness	Maximum thickness of drawing media >= 5mm.	3cm	Passed		Group 29_Technical Specification.xlsb	HW/ME
Module Coding, Control & User Interface								
VerR12	VerP12	Start, Calibrate (5x), Test Emergency Stop. Establish starting point, Align X and Y, Move to point, Check error.	Execute all the given tasks/functions.	All the functions were working properly.	Passed		Group 29_Technical Specification.xlsb	SW

Table 5.3 Validation Test Protocol

Validation Protocol				
ValP #	**ref. to UR #**	**Validation procedure (description of routine)**	**ref. # (i.e. validation protocol, customer test, etc.)**	**Validation criterion, target value**
ValP1	UR1, UR2,	Install the pen plotter in the university lab, initiate the pen plotter under the student's supervision, and proceed to create a drawing of Nikolaus Haus.	Group 29_Technical Specification.xlsb	Plotter must draw Nikolaus Haus in one run.

ValP #	ref. to UR #	Validation procedure (description of routine)	ref. # (i.e. validation protocol, customer test, etc.)	Validation criterion, target value
ValP2	UR3	Put the pen plotter into a box of 56x39x42 cm provided by Uni Lab.	Group 29_Technical Specification.xlsb	Fits perfectly
ValP3	UR4	Place the pen plotter assembly on a measuring scale with an accuracy of ± 1gm	Group 29_Technical Specification.xlsb	Total weight <= 3.5kg
ValP4	UR3	Continuous drawing up to 30 min at a time.	Group 29_Technical Specification.xlsb	30 min.
ValP5	UR4	Compare the calculated mean value with expected results or specifications to ensure the accuracy of the timing measurements.	Group 29_Technical Specification.xlsb	Average error <= ±0.25mm
ValP6	UR4	Start the pen plotter and take noise level measurement by sound level meter.	Group 29_Technical Specification.xlsb	Average noise measure <=60 dBA

Table 5.4 Validation Test Report

Validation Report			
ValR #	**ref. to ValP #**	**Criteria (passed/failed)**	**ref. # (i.e. test report, etc..)**
ValR1	ValP1	Passed	Group 29_Technical Specification.xlsb
ValR2	ValP2	Passed	Group 29_Technical Specification.xlsb
ValR3	ValP3	Passed	Group 29_Technical Specification.xlsb
ValR4	ValP4	Passed	Group 29_Technical Specification.xlsb
ValR5	ValP5	Passed	Group 29_Technical Specification.xlsb
ValR6	ValP6	Passed	Group 29_Technical Specification.xlsb
ValR7	ValP7	Passed	Group 29_Technical Specification.xlsb
ValR8	ValP9	Passed	Group 29_Technical Specification.xlsb
ValR9	ValP10	Passed	Group 29_Technical Specification.xlsb

6. CONCLUSION AND ACKNOWLEDGEMENTS

In summary, the realization of our pen plotter project exemplifies the seamless integration of a diverse array of components. This achievement stands as a testament to the dedication, expertise, and collaborative spirit of our team. The incorporation of key elements, including DC motors, an ESP32 board for efficient control, a DC-DC converter for optimized power management, a Hall sensor and encoder for precise positioning, a linear ball bearing for smooth pen movement, pulleys for accurate belt drive, a DC solenoid for pen lifting, an OLED display for intuitive user interaction, and micro limit switches for reliable end stop detection, has resulted in the development of a high-performance and user-friendly pen plotter.

We express our sincere gratitude to all those who contributed to the success of this project. Our thanks extend to the team members who diligently worked on every facet, from design to implementation, ensuring the pen plotter's functionality and performance. Additionally, we acknowledge the invaluable support and guidance provided by our mentors and advisors throughout the project's development.

The accomplishment of this pen plotter project not only marks the realization of a creative and functional tool but also opens up new avenues for artistic expression and design. We anticipate further refinement and expansion of its capabilities in the future.

6.1 Bill of Materials

Table 7.1 Bill of Material

Bill of Materials							
Item	**Description**	**Material**	**Source**	**QTY**	**Measurement**	**Unit Price**	**Total Price**
Mechanical Components							
M01	Guiding Shaft 6mm	Steel	University Lab	4	Piece	€ 3.00	€ 12.00
M02	Timing Belt GT2	Nylon	University Lab	1.2	meter	€ 2.06	€ 2.47
M03	M3 Nut	Steel	Hellweg	20	Piece	€ 0.10	€ 1.99
M04	M3 Bolt	Steel	Hellweg	7	Piece	€ 0.09	€ 0.60
M05	M4 Nut	Steel	University Lab	5	Piece	€ 0.10	€ 0.50
M06	M4 Bolt	Steel	University Lab	5	Piece	€ 0.20	€ 1.00
M07	M5 Nut	Steel	University Lab	12	Piece	€ 0.10	€ 1.20
M08	M5 Bolt	Steel	University Lab	12	Piece	€ 0.20	€ 2.40
M09	Wood screw 3.5x30 mm	Steel	Hellweg	9	Piece	€ 0.15	€ 1.35
M10	SS Screws M3x15mm	Steel	University Lab	20	Piece	€ 0.06	€ 1.20
M11	Silicon-Grease		Amazon	4	gram	€ 0.12	€ 0.48
M12	Super Glue		Amazon	8	gram	€ 0.45	€ 3.60
M13	2mm Magnets		Amazon	60	Piece	€ 0.03	€ 1.80
M14	2mm Brass Rod	Brass	Hellweg	0.5	meter	€ 2.39	€ 1.20
M15	6mm LMU-N6 linear bearing		University Lab	6	Piece	€ 1.10	€ 6.60
M16	Tension spring 15mm	Steel	Hellweg	2	Piece	€ 0.05	€ 0.10
						Subtotal	**€ 45.59**
Electrical Components							
E01	ESP32 Board		University Lab	1	Piece	3.2	3.2
E02	Motor Driver L298N		Amazon	1	Piece	3	3
E03	DC Motor 48:1 geared 6V		University Lab	2	Piece	4.23	8.46
E04	Limit Switch SPDT AC 250V 5A		University Lab	4	Piece	1	4
E05	Perf-Board 5x7cm		Amazon	1	Piece	2	2
E06	Screw terminals		Amazon	6	Piece	0.02	0.12
E09	Adaptor 12V (DC Power)		Amazon	1	Piece	16.91	16.91
E10	MOSFET Switch		Amazon	1	Piece	1.3	1.3
E11	49E Hall Sensor		Amazon	4	Piece	0.6	2.4
E12	DC-DC Buck Voltage Converter		Amazon	2	Piece	1.15	2.3
E13	Multi strand wires		Amazon	16	meter	0.19	3

Item	Description	Material	Source	QTY	Measurement	Unit Price	Total Price
E14	Red Push button (18mm)		University Lab	1	Piece	1	1
						Subtotal	**€ 47.69**
3D Printed Components							
P01	Encoder Wheel	PLA	University Lab	2	Piece	1	2
P02	GT2 15T Motor Pulley	PLA	University Lab	2	Piece	1	2
P03	GT2 15T idler pulley	PLA	University Lab	2	Piece	1	2
Item	Description	Material	Source	QTY	Measurement	Unit Price	Total Price
P04	X Axis Idler fixture	PLA	University Lab	1	Piece	1	1
P05	X Carriage	PLA	University Lab	1	Piece	6	6
P06	Y Axis Motor Fixture	PLA	University Lab	1	Piece	11	11
P07	Y Axis Idler fixture	PLA	University Lab	1	Piece	8	8
P08	Y Carriage	PLA	University Lab	1	Piece	16	16
P09	Base Board Cover	PLA	University Lab	1	Piece	20	20
						Subtotal	**€ 68.00**
Grand total							**€ 161.28**

6.2 Future Scope

The future of pen plotters is poised for significant innovation and growth, particularly in the realm of immersive and interactive artistic experiences. One avenue for advancement lies in the adoption of higher-quality DC geared motors with finer gear ratios. This enhancement aims to achieve more precise positioning and smoother movement, ultimately contributing to improved accuracy in the plotting process. Concurrently, efforts are being directed towards refining the plotter's design to enhance reliability and efficiency, with a specific focus on reducing vibrations to elevate the overall quality of drawn output.

Looking ahead, future designs may prioritize a reduction in size and weight without compromising functionality and performance. This approach seeks to make pen plotters more compact and portable while maintaining or enhancing their capabilities.

Beyond these technical improvements, the integration of artificial intelligence (AI) and machine learning represents a promising frontier for pen plotters. By incorporating advanced algorithms, these devices could analyze and reproduce intricate artistic styles or patterns. This would empower users to generate unique and customized drawings based on their preferences or learned artistic techniques, ushering in a new era of personalized artistic expression.

Another avenue for innovation involves expanding the capabilities of pen plotters to accommodate multiple colors or various drawing mediums such as pencils or markers. This diversification opens up new possibilities for creativity and artistic exploration, allowing users to create more dynamic and visually engaging artworks.

Collaborative features represent yet another exciting prospect for the future of pen plotters. The development of functionalities that enable multiple pen plotters to collaborate on a single drawing or work synchronously on artwork could facilitate group projects, interactive installations, and even live art performances. This collaborative aspect holds the potential to transform the way artists and enthusiasts approach artistic creation, fostering a sense of community and shared creativity.

In summary, the future of pen plotters is marked by advancements in accuracy, connectivity, control systems, AI integration, and collaborative capabilities. These developments promise to deliver immersive and interactive artistic experiences, propelling pen plotters into new dimensions of creativity and expression.