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A PROJECT REPORT
on

TWO-DIMENSIONAL PEN PLOTTER

Submitted in partial fulfillment for the award of the degree of

Master of Engineering
in
Mechatronics and Robotics

by

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DEPARTMENT OF MECHATRONICS & ROBOTICS

DECLERATION

This is to certify that the project work entitled **TWO-DIMENSIONAL PEN PLOTTER** has been successfully completed under the guidance of Prof. Dr. Stefan Roth & Prof. Dr.-Ing. Silvio Bachmann and is a bonafide work carried out by:

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in partial fulfillment for the award of the degree of Master of Engineering in Mechatronics & Robotics during the academic year 2022-23.

Prof. Dr. Stefan Roth
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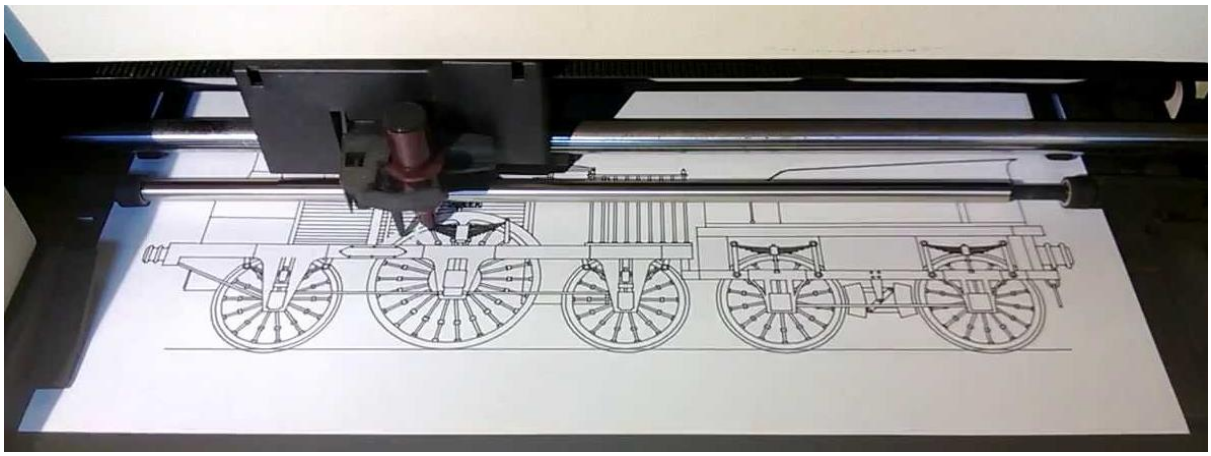


Figure-1: Concept example of XY Pen Plotter

The XY pen plotter is a sophisticated device that is used to draw texts and graphical artwork with extreme speed, precision and accuracy with the help of a computer-driven program. The pen plotter is an ideal example of a mechatronic system that operates by means of a synchronous collaboration between electrical, software and mechanical fields with the latter being the dominant discipline.

The original designs for a pen plotter were obtained from early analog measuring devices such as seismographs. From these origins, technological advancements have resulted in modern-day computer-driven XY pen plotters.

A text or an image is produced by utilizing a system of complex writing implements, which can be moved over a sheet of paper to draw. In other words, the pen plotter comprises of a two-axis control in order to allow it to move in both X & Y axes. Furthermore, there exist complex designs of pen plotters that employ a special writing assembly in order to raise or lower the pen. A hole at the far-end of the assembly is provided to accommodate the pen into the system. More than one type of pen can be used to generate coloured texts or graphics. Present-day pen plotters work with SVG (Scalable Vector Graphics) and similar files, with which you can combine different shapes, paths, text and graphic elements to create all kinds of visuals.

1.1 TASK DESCRIPTION:

The main aim of this project is to design and fabricate a XY pen plotter that is capable of drawing the Nikolaus House (a simple diagram of a house made up of 8 lines) as shown in the figure below, without any errors.

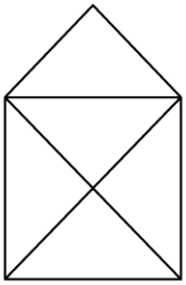


Figure-2: Nikolaus House

Furthermore, the following functions must be realized as part of the project requirements:

- Designing a rigid mechanical system that consists of a pen-holder with the help of 3D printing
- Designing a viable IC-layout system to provide the required electrical assistance to the pen-plotter.
- To formulate a working code using software that governs the movement of the pen plotter to successfully draw the Nikolaus House.
- Realization of synchronous working between all three domains to effectively draw the required Nikolaus House.

2. PLANNING & CONCEPTUALIZATION

2.1 CONCEPT DESIGN OF PEN PLOTTER:

Our primary approach prior to design conceptualization was to have a general brain-storming session in the group and to review the pre-existing designs available on the Internet. Among the various available designs, we decided to proceed with the H-Bot Pen Plotter Mechanism as depicted in the figure below.

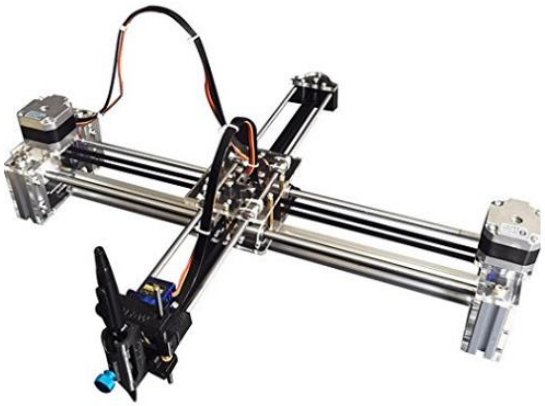


Figure-3: H-Bot Pen Plotter Mechanism

2.2 WORKING MECHANISM OF XY PEN PLOTTER

Upon our understanding, the current design of the XY plotter uses two DC motors to position the penholder. However, these two motors are mounted on the x-axis opposite to each other rather than along the x and y axes directly. The drive belt is looped through the movable chassis both along the x and y axes. This facilitates the movement of the assembly diagonally (45° angle) by actuating one motor while holding the other in place. Turning the other motor, while holding the first one still, moves the penholder along the opposite diagonal.

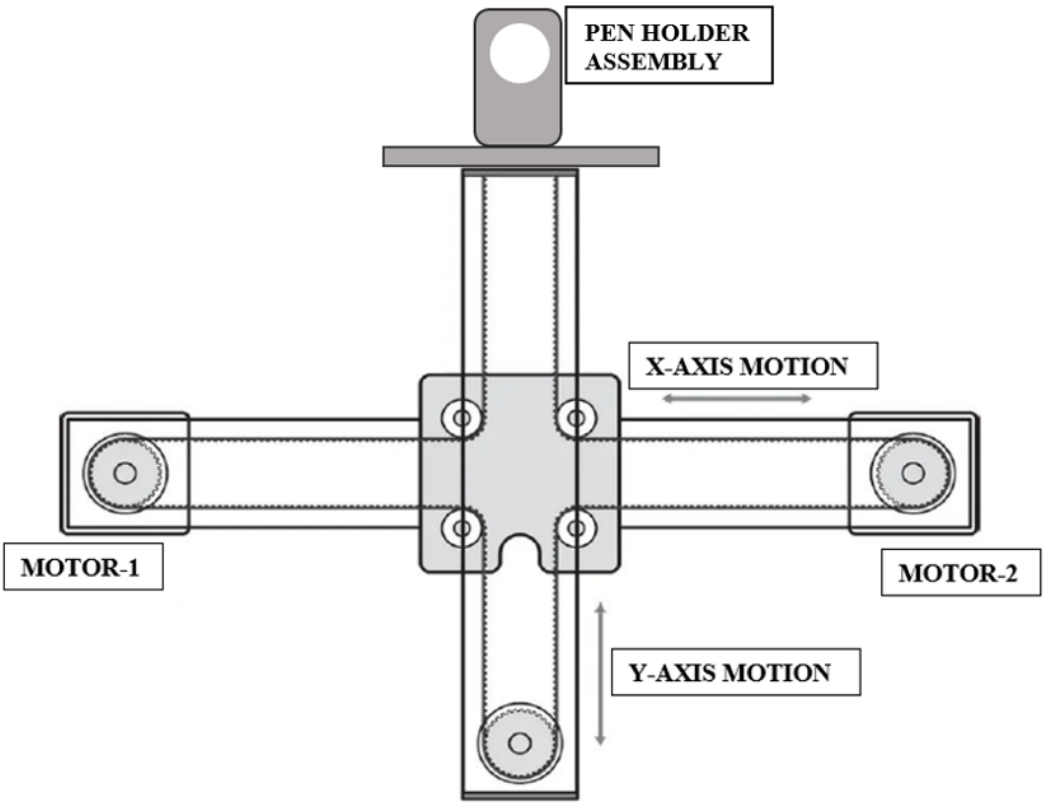


Figure-4: Working model of the H-Bot Mechanism XY Pen Plotter

2.3 DEVELOPMENT OF V-MODEL

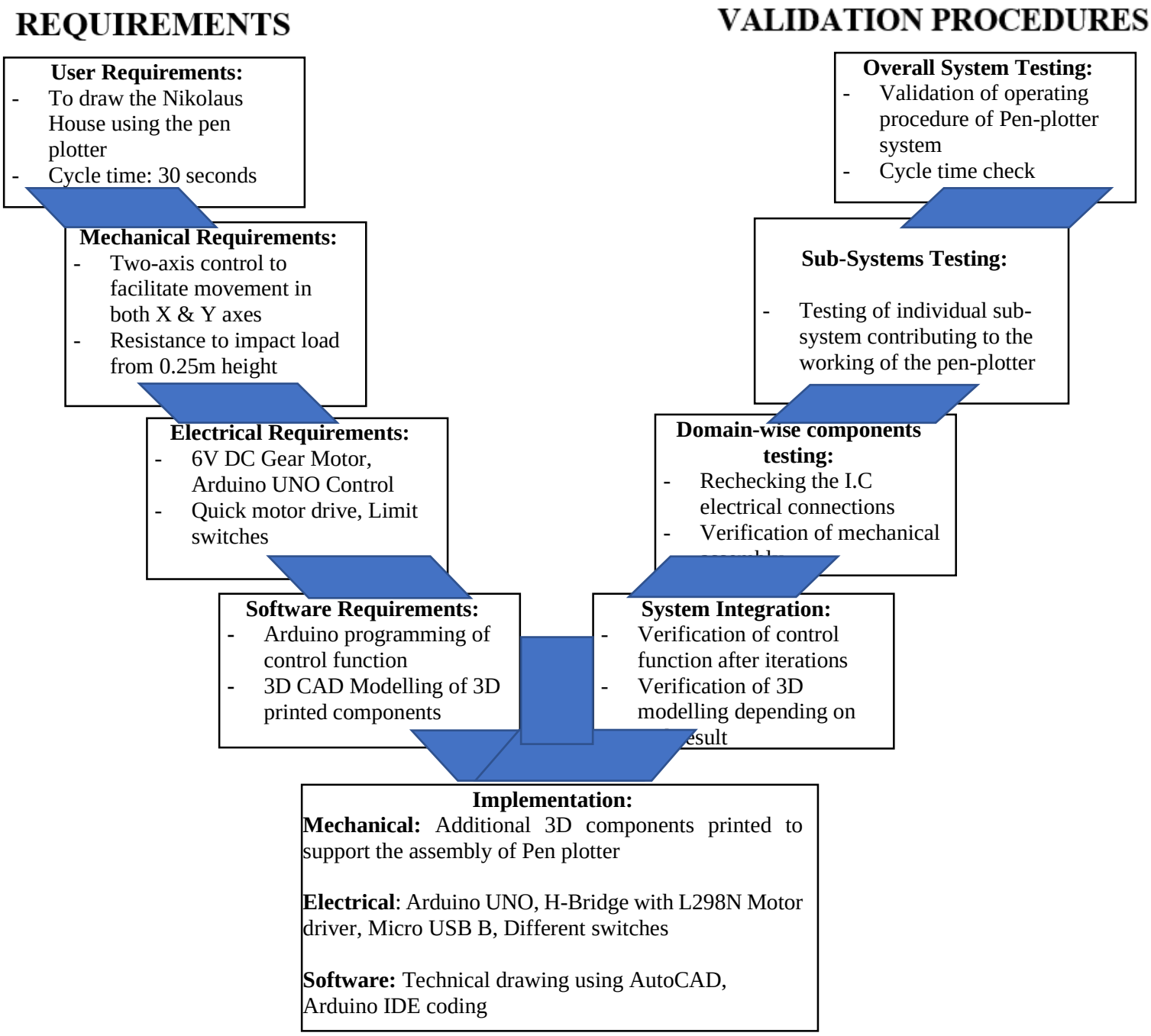


Figure-5: V-Model

2.4 USER REQUIREMENTS

The detailed user requirements essential for the design of the XY pen Plotter are mentioned as follows:

2.4.1 INTENDED USE

- The XY-pen plotter is designed to draw a Nikolaus' house after programming.
- The main focus group of the XY-Pen plotter are the students of Master's Degree Course in Mechatronics and Robotics, used by both males & females and mostly between the age of 20-30 years.
- This plotter is intended to be used only used for educational purposes in university workshop. The product is designed for laboratory work only.

2.4.2 USE CASE

- The pen plotter has to draw the Nikolaus' house precisely.

2.4.3 GENERAL FUNCTIONS

- Pen plotter has to be portable and light-weight to facilitate easy in carrying. It should be very easy to assemble or dissemble.
- The permissible lifespan of this pen plotter should be at least 7 cycles without any failure
- The cost of the pen-plotter must be around 150-170 €.

2.4.4 MODULE FUNCTION: Mechanical

- **Frame & Base Plate**: The base plate mounting must be firm and rigid to provide fundamental support to other modules. The surface of the base plate must be level to reduce errors while functioning. The frame and base plate must be rugged enough to damp unnecessary vibrations and jerks.

- **Drive belts**: Drive belts are used to link motor and other pulleys within the assembly. They must be sturdy enough with equally distributed serrations to prevent slipping conditions.

- **Drive Pulley:** Drive pulleys are used to transfer power from the DC motors via the drive belts. The drive pulleys and the drive belts must be coupled perfectly in order to avoid slipping condition and thereby hindering the function of the pen plotter. Also, noise level during transmission must be minimal.

- **Guide Rods:** Guide rods are the main axle rods upon which the entire pulley assembly is mounted. Guide rods must help in smooth movement of the assembly to facilitate easy movement of the pen.

- **Ball Bearing**: The ball bearings are the mechanical components into which the guide rods are inserted. The contact between the guide rods and the ball bearings must have minimum friction to ensure smooth and precise movement of the entire assembly.

2.4.5 MODULE FUNCTION: Software

- **3D CAD Modelling**: A widely used and user-friendly CAD software must be used to model the required 3D designs of secondary and tertiary components.

- **Programming**: Control function for the entire pen plotter must be programmed with a user-friendly software to facilitate multiple iterations while testing and validation.

- **IC-Layout Design**: Suitable user-friendly software must be utilized to design the required IC layout design.

2.4.6 MODULE FUNCTION: Electrical Hardware

- **Power supply**: Must have a valid CE certification.

- **Motor driver**: A fully-functional DC servo-motor or a stepper motor of considerable quality must be used as the motor module.

- **Emergency**: Emergency power on and off switch must be used for safety purposes.

- **Controller**: A valid user-friendly controller must be used for ease in making connections and also programming.

- **Limit switch**: Limit switches must be employed to prevent the pulley assembly from damage.

2.5 TECHNICAL REQUIREMENTS

The detailed technical requirements essential for the design of the XY pen Plotter by carefully considering the above-mentioned user requirements are as follows:

2.5.1 INTENDED USE

- The XY-pen plotter is designed to draw a Nikolaus' house after programming and all the technical aspects working simultaneously must help in drawing the same without any flaws.

2.5.2 USE CASE

- The pen plotter has to draw the Nikolaus' house precisely within the maximum permissible space of 150 x 130 mm.

2.5.3 GENERAL FUNCTIONS

- Weight of the entire pen plotter assembly is around 3.5kg
- The permissible lifespan of this pen plotter is around 7 cycles without any failure and is durable for a span of 1 year.
- The cost of the pen-plotter is around 160 €.
- The entire XY pen plotter is durable enough to withstand a drop from a height of 0.25m.

2.5.4 MODULE FUNCTION: Mechanical

- **Frame & Base Plate**: The weight of the frame does not exceed 1kg. The base plate mounting material is made of out of fine quality 3D printed material. The 3D printed material used must be rigid and durable enough to withstand unnecessary vibrations.

- **Drive belts**: Plastic drive belts with equally distributed serrations are used to facilitate smooth connection with the pulley.

- **Drive Pulley:** 3D printed drive pulleys with proper serrations are used to synchronously work with the drive pelts to transmit motion. The noise level is within the range of 50-55 db.

- **Guide Rods:** Proper grade material (Stainless Steel) of Guide rods must be used to ensure minimum friction between them and the ball bearings.

- **Ball Bearing**: The ball bearings must be cast from fine grade iron material to ensure sufficient strength.

2.5.5 MODULE FUNCTION: Software

- **3D CAD Modelling**: The 3D models of the secondary and tertiary components required for assembly were designed using AutoCAD and Catia.
- **Programming**: An open-source software called Arduino IDE was used to program the control function of the pen-plotter.
- **IC-Layout Design**: Fritzing software was used to design the I.C components required for the entire assembly.

2.5.6 MODULE FUNCTION: Electrical Hardware

- **Power supply**: CE certified battery pack or power bank is used.
- **Motor driver**: 6V DC Servo motor having speed designation above 112 rpm is used for this application.
- **Emergency**: Standard CE Emergency Power ON and OFF toggle switch is used for safety reasons.
- **Controller**: Arduino Uno is the controller used to make the vital electrical connections as per the designed IC layout.
- **Limit switch**: Standard CE certified limit switches have been utilized.

3. DESIGN PHASE:

3.1 MECHANICAL DESIGN:

Based on the analysis of the design of a H-bot XY pen plotter, we made a list of all the required secondary and tertiary sub-components that were essential for the assembly of the entire system. Then, we used a Catia to design all these sub-components by carefully calculating and analysing the required specifications. Upon completion, we transferred the 3D drawing to the required STL file format essential for 3D printing (Additive Manufacturing). During this activity, we learnt about the different types of materials that are used for 3D printing- PLA (Polylactic Acid), Nylon and ABS (Acrylonitrile butadiene). We decided to use PLA material for printing our sub-components since, it has higher stiffness and strength than Nylon and ABS. Furthermore, PLA is a material having excellent thermoplastic properties with a low melting temperature and warping.

The following represents the sub-components that have been 3D printed specifically as a part of the mechanical sub-components required for assembly. The detailed 3D part drawing is depicted in the appendix section of this report.

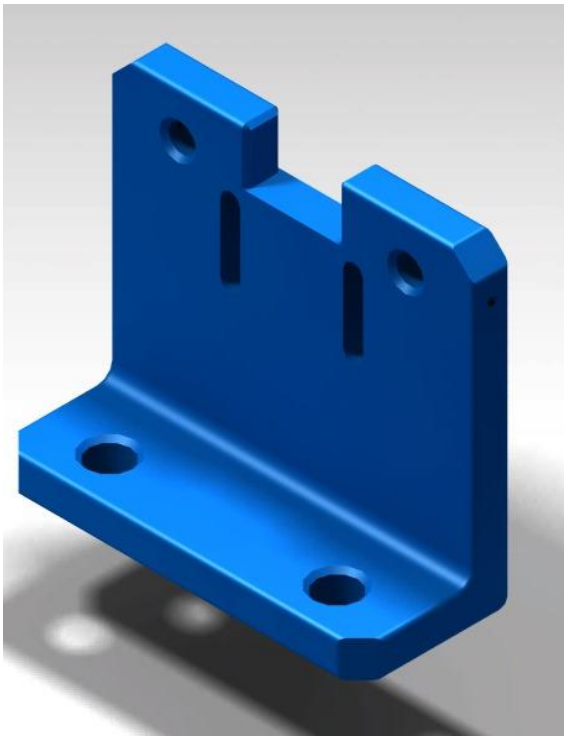


Figure-6: Support Bracket (LHS & RHS)

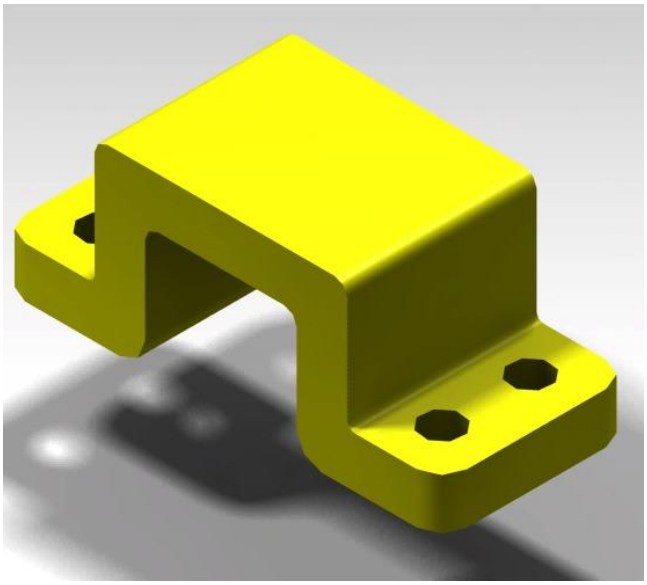


Figure-7: Bracket for Motor Mounting

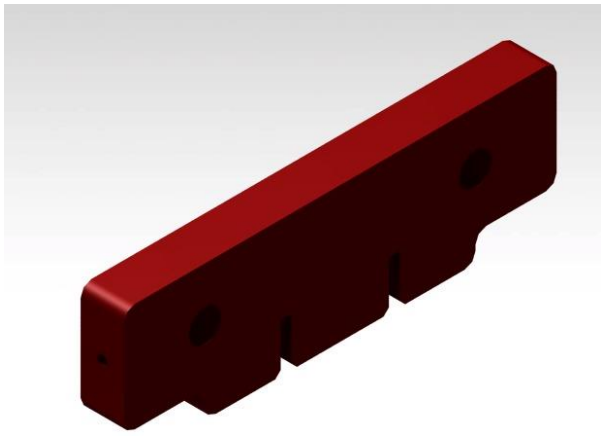


Figure-8: Tensioner Bracket (y-axis)

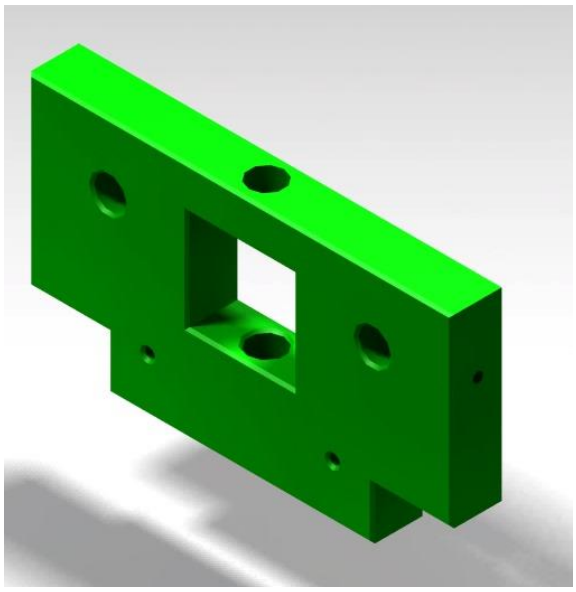


Figure-9: Front Support Bracket

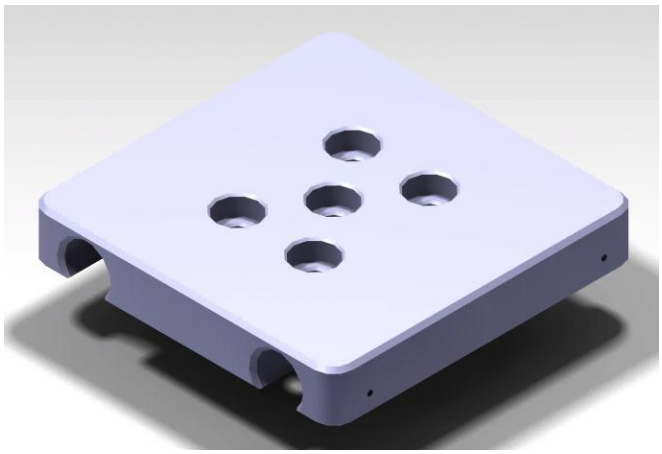


Figure-10: Pulley Bracket Top-Section

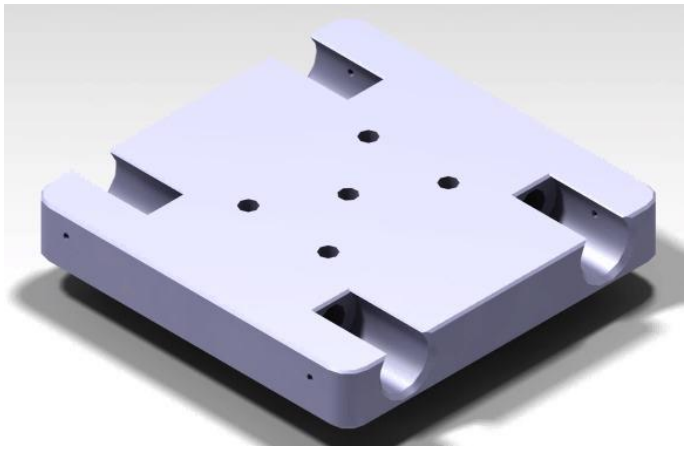


Figure-11: Pulley Bracket Bottom-Section

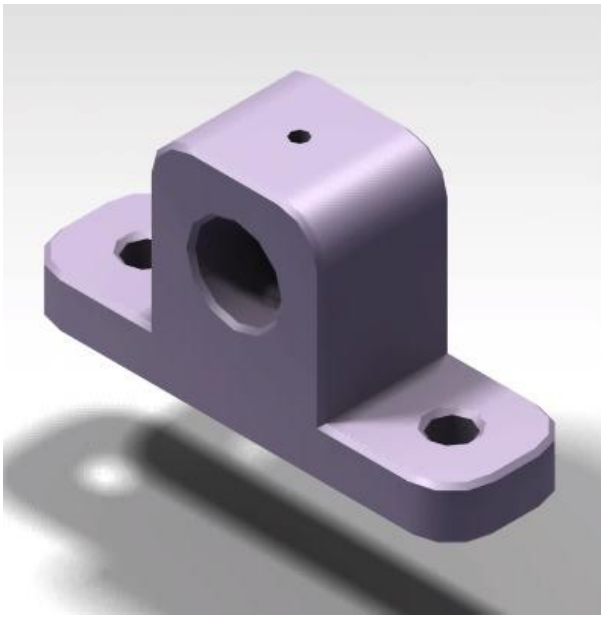


Figure-12: Pen Holder Bracket

The entire procedure of 3D printing the sub-components was a tedious and iterative procedure since, we had to make some minor adjustments during every iteration to finalize the assembly of the fundamental support system. Eventually, we were able to build the entire support structure assembly comprising of 3D printed mechanical sub-components whose layout is depicted in the figure below.

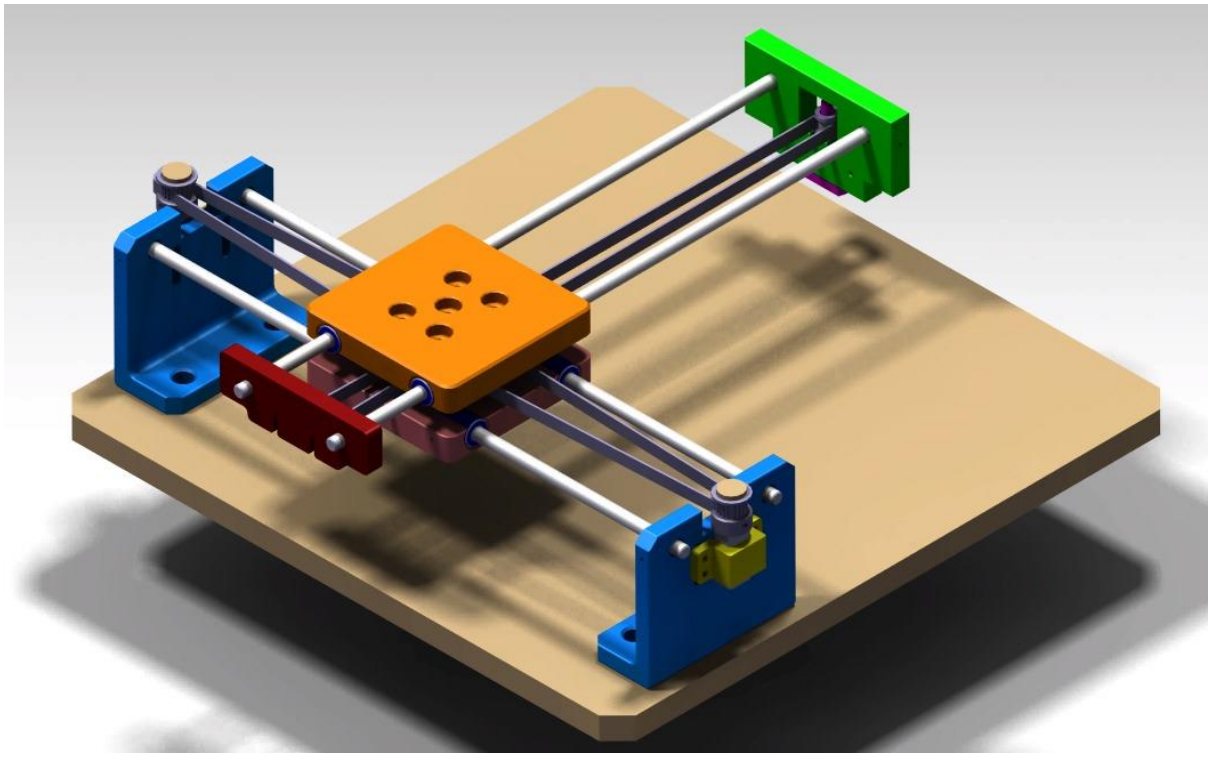


Figure-13: 3D Printed Support Structure Assembly of XY Pen Plotter

3.2 ELECTRONICS HARWARE DESIGN

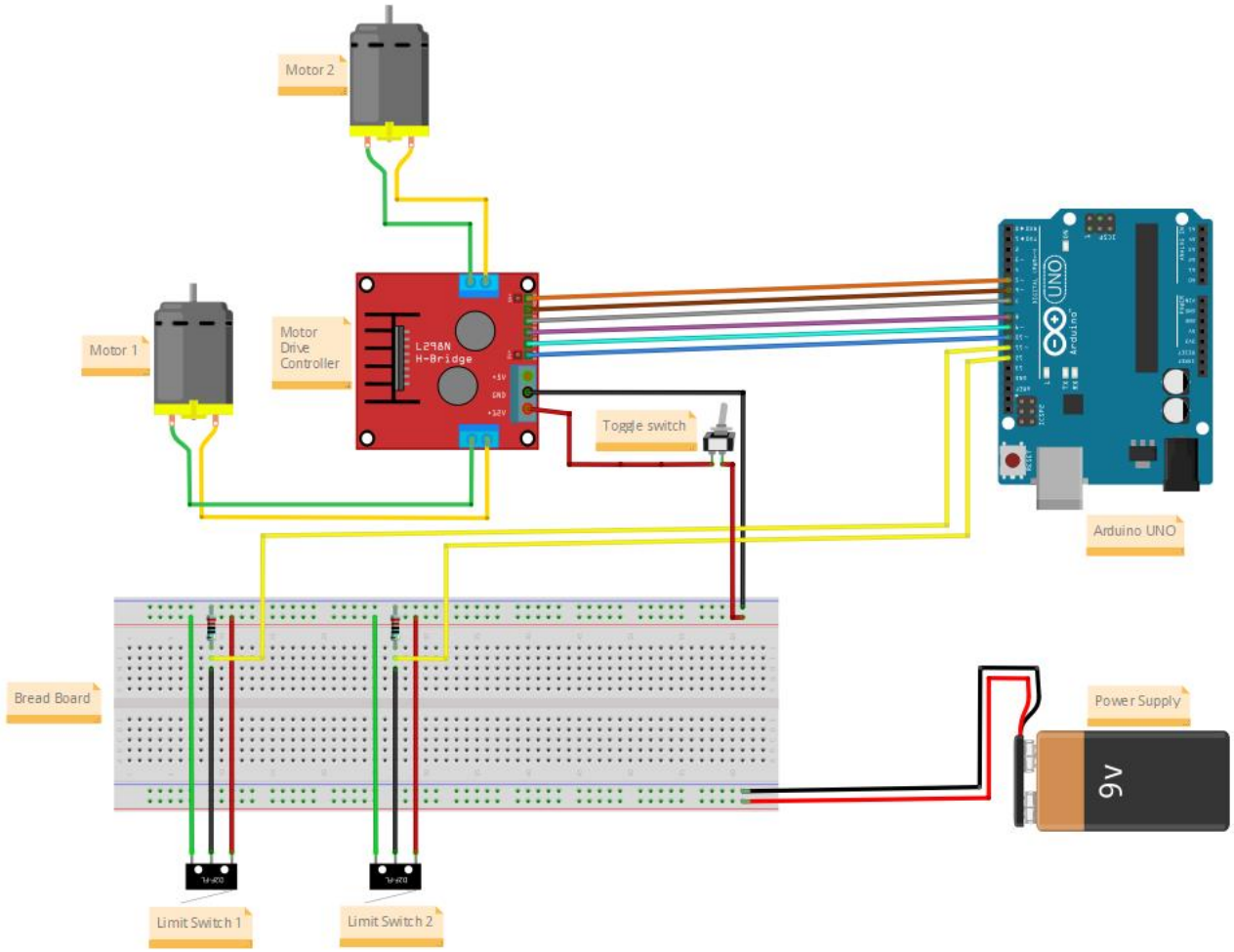


Figure-14: Electronic Circuit Layout

For our electronic circuit layout depicted in the figure above, we used an external software called Fritzing for designing and necessary modifications. The detailed part description of the electronic components used for our layout is mentioned as follows:

Power Supply: CE certified Power Bank 1000 mAh

Serial Communication: A standard CE certified Breadboard component

Microcontroller: Arduino Uno Microcontroller

Motor Driver Controller: L298N H-Bridge Motor Controller

Motors: 2 x 6V DC Servo Motors

Limit switches: D2F-FL Omron Snap Action Limit Switch

The layout includes two 6V DC Servo motors that are run with a L298N H-Bridge Motor Drive Controller. Arduino Uno is the microcontroller used to program the control function for the entire pen plotter assembly. Both these controllers are powered by an external power bank (1000 mAh capacity). A serial bread board is used to make secondary and tertiary connections pertaining to the two controllers. Two Limit switches are used in parallel in order to ensure that the pulley assembly does not collide with the support structures.

3.3 FINAL ASSEMBLY OF THE PEN PLOTTER

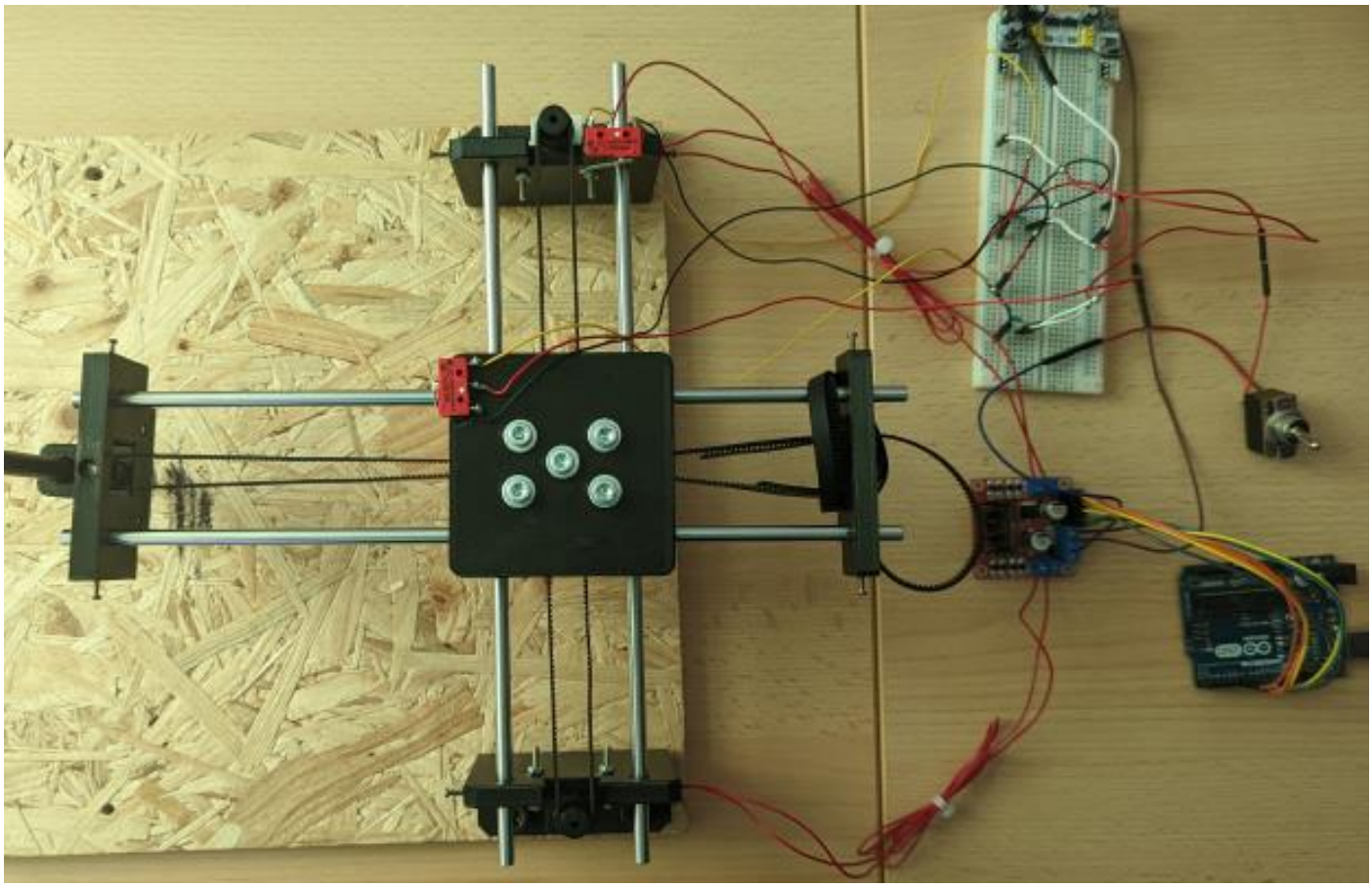


Figure-15:
Assembly of Integrated Mechanical components and Electrical Circuit Layout

3.4 SOFTWARE DESIGN

The control function of the pen plotter is one of the most crucial and tedious tasks which requires adequate programming skills in the required fields. As mentioned earlier we worked with Arduino Uno and its complementary programming software to draft a control function program that is capable of guiding the motion of the pen plotter assembly in order to draw the required Nikolaus House.

The final program is the result of a tedious and monotonous iterative procedure and it is as follows:

```
int enB = 5;
int in3 = 6;
int in4 = 7;
int enA = 10;
int in1 = 8;
int in2 = 9;

void setup() {
pinMode(enA, OUTPUT);
pinMode(enB, OUTPUT);
pinMode(in1, OUTPUT);
pinMode(in2, OUTPUT);
pinMode(in3, OUTPUT);
pinMode(in4, OUTPUT);
}
void loop(){
 digitalWrite(in3, HIGH); //UP SIDE
 digitalWrite(in4, LOW);
 analogWrite(enB, 200);
 digitalWrite(in1, HIGH);
 digitalWrite(in2, LOW);
 analogWrite(enA, 200);
```

```
delay(2000);

digitalWrite(in3, HIGH); // RIGHT SIDE
digitalWrite(in4, LOW);
analogWrite(enB, 200);
digitalWrite(in1, LOW);
digitalWrite(in2, HIGH);
analogWrite(enA, 200);
delay(2410);

digitalWrite(in3, LOW); // DOWN SIDE
digitalWrite(in4, HIGH);
analogWrite(enB, 200);
digitalWrite(in1, LOW);
digitalWrite(in2, HIGH);
analogWrite(enA, 200);
delay(2000);

digitalWrite(in3, LOW); // LEFT SIDE
digitalWrite(in4, HIGH);
analogWrite(enB, 200);
digitalWrite(in1, HIGH);
digitalWrite(in2, LOW);
analogWrite(enA, 197);
delay(2410);

digitalWrite(in3, HIGH); //UP-LEFT SIDE(/)
digitalWrite(in4, LOW);
analogWrite(enB, 240);
digitalWrite(in1, LOW);
digitalWrite(in2, LOW);
```

```
  analogWrite(enA, 00);
  delay(4150);

  digitalWrite(in3, LOW); // UP-RIGHT SIDE(\)
  digitalWrite(in4, LOW);
  analogWrite(enB, 00);
  digitalWrite(in1, HIGH);
  digitalWrite(in2, LOW);
  analogWrite(enA, 250);
  delay(2200);

  digitalWrite(in3, LOW); // DOWN-LEFT SIDE(/)
  digitalWrite(in4, HIGH);
  analogWrite(enB, 250);
  digitalWrite(in1, LOW);
  digitalWrite(in2, LOW);
  analogWrite(enA, 00);
  delay(3250);

  digitalWrite(in3, LOW); // DOWN-RIGHT SIDE(\)
  digitalWrite(in4, LOW);
  analogWrite(enB, 00);
  digitalWrite(in1, LOW);
  digitalWrite(in2, HIGH);
  analogWrite(enA, 250);
  delay(7000);
}
```

4. VERIFICATION & VALIDATION PHASE:

In this phase, the resultant model of the XY Pen plotter with the necessary electrical connections and the uploaded control program is validated for the output and to verify whether it functions accordingly to produce the desired output of the Nikolaus House.

After numerous iterations, we were able to minimise the errors observed in the final output of the Nikolaus House. The discrepancies which were previously observed were rectified with some tweaks made in the control program of the pen plotter.

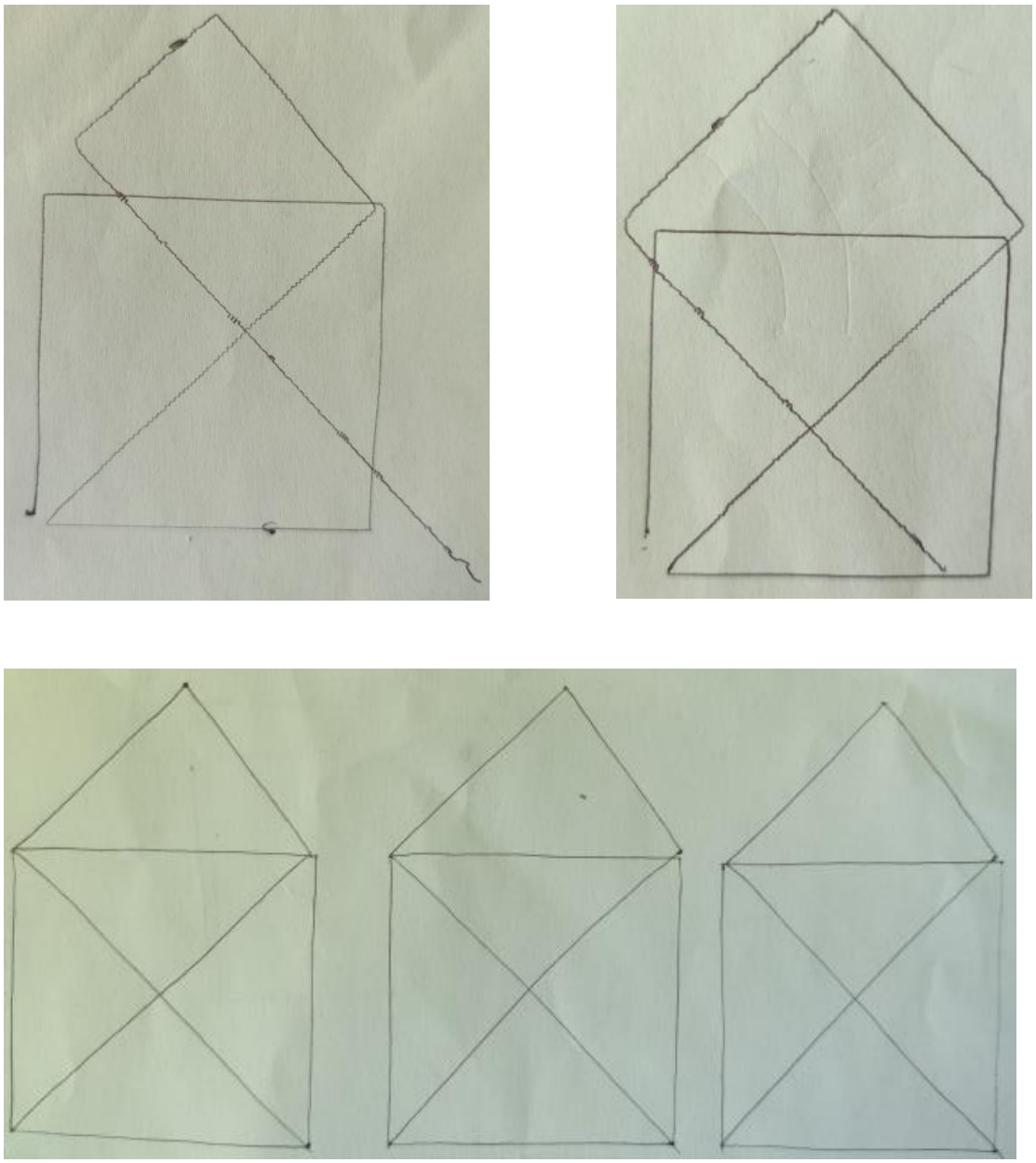


Figure-16: Verification & Validation Procedures

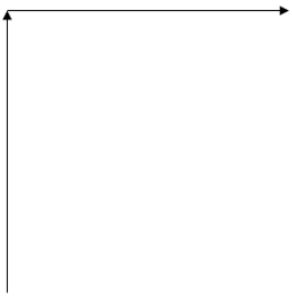
Verification Protocol Number (ValPr.)	Remarks	Criteria (Pass / Fail)
VerPr. 1	Place pen plotter on table with A4 paper, Turn ON Power source, Turn ON electrical circuits	Pass
VerPr. 2	Put pen plotter in box, carried out by focus group, easy to handle	Pass
VerPr. 3	Connect controller with laptop using USB cable	Pass
VerPr. 4	Set-up pen plotter, Start pen plotter by student, Draw Nikolaus' house	Pass
VerPr. 5	Functionality of Limit switch	Pass
VerPr. 6	Press Emergency Stop Button during instance	Pass

4.1 RESULT OF THE CONTROL PROGRAM:

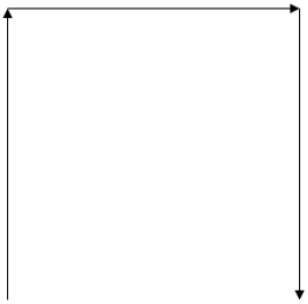
Upon executing the above program, the pen plotter assembly is successfully able to draw the required Nikolaus House of specified dimensions as per the requirements. The course of action that is followed by the system to draw the Nikolaus is as per the figure mentioned below.

Step-1:

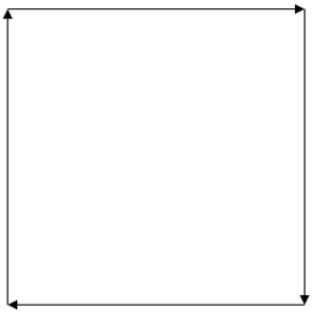
Step-2:



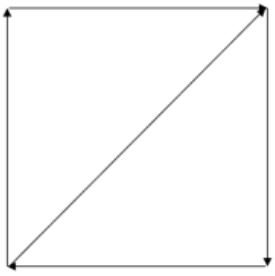
Step-3:



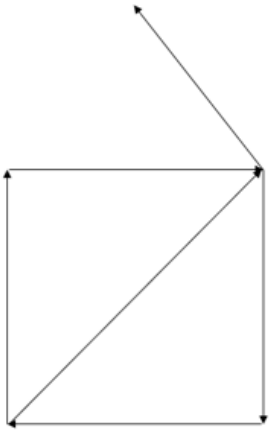
Step-4:



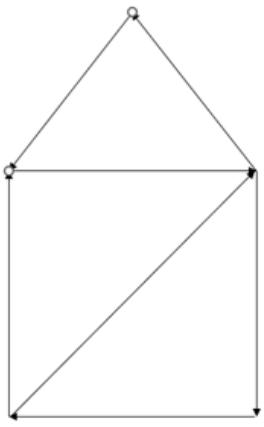
Step-5:



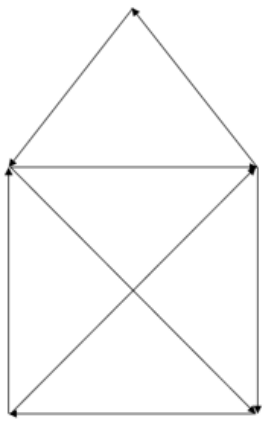
Step-6:



Step-7:



Step-8:



5. CONCLUSION

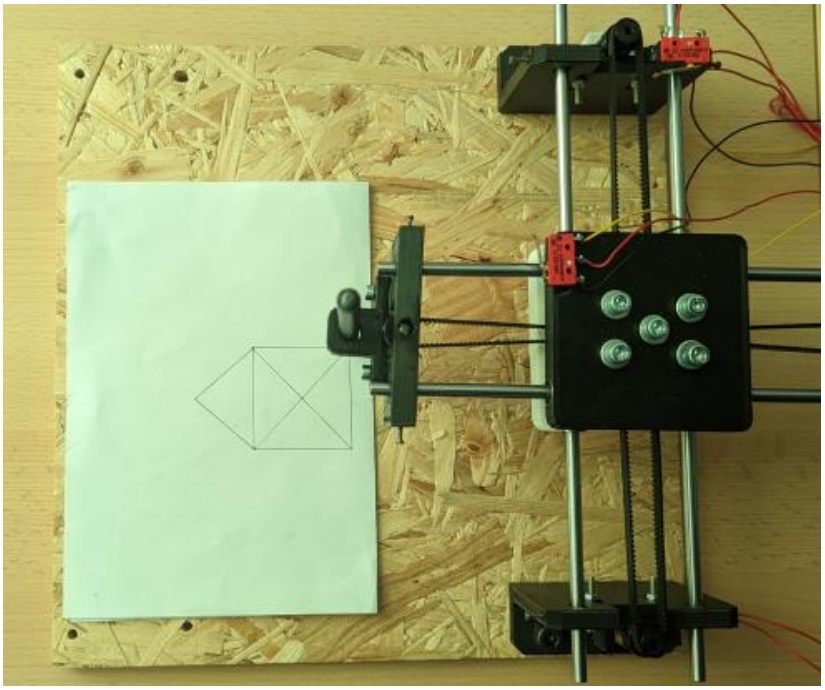
We have finally developed a fully functional XY Pen plotter that is capable of drawing the Nikolaus House as per the specification mentioned in the user requirements. All the components that were provided for this project have been used apart from the Hall effect sensor whose functionality was not required for the current design of our pen plotter.

5.1 RETROSPECTIVE POINTS:

- The entire task of designing and programming the XY Pen Plotter proved to be a great experience for the entire team in aspects of coding, 3D modelling, team work and time management.
- During the task of 3D modelling, there were certain defects that proved to affect the assembly of the pen plotter. For instance, the connection between the 3D printed pulleys and the drive belt resulted in a partially accurate synchronicity. This sometimes resulted in slip condition between the two parts thereby causing the drawing of the Nikolaus house to be slightly distorted from the ideal drawing.
- The DC motors provided to us proved to be insufficient in terms of power output. This resulted in slip conditions in very few cases thereby resulting in distortions in the final output drawing of the Nikolaus House. Instead, of the conventional DC Servo motors, we could have used Stepper motors that would have proved much for efficient in terms of power output and performance.
- In some situations, the Motor Driver Controller caused unequal power distribution to the two motors. This resulted in asymmetrical drawing of the Nikolaus House during few iterations.
- The vibrations of the entire assembly cannot be completely damped due to certain defects in the mechanical components (Ball Bearings, Guide Rods) provided.

5.2 FINAL MODEL

The final outlook of our designed model is as shown in the figure below. The resultant XY pen plotter is capable of successfully drawing the Nikolaus House within the specified limits as per the user requirements with an operating time of roughly 30 seconds for each cycle.



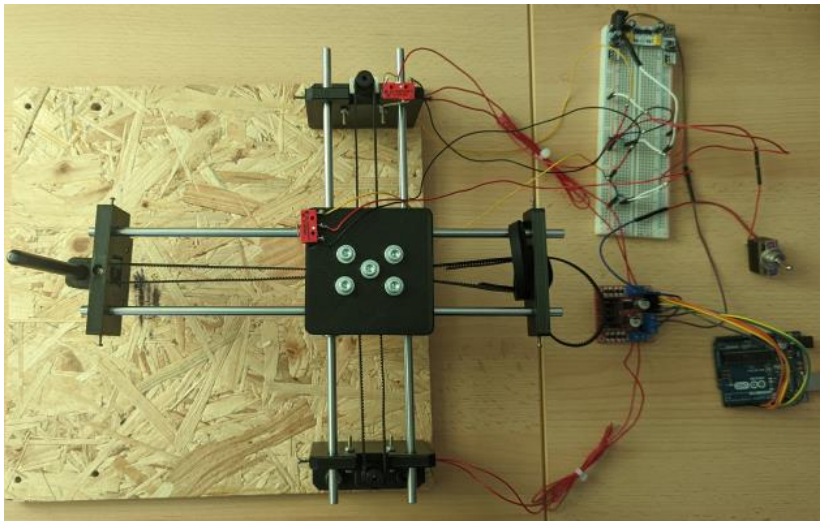
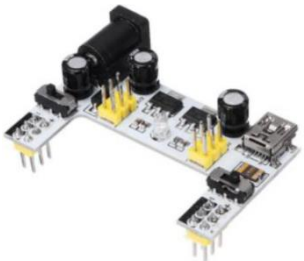


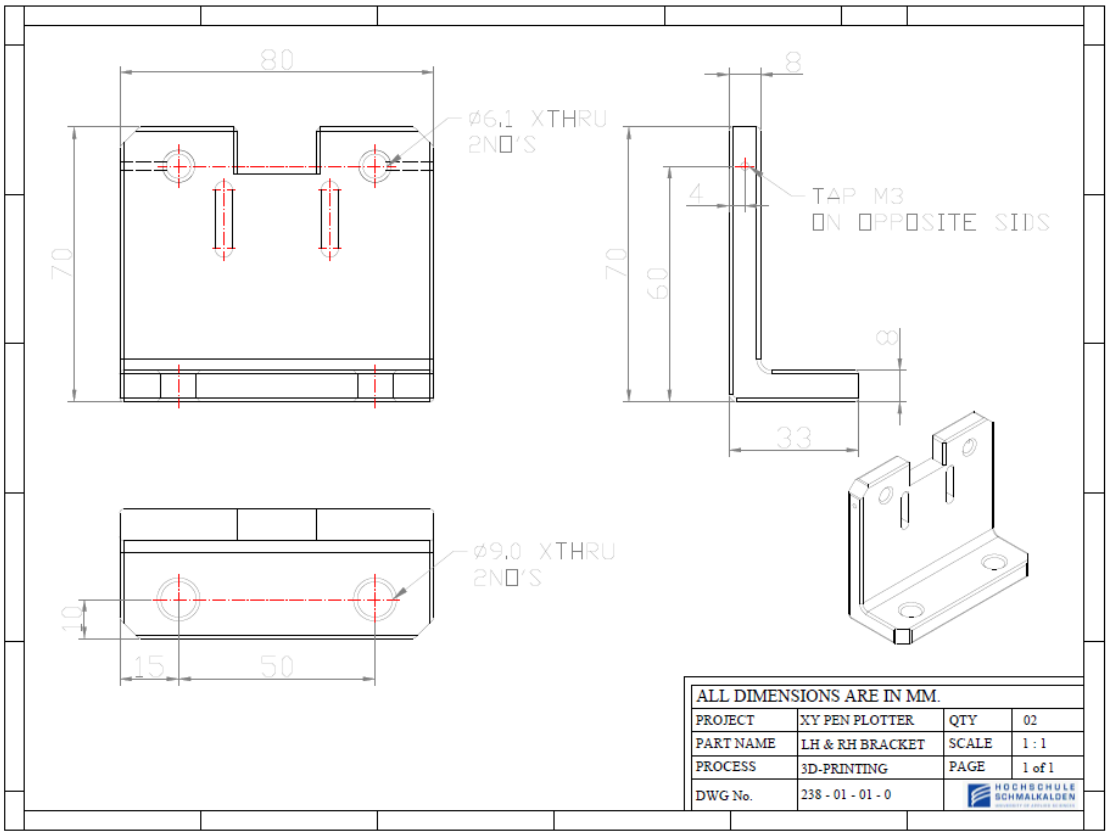
Figure-17: Final Working Model of XY Pen Plotter

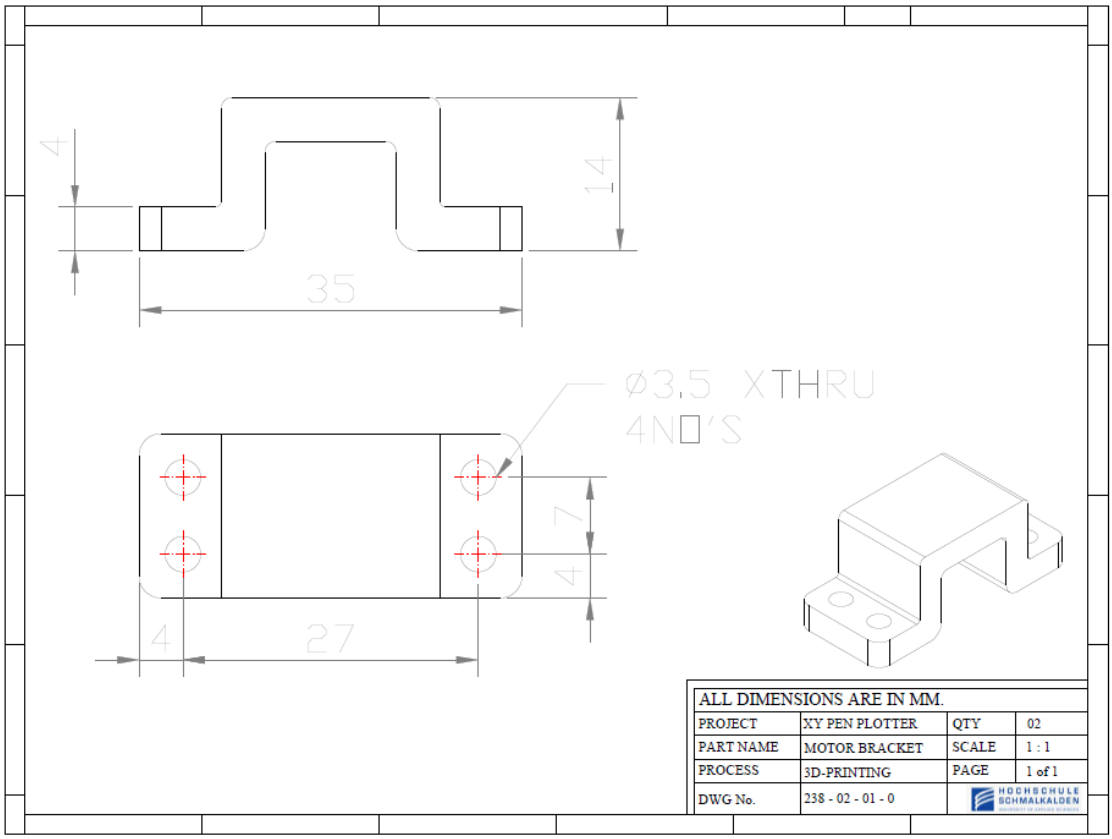
6. APPENDIX

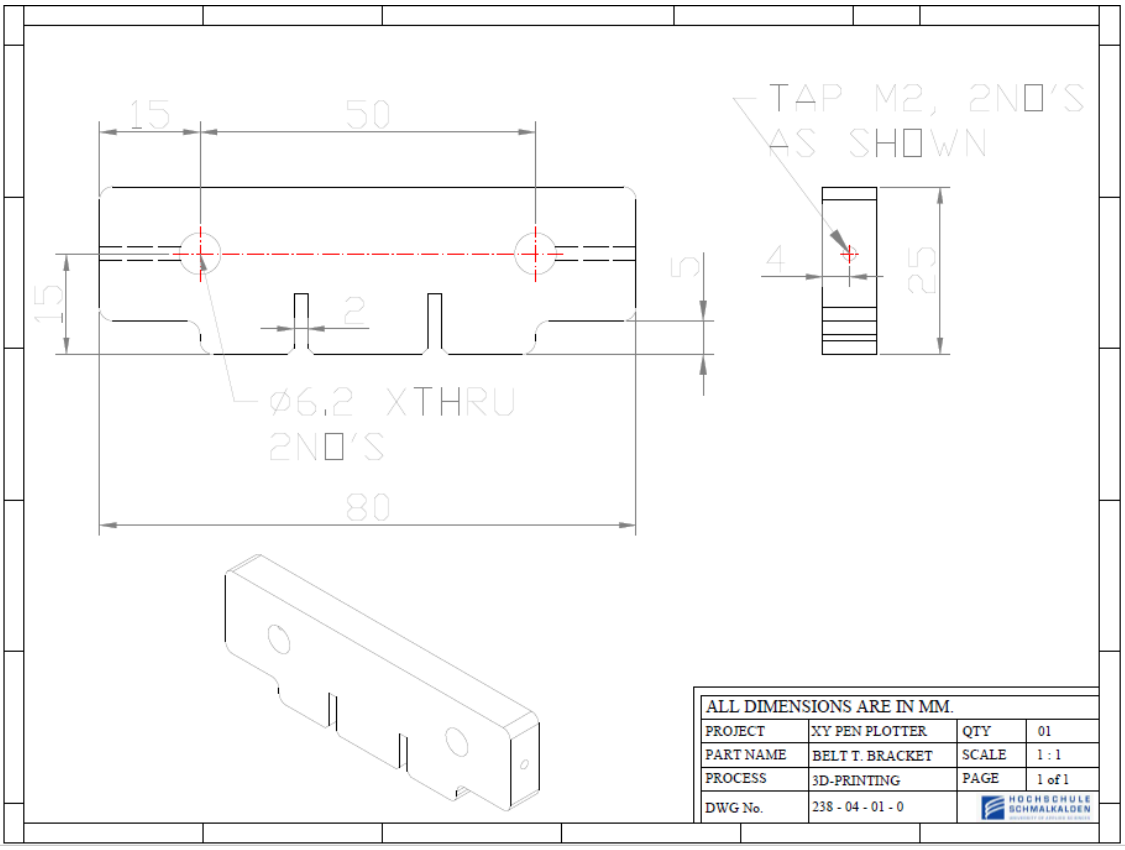
Part Description	Image for Reference
Arduino Uno- Microcontroller AT Mega 16U2 16 MHz 2Kb SRAM; 32Kb Flash, 1KB EEPROM	
Motor Driver H-Bridge L298N; Driver: L298N Logic voltage: 5V DC; Drive voltage: 5-35V Drive current: 2 A; Power: Max 25 W	
DC Motor 6V Micro (10x12mm), 112rpm	
Power supply (XD-42 5V/3.3V) Dual Channel Solderless Breadboard Power Supply Module	
Emergency Toggle switch Switch ON / OFF condition	

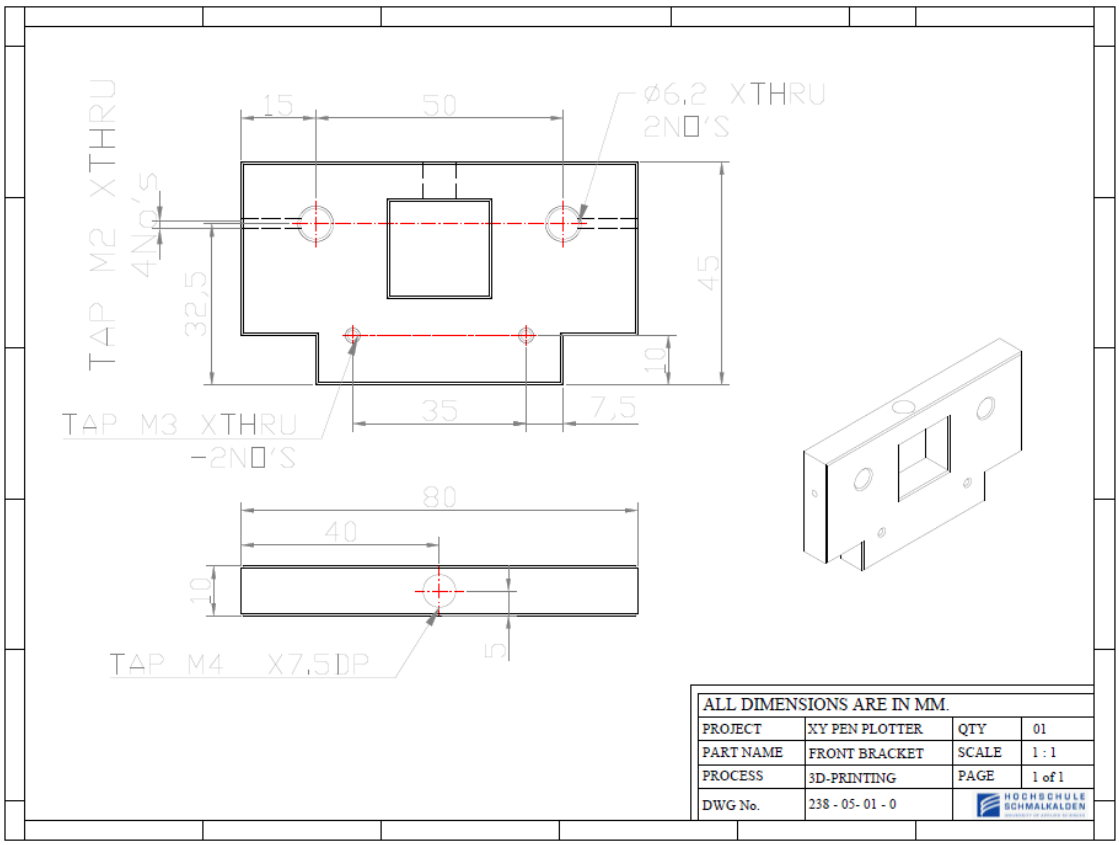
Limit switch (D2F-FL Omron) Snap Action Limit Switch with Level	
Jumper Cables JST SH 4-Pin Cable QWIIC Compatible, 100mm long	
Drive Pulleys Length: 10.5 mm; Inner Ø: 14 mm Outer Ø: 17 mm; Shaft Ø: 5.2 mm Fix Ø: 3.5 mm	
Transmission belts Belt Height: 2 mm; Belt Width: 6 mm. Material: Plastic; Length: 500 mm.	
Guide Rods Misumi Stainless Steel (600 mm)	
Linear Ball Bearing LMU-N6 Stainless Steel	
Breadboard MB-102 Plug-In board 830 p Ins60320025	

The 3D CAD drawings of the various printed parts are depicted for reference.






15
50
TAP M2, 2NO'S
AS SHOWN
15
2
5
4
25
Ø6,2 XTHRU
2NO'S
80
ALL DIMENSIONS ARE IN MM.
PROJECT
XY PEN PLOTTER
QTY
01
PART NAME
BELT T. BRACKET
SCALE
1 : 1
PROCESS
3D-PRINTING
PAGE
1 of 1
DWG No.
238 - 04 - 01 - 0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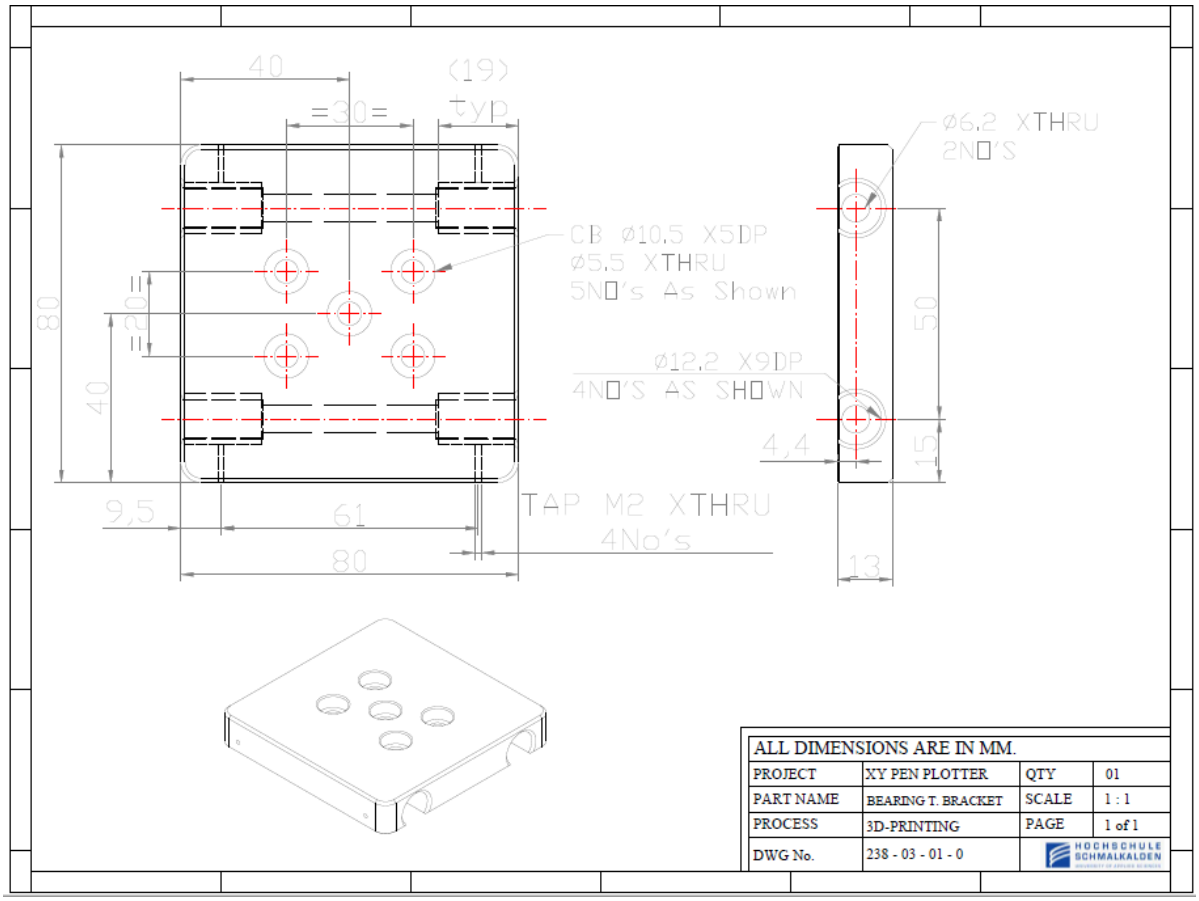
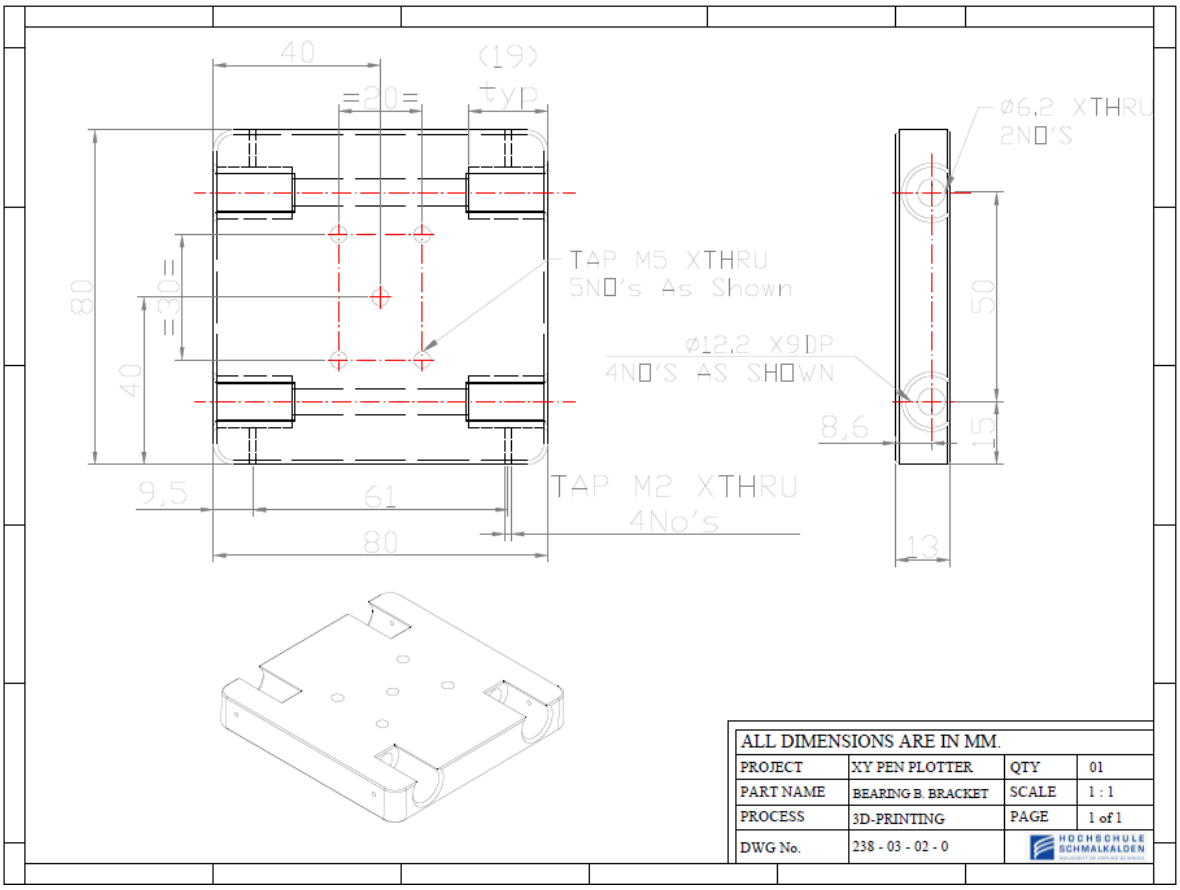
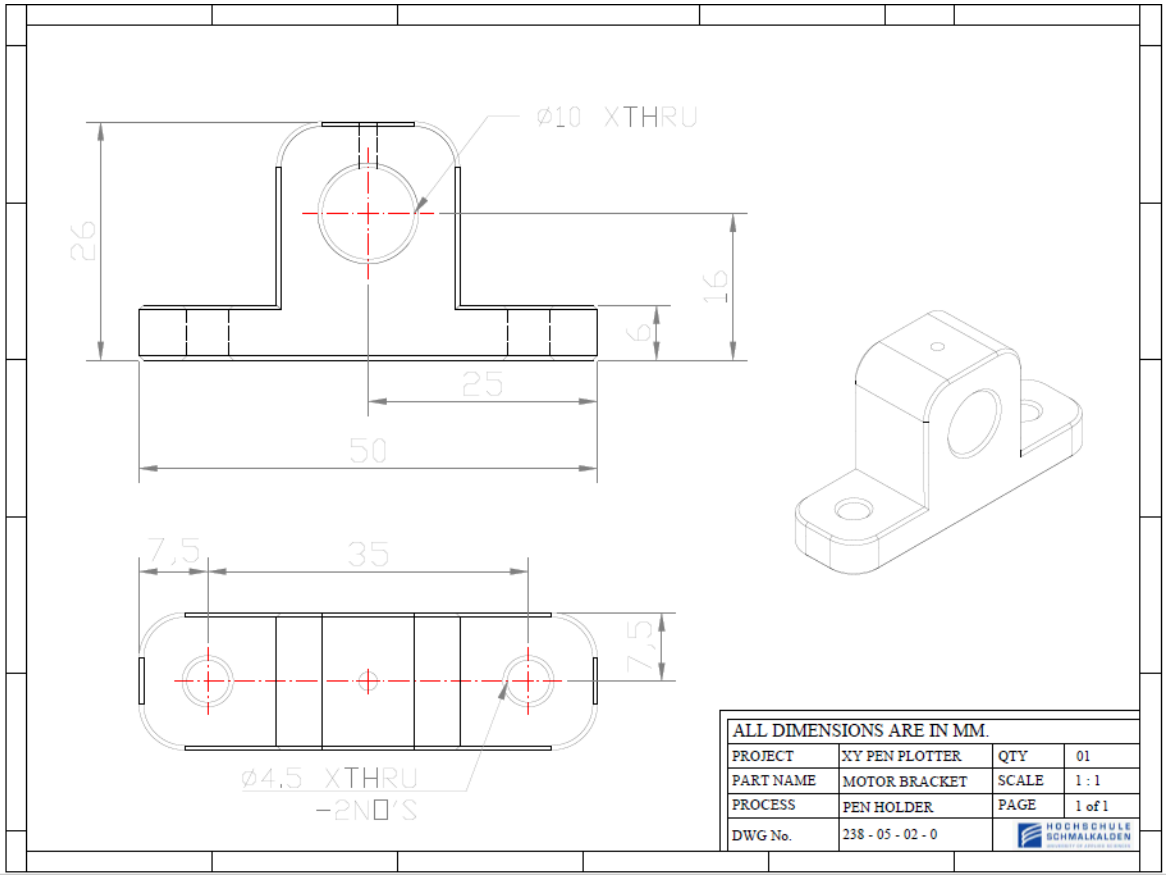
4NO'S
15
50
Ø6,2 XTHRU
2NO'S
32,5
45
19
TAP M3 XTHRU
-2NO'S
35
7,5
80
40
19
TAP M4 X7,5DP
ALL DIMENSIONS ARE IN MM.
PROJECT
XY PEN PLOTTER
QTY
01
PART NAME
FRONT BRACKET
SCALE
1 : 1
PROCESS
3D-PRINTING
PAGE
1 of 1
DWG No.
238 - 05- 01 - 0


40
=30=
(19)
typ
80
40
20
9,5
61
80
CB Ø10,5 X5DP
Ø5,5 XTHRU
5NO's As Shown
Ø12,2 X9DP
4NO'S AS SHOWN
TAP M2 XTHRU
4No's
Ø6,2 XTHRU
2NO'S
50
4,4
13
ALL DIMENSIONS ARE IN MM.
PROJECT | XY PEN PLOTTER | QTY | 01
PART NAME | BEARING T. BRACKET | SCALE | 1 : 1
PROCESS | 3D-PRINTING | PAGE | 1 of 1
DWG No. | 238 - 03 - 01 - 0


40
=20=
(19)
typ
80
40
30
9,5
61
80
TAP M5 XTHRU
5NO's As Shown
Ø12,2 X9DP
4NO'S AS SHOWN
TAP M2 XTHRU
4No's
Ø6,2 XTHRU
2NO'S
50
8,6
13
ALL DIMENSIONS ARE IN MM.
PROJECT | XY PEN PLOTTER | QTY | 01
PART NAME | BEARING B. BRACKET | SCALE | 1 : 1
PROCESS | 3D-PRINTING | PAGE | 1 of 1
DWG No. | 238 - 03 - 02 - 0



ALL DIMENSIONS ARE IN MM.			
PROJECT	XY PEN PLOTTER	QTY	01
PART NAME	MOTOR BRACKET	SCALE	1 : 1
PROCESS	PEN HOLDER	PAGE	1 of 1
DWG No.	238 - 05 - 02 - 0	HOCHSCHULE SCHMALKALDEN	

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