Université Libre de Bruxelles and Vrije Universiteit Brussel

Mechatronics - Design Methodology

Draw Robot

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Abstract

The Draw Robot is an ultimate multi-purpose machine that is designed to meet a wide range of expert calligraphic writings as well as general drawings on a flat surface. One can use their computer to produce beautiful handwriting using a real pen that appears handcrafted, which has no mistakes. The main objective of this project is to apply pressure on the pen in order to have varied thicknesses. The result shows that the robot is capable of drawing a line with varied thicknesses with a step size of 0.0316mm. Therefore, depending on the calligraphy pen the robot can draw a line with different thicknesses.

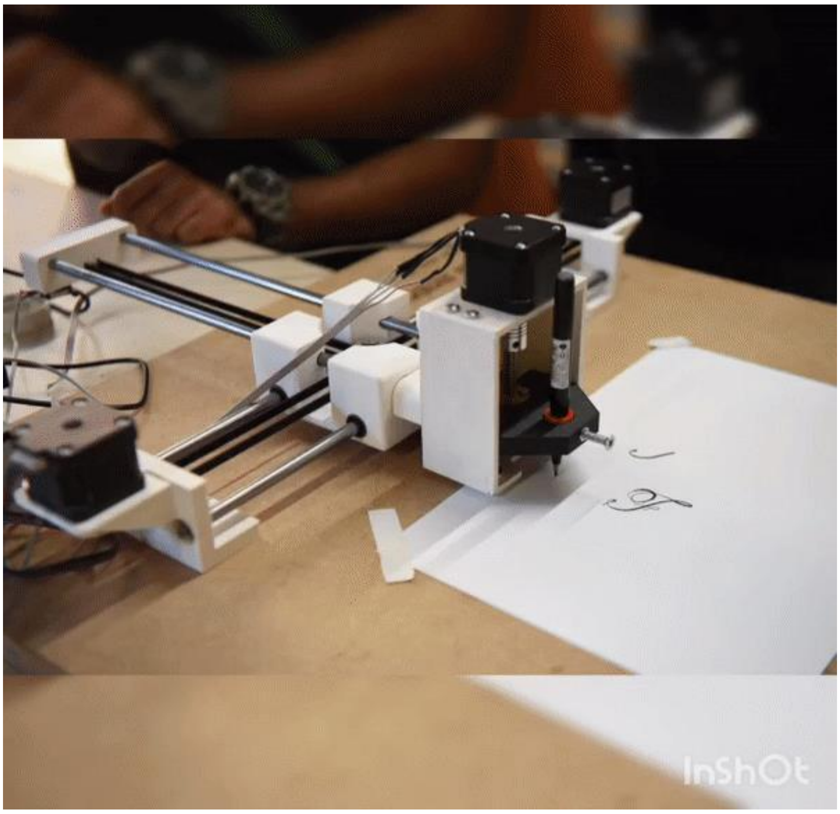


Figure 1: Short video of the whole project

1. Project Motivation

Perhaps one loves calligraphic writing and they cannot write with the same accuracy and precision, here is the solution – Draw Robot. The Draw Robot is a device that can write and draw figures with utmost accuracy and precision. This figure seen below is the handwriting of our colleague's brother. Isn't it beautiful? Me and my colleagues, when we try to write in this same fashion, fail to do so. It's not everyone's cup of tea, so we decided to design and manufacture a drawing robot that can fulfil our needs.

After our decision, we found out that there are many draw robots available in the market but are expensive and they do not completely fulfil our needs. So, we decided to uplift our task by one step more and make it affordable with some really good extra features for the users to experience a quality product.

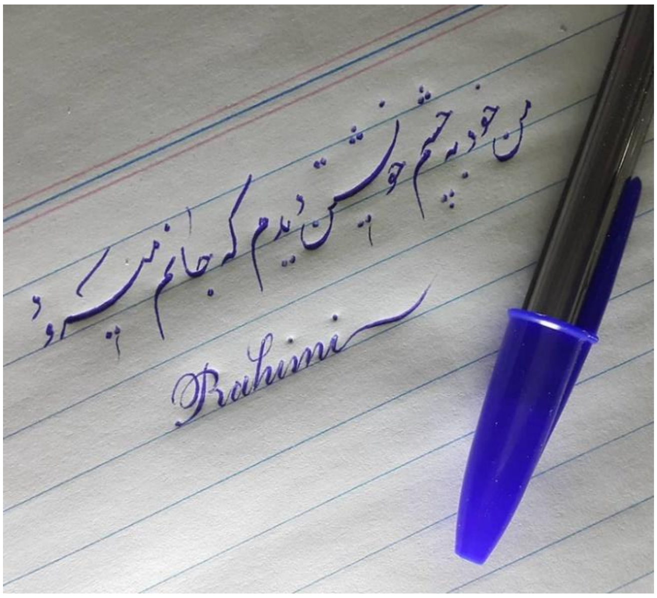


Figure 2: Project Motivation – Beautiful English and Persian Calligraphy

i. Need Identification

To have a clear vision of the needs, firstly we have done a global analysis which is discussed below.

i. What is the utility of the Draw Robot?

The main function of the Draw Robot is to draw complex figures with accuracy and precision.

ii. Who will use it?

This draw robot is mainly focused towards the children, who can learn step by step drawing techniques and also gain interest in robotics and programming. Not only children, online retailers and restaurants can use it to make a personalised notes for the customers, calligraphers and digital artist can also use this draw robot if they want to complete a particular work with accuracy and in less amount of time, University officials & educators also use it to sign diplomas and introduce students to digital design and fabrication.

iii. What or who does the product interfere with?

The Draw Robot interferes with the user, the drawing sheet, pen, the X, Y & Z shafts, the Arduino which is the heart of the system, the laptop which is used to give commands with the help of a software.

iv. To which purpose this product has to be developed?

This product has been developed mainly to create an impact on children's mind both in the drawing perspective and learning robotics and programming in future, also different organisations can use it in different ways. Ex: A principal can use it to sign 1000 diplomas or an online retailer can use it to make a personalised thank you notes.

v. Why does it need to be improved?

There are some products in the market that have similar design and purpose but one which we designed is unique in the sense that it tackles bending of the Y-axis due to pressure created in the Z-axis. The main focus is also on the price of the product and the use of parts which can be recycled and reused in the future.

The above explanation is combined in a table given below:

Table 1. Global Need Analysis

Utility	Draw a complex figure accurately and precisely.
User	Children, University Officials, Calligraphy & Digital Artist
Interference with	Pen, Drawing Sheet, Students

In addition, the draw robot has to meet both the Subjective and Objective needs, which has been categorised and shown below:

Table 2. Need Analysis

Needs	**Objective/Subjective**
Drawing Accuracy	Objective
Human Safety	Objective
Working Area	Objective
Weight	Objective
Maintainable	Objective
Speed	Subjective
Cost	Subjective

2. Functionality

Functions of a Draw Robot can be categorised into external functions and internal functions. The external functions are the ones which are directly useful to the customer and it can be divided into two categories: Principal functions and complementary functions whereas the internal functions depend already on the design choices. The external functions include the principal and complementary functions and the internal functions represents the limitations and considerations that should be considered when making design choices.

The following table displays the categories of functions:

Table 3. Categories of Functions of the Draw Robot

External Functions	Principal Functions	1. Drawing Accuracy 2. Simple software
	Complementary Functions	1. Easy to assemble 2. Easy to use 3. Noiseless 4. Reasonably Prices
Internal Functions		1. Pre-programmed Arduino 2. Limitation in movement of XY axis implementing push buttons 3. Easy to calibrate the device
Constraints		1. Stepper motor life cycle 2. Linear bearing life cycle

The next step is to make a function chart that exhibits some characteristics of the Draw Robot according to their nature. In the table given below, the co-efficient K refers to the level of importance of a function—that is—functions with co-efficient K=1 is more important than K=2. The flexibility level is described using the co-efficient F where F1 represents small flexibility, F2 represent moderate flexibility, and F3 represents large flexibility.

Table 4. Functions Characteristics of the Draw Robot

	Description	K	Criterion	Level	F
1.	Working Area	1	Millimetres	400×360	F1
2.	To be Light weight	1	Kilograms	6.3	F1
3.	To be able to adjust pressure	1	Pascal	800 - 8000	F1
5.	Life Cycle	2	Life Span (hour)	10,000*	F2

*The typical life time for the stepper motor is 10,000 according to [1]

3. State of art and patent analysis

vi. Robotic Drawing

Publication Number: WO2020072785A1

Publication Date: 2020-04-09

Website: https://worldwide.espacenet.com/patent/search?q=pn%3DWO2020072785A1

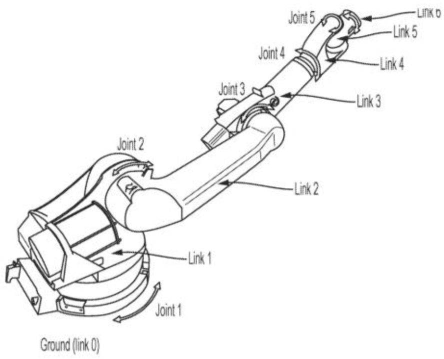


Figure 3: Patent 1

Conclusion: The manufacturing cost and maintenance of this robot is very expensive.

- Drawing Robot System

Publication Number: WO2021103417A1

Publication Date: 2021-06-03

Website: https://worldwide.espacenet.com/patent/search/family/071850203/publication/WO2021103417A1?q=drawing%20robot

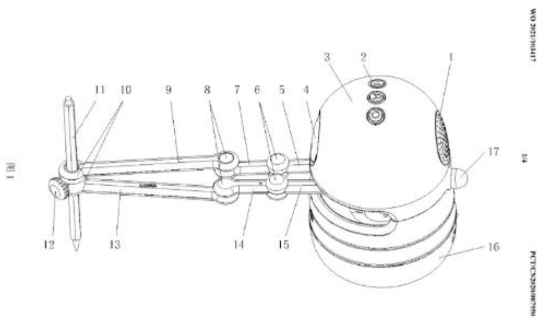


Figure 4: Patent number 2

Conclusion: The working area is limited and it does not meet our objective, applying pressure.

4. High-level Design

The design of the draw robot is very simple with minimum number of components. This helps the user to assemble/dissemble it easily and if there is any problem in the functioning of any electronic or mechanical component, it is easily maintainable.

a) **Cart:** The cart consists of four shafts, both for X & Y axis. These shafts are connected to the stepper motor mounting on which the motors have been fixed that enables the movement of the cart in linear direction with the help of a continuous belt. The idler pulleys as seen in the figure below establish a frictionless movement and helps to maintain tension in the belt. When pressure is applied, there might be a negligible bending which is overcome by the wheel supports.

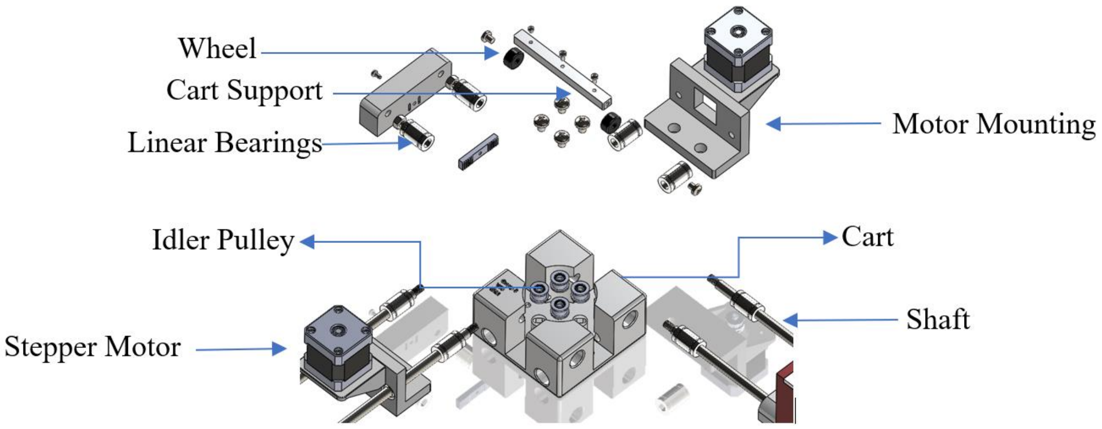


Figure 5: Different Parts of the Robot

b) **Z-Axis housing:** As our main aim of our project is to write with varied thickness, this can be achieved with a simple yet important mechanism of converting the rotational to linear motion with the help of flexible coupling and lead screw. The stepper motor is connected with flexible coupling which moves in up and down direction with the help of lead screw, thereby creating variable thickness. This complete setup is enclosed in a special house, named as Z-Axis housing.

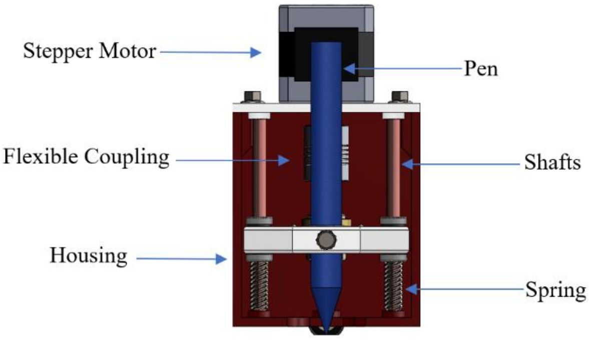


Figure 6: Z-Axis Parts

c) **Electronic Setup:** The electronic and electrical setup is enclosed in a special box to avoid accidents. The Arduino is connected with the CNC shield and drivers to drive the three stepper motors is powered electrically with 12V DC current and is connected to a laptop. In order to avoid overheating, a cooling fan is attached to the box which is shown in figure below. This casing if fixed in the corner of the board so that it does not interrupt the robot.

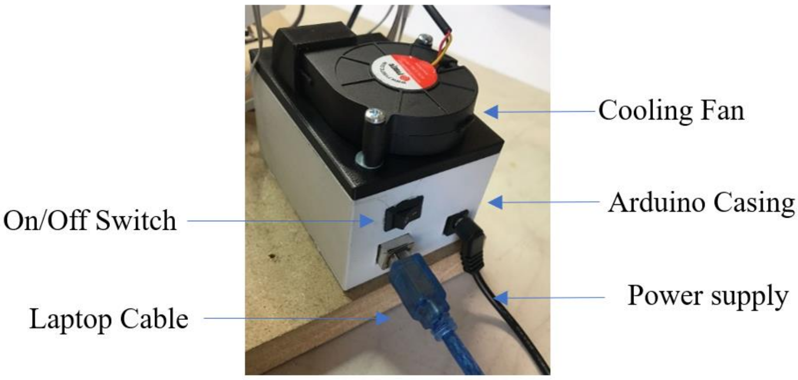


Figure 7: Electronic Unit

5. Design of the subsystem

i. Mechanical Systems

In this project, the CAD design has been made using SolidWorks software. The most basic principle such as statics, dynamics, vibration, and reliability have been considered in the design process.

Before diving into fabricating the robot, stress analysis had been done using the software Autodesk Inventor to see whether or not it satisfies the needs. Since the most concern of the system was bending, the structure should have minimum bending at the end of Y-axis. The stress analysis, shows that the static bending is negligible.

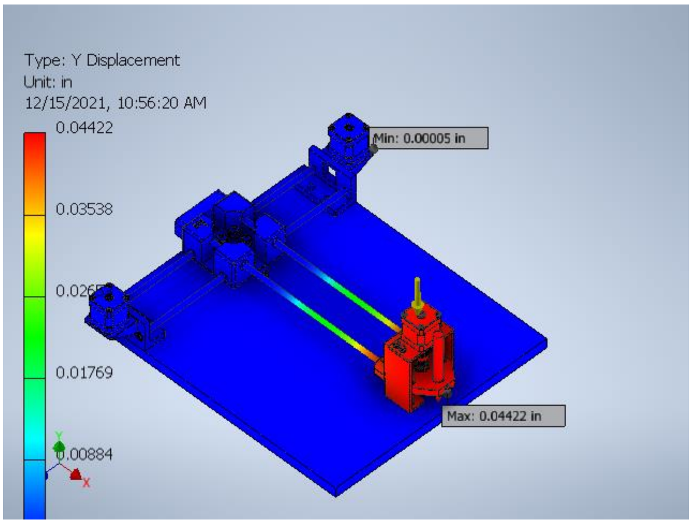


Figure 8: Static Stress Analysis

However, due to the misalignment of the linear ball bearing the actual bending is more than what is shown in figure 8. shows the misalignment, which caused by tolerance defects, mounting errors or inaccuracies in the adjacent construction. In section 13, the solution proposed to overcome this problem will be explain in more details.

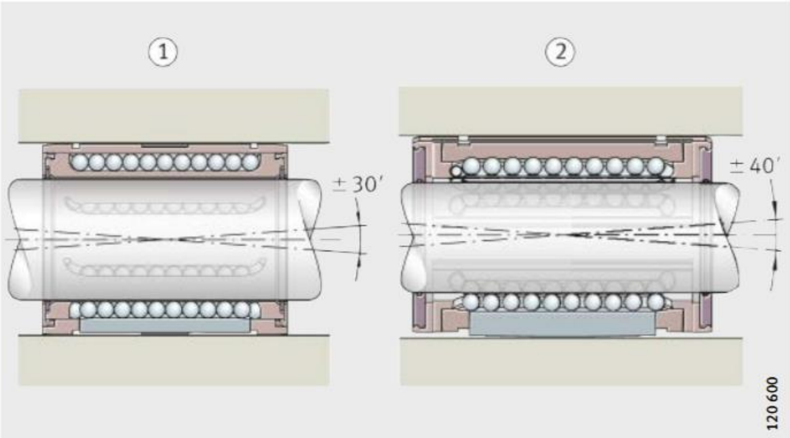


Figure 9: Misalignment of two different series of bearing

The cart is designed in a way that the idler bearing pullies, rolling to provide the tension and guide the engine driving belt, attached to it can be adjustable to have varied tensions.

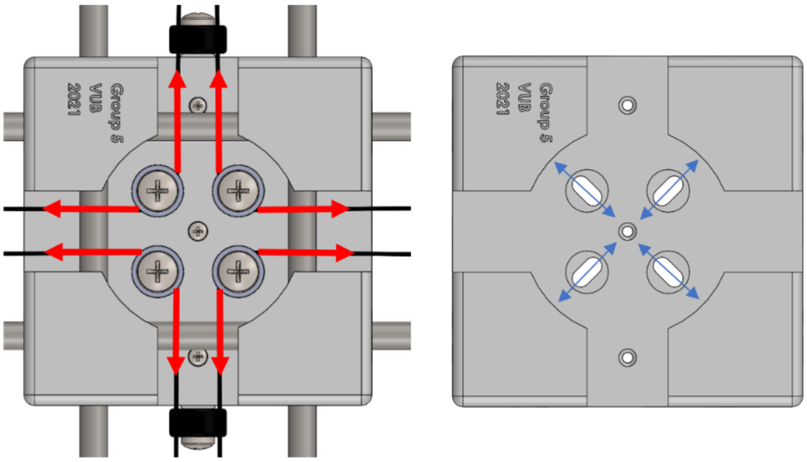


Figure 10: The cart and Adjustable Tension

The mechanical design for Z-axis contains a stepper motor, housing, lead crew, flexible coupling, linear ball bearing, and two bearings. The flexible shaft is used in the mechanism to overcome the misalignment of the leadscrew and the shaft of the motor. Furthermore, the springs attached to the end of the shafts prevent the unexpected perturbation of the nut of the lead crew.

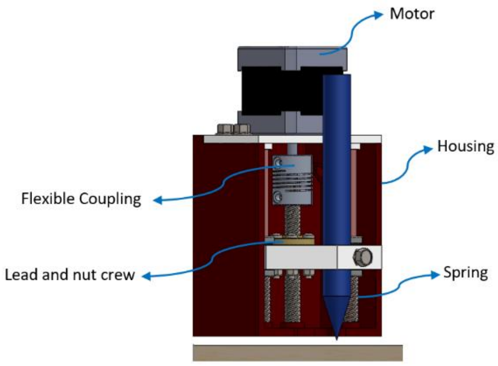


Figure 11. Mechanical Design of the Z-Axis

a. **Requirements:** A requirement list is a nested list which contains adequate quantitative and qualitative information. Determining the requirements of a Draw Robot, helps us to focus on the appropriate design criteria and implement appropriate design decisions. The crucial values of the project will be analysed by prioritizing and categorizing techniques.

Table 5. Requirement List

Categories	Item	Value	Importance
Geometry	Working Area	360mm×300mm	High
	Space requirement of the System	600mm×450mm	High
Kinematics	Types of Motion	Rotational to linear	Medium
	Direction of Motion	X, Y, Z Axis	Medium
Energy	Electrical Supply	12V DC	Medium
	Friction	0.1 to 0.6 Static Friction	High
Material	Shaft, Bearing, Pulleys	Steel	Medium
	3D Printed Parts	Plastic	Medium
	Continuous Belt	Rubber	Medium
Safety	Direct Safety	Parts designed with smooth edges	High
	Environmental Safety	Can be Recycled	High
Transport	Weight + Fragility	Compact Design	High
Quality control	Percentage Of Error		
Operation	Noise	Negligible	Medium
	Marketing Area	Students, Calligraphers, Digital Artists etc.	High
Maintenance	Service Intervals of Motors	Idler Pulleys = 200 Hours, Bearing Lubrication= Every 3 months	High
Cost	Manufacturing Cost	186 €	High
	Max. Selling Price	558 €	High
Schedules	Development Time	3 months	Medium

b. Conceptual Design

Essential Problems: The next step after the requirement list is to find concepts to reach the design criteria. The conceptual design is the initial level of the design process where different concepts are considered and analysed. Several parameters should be considered and discussed in order to select the best one and to improve the final design.

The main challenge in our project is to guide the pen to the correct vector lines so that it creates a picture with utmost accuracy and precision. In the table below, the essential problems and respective solutions have been discussed.

Table 6. Problems and its respective solutions.

Problem	Solution
Designing and building a 3-dof Draw Robot	Means to identify the design requirements of the Z-Axis
Draw the given picture accurately	Means to convert the vector lines into G-Codes
Adjusting Pressure	Means of a Stepper motor
Must be portable	Means to be compact and detachable
Noiseless	Means to have frictionless movement between the shafts and bearing.

Preliminary Concepts and Selections:

Similar products available in the market are:

1. **Single arm XY Plotter:** Like a robotic arm in two dimensions, these devices move a single arm from one corner of the work area to another with the help of motors and belts. A picture of a single arm XY plotter is shown below [1]:

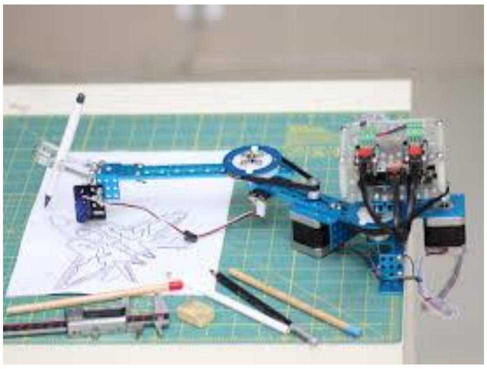


Figure 12: Single arm XY Plotter

2. **Make Block XY Plotter:** As shown in the figure below, the Make Block XY plotter has a sturdy frame. This plotter uses two software's mDraw and Benbox. The cost of this plotter is 399/- Euros [2]:

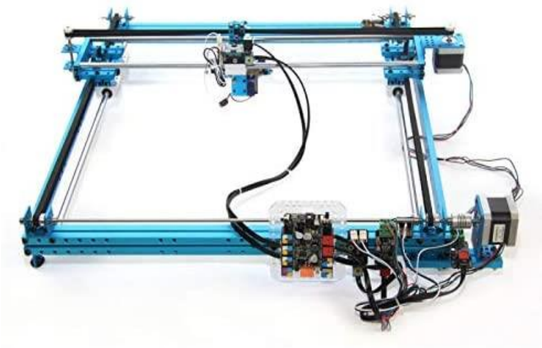


Figure 13: Make Block XY Plotter

As all of our team mates are from engineering background, each of them has proposed their own ideas and thoughts about the different types of concepts which can be adopted for this project. Out of these, we choose the one which satisfied all the conditions mentioned in Table No.7.

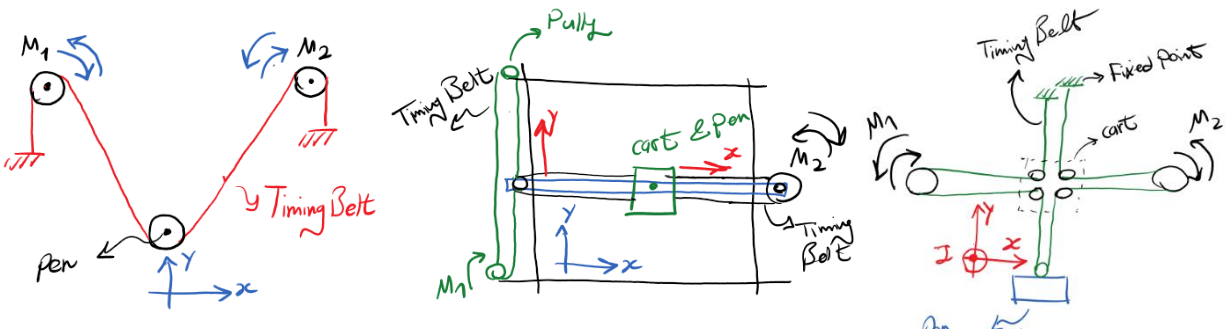


Figure 14: Initial Concepts - Concept 1 to 3 from left to right

The following concepts have been compared and summarized in a grading system which is shown below:

Table 7. Concept Grading System

	Accuracy	Weight	Z – Axis	Maintainability	Noise	Compact Design	Price	Total Price
Importance	Very Important	Very Important	Very Important	Important	Important	Important	Important	
Concept 1	-	+	-	-	+	-	+	3

Concept 2	++	-	+	+	-	-	-	4
Concept 3	++	+	-	+	++	+	+	6

The table below explains the grading's meaning from the above grading system.

Table 8. Grading meaning

Bad	Good	Very Good
-	+	++

1. Morphological Chart

The different concepts mention above are compared on different criteria. The features we considered with the above concepts and the means have been described in a table below.

Table 9. Concept Grading

Features	Means	Compatibility	Current Demand	Reasonable cost	Safety Measures	Decision
Power	Electric	+	+	+	+	+
	Petrol	-	-	-	-	-
	Diesel	-	-	-	-	-
XY Axis - Movement	Belts	+	+	+	+	+
	Gears	-	+	-	-	-
	Chains	+	-	+	-	-
Motors – XYZ Axis	Stepper	+	+	+	+	+
	DC	+	+	-	-	-
	Servo	-	+	+	+	-
Control	Arduino	+	+	+	+	+
	Raspberry Pi	+	+	-	+	-

All the chosen means are summarised in the morphological chart below

Table 10. Morphological Chart

Features	Means
Power	Electric
XY Axis - Movement	Continuous Belt
Z Axis - Movement	Stepper Motor

XY Axis Motor	Stepper Motor
Control	Arduino
XY Limit	Switches

c. Embodiment Design

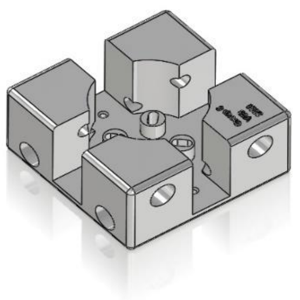
The embodiment design is the step of the design process where the design of the product is developed with consideration of both technical and economic criteria. The three basic rules for this step are clarity, simplicity and safety.

- **Clarity**: Clarity requires that the chosen design guarantees an orderly flow of energy, materials, and signals. Otherwise, undesirable and unpredictable effects such as excessive forces, deformations or wear may occur. The Robot detects its Initial point automatically and depending on the image, the pressure is adjusted by the Robot in calligraphy writing.
- **Simplicity**: The draw robot is very simple as it has minimum number of components, which makes it cost effective.
- **Safety**: We have considered both the safety of the humans as well as the safety of the environment. The parts we have designed are of smooth edges so that the user doesn't get hurt and in order to prevent electrical accidents, we have separately designed a box where we can fix the Arduino so it is out of reach of children and it doesn't interfere with the user. Considering the environmental safety, the parts are recyclable.

2. Draw Robot Components

The different components of a Draw Robot are discussed below:

a) Cart:



It is the main component of the draw robot which works on sliding mechanism. It consists of linear bearings which creates a friction less and parallel movement between the X & Y axis with the help of roller bearing and timing belt.

Figure 15: Cart

b) Supporting structure for X – Axis:

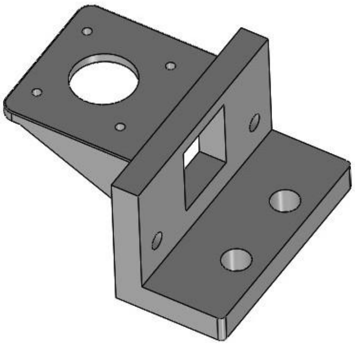


Figure 16: Supporting Structure

The figure shown on the left is the supporting structure for X – Axis as well as the stepper motor. These are placed on the either side of the shafts. These supports are very useful in keeping the shafts exactly parallel to each other so that the cart can move without any disturbance.

c) Supporting structure for Y – Axis:

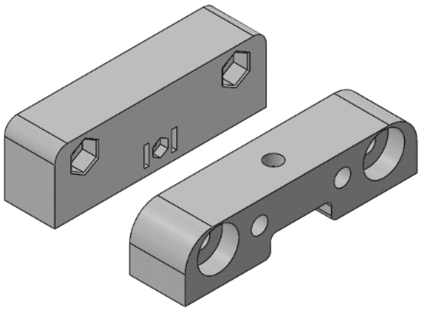


Figure 17: Supporting Structure

The figure shown on the left is then end supports of Y – Axis on which the shafts are fixed. The Z – Axis housing is fixed on one end and other end is attached with a switch in order to limit the motion of the Y – Axis.

d) Z – Axis Housing:

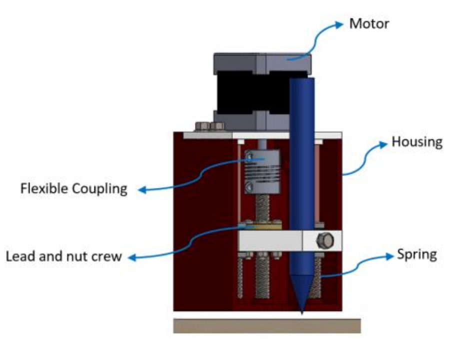


Figure 18: Z-Axis Housing

The Z – Axis housing consists of a pen holder, lead screw and nut, stepper motor - to drive the up & down movement of the pen with the help flexible coupling, lead screw and springs on each shaft. This up and down movement creates a pressure which is the main goal of our project.

e) Wheels & its Support:

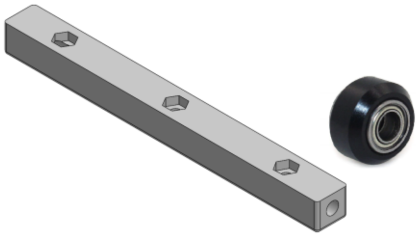


Figure 19: Wheels & its Support

Two wheels attached on the either side of the shaft as shown in the figure is exactly below the card in order to overcome the bending when pressure is in action. This feature helps to maintain the durability of shafts and the cart in a long run.

f) Shafts:

Figure 20: Shafts

The shaft which we used in our project is made up of steel. We use four shafts with diameter of 8mm and length 400mm (2) & 360mm (2) respectively for X & Y – Axis. The cart is mounted with the help of this shafts for linear motion in X & Y plane.

3. Material Analysis

Choosing the material for the product is a very important aspect of design since it determines the quality, strength and price of the product. We adopted the method of Pass/Fail Selection. The choice of material is crucial in order to create a good working structure. The main aspects taken into account while material selection is their properties, shape, type of process.

Two materials which we used are Steel and Plastic (PLA).

1. Steel: We adopted the method of Pass/Fail Selection. The cost of Steel when compared to aluminium is cheap. The corrosion rate of steel in air is 0.2%. Considering the mechanical properties, the strength, toughness of steel is very high compared to that of aluminium. The yield strength is 250MPa and ultimate tensile strength is 400-500MPa [8].
2. PLA: When designing for safety, material behavior is of the utmost importance, relying on stress limits, toughness, elastic/plastic behaviors, thermal expansion etc. The plastics are sufficiently strong and can withstand the load of the shaft and the cart. Especially

PLAs are durable, they easily maintain their shape and do not go under plastic deformations. PLAs are made of starch/sugarcane, therefore can easily be recycled.

d. Final CAD Design

As we focused more on the project, we experienced a minimum bending in the prototype shown in figure 31. This bending would create a negative impact on the lifetime of the robot and thus we changed the design of the cart and made it a single solid component as shown in the figure 32. This helped us to overcome bending at the maximum level as shown in figure 9.

"The idea of adding a counter weight on the opposite side of the Y-Axis has not been tested."

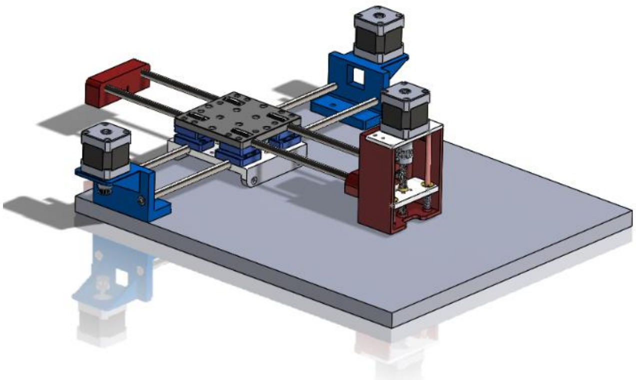


Figure 21: Improved Design

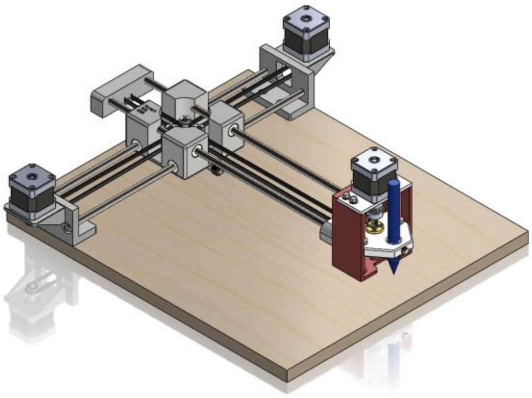


Figure 22: Final Design

ii. Circuitry & Sensors

The Arduino Microcontroller controls the position of the stepper motors using software instructions. It makes it easier to build any control system by providing a standard board that can be programmed and connected to the system without the requirement for extensive PCB design and implementation.

A brushless DC electric motor that divides a whole rotation into a number of equal steps is known as a stepper motor. Because the project's stepper motor has a 1. 8 step resolution, 200 pulses would be required to rotate the shaft one full revolution in full-step operation. Three stepper motors for the X, Y, and Z axes are used to provide precise control over the drawing pen for object sketching. Cart movement along the X and Y axes, as well as movement along the Z-axis, will represent the motor's output.

Stepper motor drivers are used to drive stepper motors that can rotate continuously while maintaining precise position control without the need for a feedback system. With the Arduino CNC Shield, you can have your CNC projects up and running in a few hours. It uses open-source computer code on Arduino to operate four stepper motors using four pieces of the A4988 Stepper Motor Driver breakout board. The purpose of this CNC shield is to control the three axes of the CNC plotter machine, meaning control on the stepper motors. It is very convenient to use with the microcontroller such that it is placed above the Arduino. Here we used to limit movement of cart in x and y directions and also for defining the plotter home position. The limit switch is used in a normally open mode.

The electrical schematic of the system containing—Arduino, the heart of the system, DMOS Micro steeping Motor Driver, three stepper motors, three $100\mu F$ capacitors, and two switches—are depicted in figure 23.

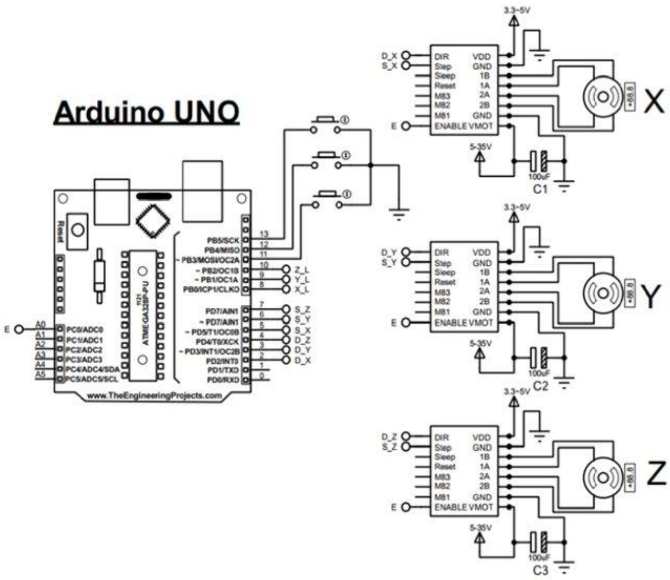


Figure 23: Schematic of the Electrical Design

The direct current (DC) voltage needed for the Arduino is between 9 and 12. However, the microcontroller Atmega8 embedded on the Arduino board needs 5 volts to run. To convert this voltage, an integrated circuit (IC) MC33269 - Voltage Regulator Adjustable Output – is already provided to make the voltage needed for it. The capacitors provided at each driver filter the noise to make sure that the drivers work properly.

Arduino, which is already programmed, sends two commands to each driver namely direction- and step-pin. The direction-pin, indeed, controls the direction of the stepper motor to turn clockwise (CW) or counterclockwise (CCW), and the step pins control the speed of the motor by providing different time duration. However, as always, there is a limitation of time duration which is illustrated if figure below with details [2].

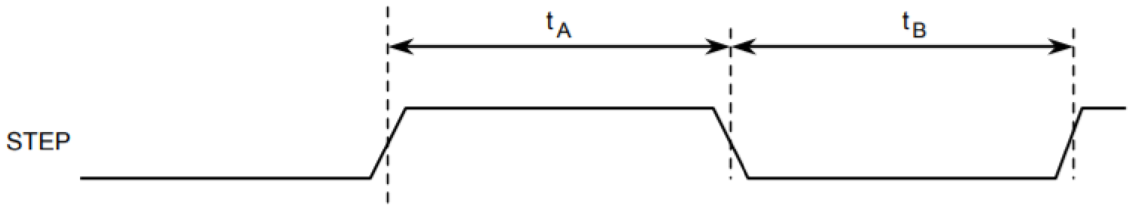


Figure 24: Logic Interface Time Diagram

Time Duration	Symbol	Type	Unit
STEP minimum, HIGH pulse width	t_A	1	$1\mu s$
STEP minimum, LOW pulse width	t_B	1	$1\mu s$

Therefore, the driver is capable of doing full step at 500khz. However, there is a limit to what voltage can accomplish in the ways of overcoming inductance. The motor used in this project, according to the initial experiment, accepts 3.4khz. Therefore, the maximum angular velocity of the stepper motor which has 200 steps per revolution is $1020RPM$. The maximum translation speed follows by simple calculation using the equation bellow:

$$v_{tranlation} = r\omega \tag{1}$$

Where, r is the radius of the pulley. The maximum translational speed is obtained was 4.27 cm/sec. Also, the moving part – which is illustrated with blue color in figure bellow – has an approximate mass of 1.7kg. However, since the mass is guided by two linear shaft and the static friction between the two wheels with the surface is negligible, the motors used is capable of moving this mass which is guided by the shafts. Please note that the transient response of the system has not been calculated.

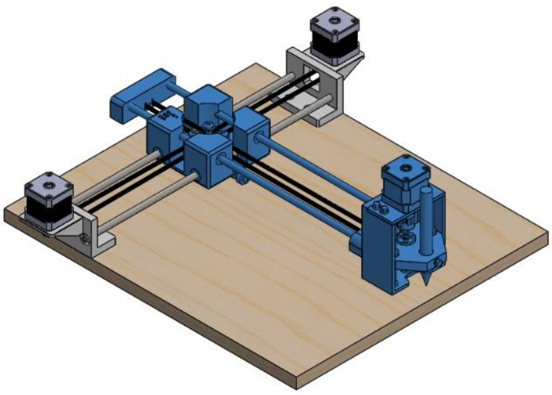


Figure 25: Moving Part with the approximate mass of 1.7kg

Another important factor that must be taken in to account is the temperature of the drivers. According the datasheet of the driver [2], the temperature affects the power dissipation. **Error! Reference source not found.** shows that when the temperature is increasing, the power dissipation is decreasing.

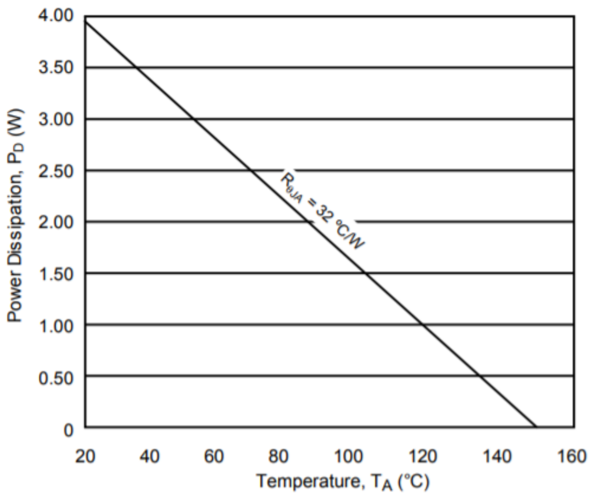


Figure 26: Power dissipation versus Ambient Temperature

To prevent the effect of temperature on the performance of the driver, a cooling fan is implemented on the electrical part shown in figure bellow:

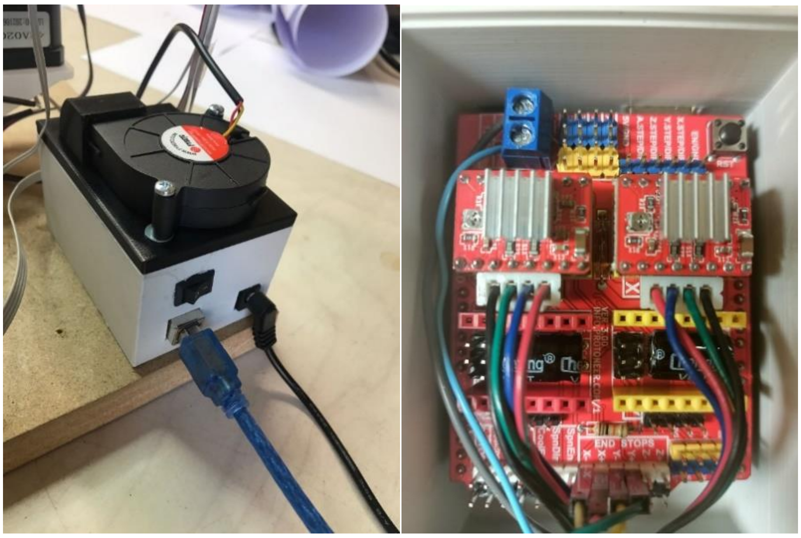


Figure 27: Cooling Fan (the driver for the Z-Axis is missing in the right figure)

Please note that a spacer is implemented between the fan and the box so that the air can easily flow into the fan. By doing so, external disturbances cannot interfere with the fan while it is working.

The kinematic modelling of the robot is based on so-called XY-core. The design of this mechanism is illustrated in figure bellow:

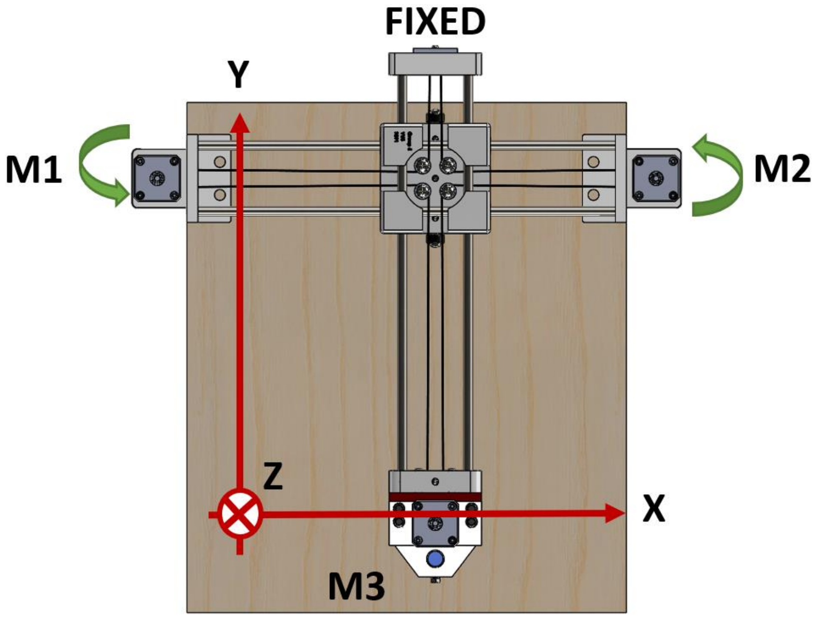


Figure 28: XY Plane

One can find how the pen can move by two coupled motors in x-, and y-axis in table below:

Table 11. XY-core Kinematics (CW: Clockwise, CCW: Counter Clockwise)

M1	M2	Y direction +/-	X direction +/-	Resolution
CW	CW	0	+	$\approx 0.03\ mm$
CW	CCW	-	0	$\approx 0.03\ mm$
CCW	CW	+	0	$\approx 0.03\ mm$
CCW	CCW	0	-	$\approx 0.03\ mm$
STOP	CW	+	-	$\approx 0.03\sqrt{2}\ mm$
STOP	CCW	-	+	$\approx 0.03\sqrt{2}\ mm$
CW	STOP	-	+	$\approx 0.03\sqrt{2}\ mm$
CCW	STOP	+	-	$\approx 0.03\sqrt{2}\ mm$

To have better resolution the driver is provided the dividing steps by configuring the pins MS1 to MS3, which can be found in the electrical schematic. The configuration provided by the datasheet [2] is as follows.

Table 12. Steps Configuration

MS1	MS2	MS3	Micro-step Resolution
L	L	L	Full Step
H	L	L	Half Step
L	H	L	Quarter Step
H	H	L	Eighth Step
H	H	H	Sixteenth Step

In this project, step resolution decreases to have better resolution. Furthermore, by doing so, the vibration of the system has reasonably decreased. The final resolution is calculated considering the radius of the pully attached to the stepper motor and the step size of the motor. The drawback of this configuration is that it will reduce the speed of the motors. The minimum and maximum thickness can be produced by the robot depends on the type of the pen. In this project, a pen is capable of making the maximum thickness of 2mm and minimum of 0.1mm is used.

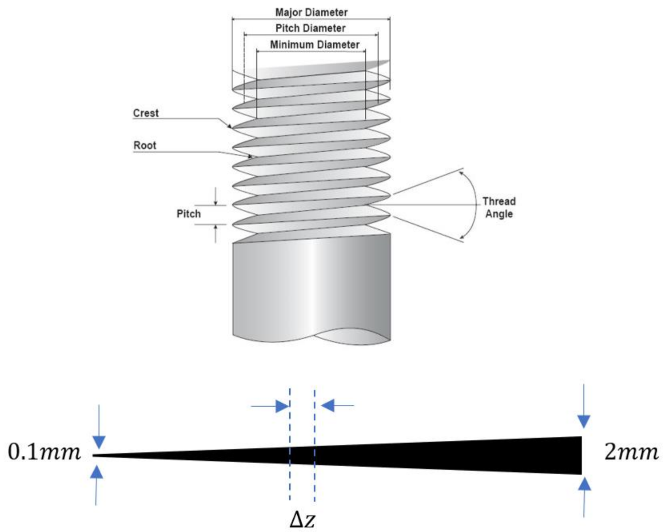


Figure 29: Thread Angle and Varied Thickness

The minimum step Δz can be found as follows:

$$\Delta z = \frac{360}{step \times microstep} \frac{\pi}{180} \cos\left(\frac{ThreadAngle}{2}\right) \times r_l \quad (2)$$

$$\Delta z = 0.0316\text{mm}$$

Were, r_l is the radius of lead screw, or half of major diameter; therefore, this robot can produce 60 different thicknesses.

iii. Software

- The Arduino Software that is Arduino IDE, which is open-source, makes it simple to create code and upload it to the board. Because C and C++ are the global languages for Arduino, the program is suitable for professionals who are familiar with them. G-code is used as an input, and signals are output via the Arduino pins.
- GRBL is compatible with all ATmega 328-based Arduino boards, which means you can use an uno or nano but not a mega because the mega is based on the ATmega 2560. You can also broadcast G-code commands directly over GRBL. The following are the basic installation steps: Get the most recent GRBL package (it will download as a.zip file) Install the most recent version of the Arduino IDE. Install the "GRBL" folder from the.zip file as a library in the Arduino IDE. Run the GRBL upload after connecting your Arduino to your computer. Download link for GRBL at Refer No. [3]. So here are some instructions for setting up the XY Core: Open the Config.h file by going to Documents > Arduino > Libraries > GRBL > Then open the Config. file. Remove the comment from line 113. Remove the comment from line 189. Because CNC plotter machines run and understand G language, we require software tools to translate images or text into G-code so that we may draw them on the CNC plotter machine.
- Inkscape is a free-to-download open-source software that may be customized for specific applications by adding extensions. Download the latest version of Inkscape [7]. We utilize an add-on to convert images to G-code. The extension to the Inkscape Library can be found online [11]. Copy the component from the SRC folder to the same location where you extracted the downloaded file. Then paste the copied file into Inkscape Location > Then Share > Then Extension.
- The software that connects your CNC machine to your PC is known as control software that is Candle. Controlling the machine from your computer has a number of benefits, including enhanced machine oversight and real-time toolpath visibility. It eliminates the requirement to export data to an external drive and then reload it into the machine, allowing you to view results immediately after making changes to the settings. Download the latest version of Candle at Refer No. [9].

Procedure:

1. Download and install all of the above-mentioned software, then open the Arduino IDE. Then, using the techniques explained above, we'll add GRBL to the Arduino Library.

2. Go to Menu > Examples > Then GRBL > GRBLUpload in the Arduino IDE.

3. Connect your Arduino to your computer with a USB connection, then choose the Arduino Uno Board type and the relevant port for your Arduino in the tools menu before uploading the sketch. After the upload is complete, your Arduino Uno Board is now connected to your PC.

4. Next, we'll create a G-code file from our text or image. Inkscape is used to accomplish this. A proceed, we'll first add to Extension in Inkscape to convert an image or text into G-code. We can accomplish this by using the methods given above. The steps to accomplish so are as follows:

a. Start the Inkscape program. Before we can import an image, we must first modify the page size. By heading to files > document properties, you can change the page's width and height.
b. After that, create a drawing or import an image.
c. Make sure the images/text are made out of paths/vectors rather than pixels, as this will prevent them from being translated into G-code commands.
d. The image must then be converted to a path by right-clicking it and selecting the trace bitmap. After that, we must evaluate the image in real time and, if necessary, raise the threshold before clicking OK.
e. There are two photographs after that. Then, remove the original Image and proceed. Then Go to the 'path' menu (first options: 'Object to path' or 'Stroke to path') to turn your drawing selections into a path.
f. Select MakerBot Unicorn G-code (.gcode) as the file type in File > Save, then click OK.
g. Then see a single box on which you should click OK.
h. Now close the Inkscape window after saving the G-Code file.
i. The generated G-code is wrong, and we must make changes. The following are the steps to correct this:
    i.1. Start by removing 5 lines.
    i.2. Delete the next six lines.

i.3. Remove the M300 S50 (Pen Up) and M300 S30 (Pen Down) Z-axis commands for the pen up and pen down, respectively (Pen Down).

i.4. We must now delete the last 27 lines of our code.

i.5. Remove the F3500.00 feed rate instruction from the equation.

i.6. Now we may save it, and our G-Code is ready to execute.

5. Now run the Candle software, which connects to our Draw Robot. The steps for uploading G-code into the Candle are as follows:

a. Go to Settings, then COM, then link the machine to the program, and then click to unlock.
b. Examine the motors and their basic functions, including:
c. Use the Jog Buttons to check the X, Y, and Z axis directions.
d. Make sure the homing cycle is on.
e. Set the origin, which means we must use the jog buttons to set the Zero point and adjust the Z-axis by making the bit slightly touch the material and ensuring that the gap can only pass a piece of paper, and then set the X, Y, and Z to zero.
f. After checking all that Open a G-code file by File > Open and check the code and then click “Send” to start the Drawing.
g. Now we are done our machine is now working.

Please notice that the draw robot has been calibrated. The robot may also use the X- and Y-limit switches to find its "home." Unfortunately, we were unable to use it due to this lack of time and the inability to operate the software properly and correctly, as well as possibly other concerns that are still unknown. We utilized modified G-codes to draw a calligraphy alphabet "F" in the middle of the XY plane to test the robot.

6. Integration Guide

The Draw Robot is a simple, modern and precise pen plotter capable of writing or drawing on any flat surface. This guide will allow you to use your computer to produce writing that appears to be handmade.

i. Pen, paper and the clip easel: You will need a pen & a paper to get started. There is a simple arrangement on the board where the paper can be fixed easily. To fix a pen, there is a simple screw mechanism to hold the pen firmly. The vertical position of them pen should be approximately 0.20 to 0.30 mm just above the paper. Any basic pen can be used but for calligraphic artist, a calligraphic pen is advised.

ii. Connect Power & USB: The next step is to connect power and USB cables. Connect the USB cable to USB port on your computer. The plug-in power adapter is 12V DC, regulated, centre positive which works with worldwide mains power. Do not use an adapter that changes the voltage. There is a special arrangement made on the electronic casing to switch on & off the device. Once your cables are connected, make sure that the robot has room to move, both in front and behind the machine. To make sure that cables doesn't get caught, they are properly fixed.

iii. Move to home: Prior to drawing, it is necessary to move the pen to the Home. This is exactly the centre of the machine.

iv. Calibrate the pen position: It is very important to calibrate the positioning of the pen. Candle software allows us to toggle pen up and down. If there is no movement, double check that you have power and USB connected properly.

v. Software implementation: As Candle software is an open-source software, it can be downloaded from internet [7].

vi. Document Orientation: Different types of documents can be used to write or draw. The following are the list of examples: a) Letter Size, b) A4 size sheet, c) A formal invitation ($6\frac{3}{8} \times 8\frac{7}{8}$, portrait orientation).

7. Demo Project Show and Quick Guide

The demo of the project has been made and uploaded on YouTube website to be used for engineers who are interested in building the draw robot. The link is provided here.

https://www.youtube.com/watch?v=YnW0rqTW1qc

8. Review your project critically

First of all, we have to admit that the first concept is the best fit to fulfil our desire to adjust the pressure since the bending of y-axis of this concept in comparison to the fabricated one is nothing. However, changing the details of the design and modifying the software reasonably solve the bending problem.

As mentioned, one solution to overcome the bending was modifying the codes. First, the error found as a function of y-axis as follows:

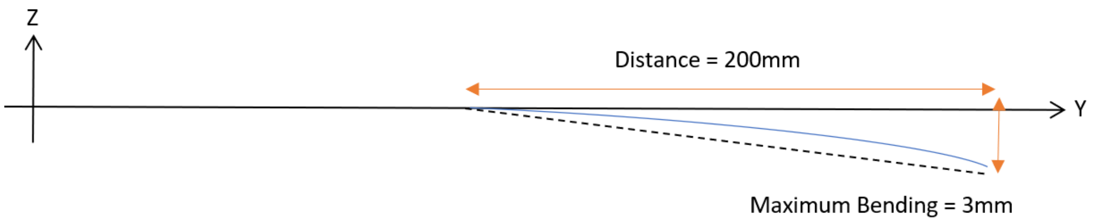


Figure 30: Error due to Bending

According to the static stress analysis **Error! Reference source not found.** 30, and the misaliment of the shaft in the linear ball bearing, the bending accurses when the pen is in the middle of the Y-axis. One can approximate the bending error with a linear function of Y. Therefore, in a simple G-codes this error can be added to position of z axis. The example is provided for better illustration.

$$G1\ X1.00374\ Y20.97682\ Z0.01 - f(Y)$$
$$G1\ X0.99614\ Y20.99744\ Z0.01 - f(Y)$$
$$G1\ X0.99238\ Y20.99773\ Z0.01 - f(Y)$$
$$e_z = f(Y) = 0.015(Y - 20)$$

G1 is a simple code used to move the pen in a specific location in XYZ area. Other g-code, however, cannot be modified as simple as explained above since they draw circles and the displacement of z cannot be changed while the pen is moving is XY plane.

Also, if we had time, we would have designed a draw robot of 5-DOF rather than 3-DOF. By doing so, we would have been able to draw more complex calligraphy which needs the rotation of pen (one extra DOF) and adjusting the angle with respect to the paper (one extra DOF) to be drawn.

Figure 31: Complex Hand writing in Persian

9. Sustainability

From engineering point of view, it is very important to create a sustainable design and the draw robot has met all the three key areas where engineers are pivotal to create a sustainable design.

i. Material Selection: The design and manufacturing of the draw robot is done in such a way that all the parts can be recycled and reused. All the mechanical parts are used of standard size which is easily available in the market and all the 3D printed parts, which are made up of PLC can be recycled easily.
ii. Energy Resource: Energy plays an important role in the manufacturing process. During the designing, all the assumptions and testing were made in software to analyse the defects in the design. The mechanical parts including nuts and bolts were utilised in the best way. The 3D printed parts were perfectly design and verified using SolidWorks software, so that there is no mistake in printing.

Improvements: As far as the design is considered, it was made sure that we utilise the resources in the best manner. The design of cart was improved to reduce the number of shafts, nuts & bolts and 3D printed parts.

10. Bill of Material (B.O.M)

The cost of the Draw Robot has been categorized into two parts.

a. Manufacturing cost of 3D printed parts &
b. Components cost.

Table 13. Manufacturing cost of 3D printed parts

Element	**Quantity**	**Time**	**Price**
End Supports X Axis	2	12hrs 59mins	5.19 €
End Supports Y Axis	2	4hrs 12mins	1.60 €
Cart	1	14hrs 45mins	5.83 €
Z – Axis Housing	1	9hrs 14mins	3.91 €
Pen Holder	1	3hrs 43mins	1.40 €
Idler Pulley	1	32mins	0.10 €
Arduino Casing	1	8hrs 12mins	3.21 €
Wheel Attachments	1	56mins	0.33 €
Timing Belt Locker	1	18mins	0.08 €
Total Price			21.65 €

Price Consideration
1. Filament - PLA
2. Electricity – 0.187 €cent/kWh

Reference Website: 3D Printing Price Calculator - Prusa Printers

Table 14. Component Cost

Element	**Quantity**	**Price**
Arduino Uno	1 × 25	25 €
Stepper Motors	3 × 12.5	37.5 €

Drivers	3 × 5	15 €
Wooden Base	1	4 €
Electrical Wires	106 cm	3 €
Shafts	8mm – 160cm 6mm – 20cm	16 € 2.15 €
Nuts	M3 – 17 M5 – 4 M6 – 16	4 €
Bolts	M3 - 16 M6 – 4	
Linear Bearings	4 × 2.5 €	10 €
Rotational Bearings	2 × 0.25 €	0.5 €
Idler Pulleys	4 × 2 €	8 €
Wheels	2 × 1.5 €	3 €
Lead Screw + Nut	7cm × 0.37 € + 6 €	8.59 €
Flexible Coupling	1 [5 × 8] × 7.99 €	7.99 €
CNC Shield	1 × 9.5 €	9.5 €
Timing Belt	175cm × 4.25 €	7.45 €
Limit Switches	2 × 0.69	1.38 €
Spring	6mm diameter	1.5 €
Total Price		164.56 €

After summarizing as shown in the table above, the total price of the project is 186.21 €

11. Results

The result shows that the robot is capable of drawing lines with varied thicknesses and a good agreement has been obtained.

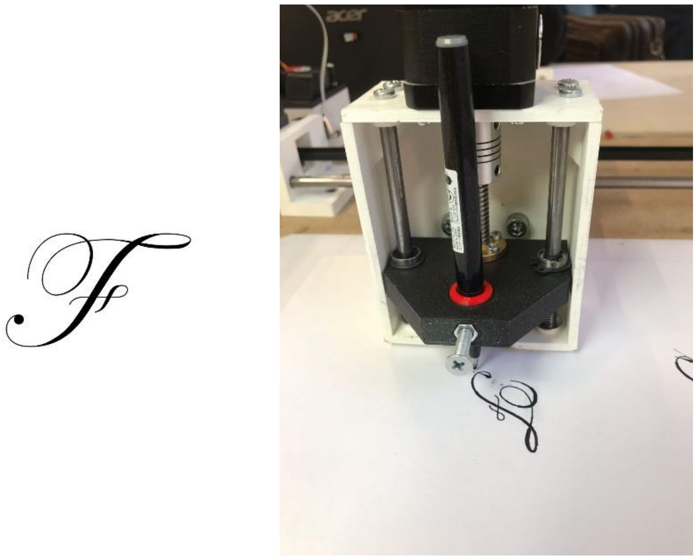


Figure 32. The comparison between the desired calligraphy word with the result

12. Conclusion

In this project, a control unit Arduino Uno which was programmed with GRBL V1.1 accepting G-codes to command the motor has been used. The minimum step size found for the Z-axis was 0.03mm which is enough for drawing calligraphy words. To apply the pressure on the pen for drawing varied thicknesses, the G-codes of the picture have been modified and the error of bending is also has been considered. However, it is so clear that the second concept in comparison with the others has no bending and it must have been chosen to have a better result.

13. Work distribution

The aim was to divide the task and develop it in parallel. Due to the lack of background in electronics and mechanics of two team members most of the work has been done by one team member. However, he tried to teach them every single part in electronical and mechanical design. Hopefully, at the end, as same as himself, they have learned a lot of things which is priceless to him.

-Table 15. Work Distribution

Working Area	Mohammad Javad Rahimi	Aiman Quraishi	Mayur Ashok
Mechanical design	100%	0%	0%
CAD – SolidWorks	100%	0%	0%
Electrical design	50%	25%	25%
Programming	50%	0%	50%
Testing	34%	33%	33%
Assembling	50%	25%	25%
Analysing the errors	50%	25%	25%
Demo Project Video	10%	10%	80%
Writing the Report	40%	40%	20%

a) *Mohammadjavad Rahimi Dolatabad* – He has received the B.Sc. Degree in Electronic Engineering program in 2010, Tehran. He obtained his first master's in Mechatronics Engineering in 2020 at Sharif University of Technology, International Campus, Kish Island, Iran—ranked first among Iranian universities.
Please visit his website for more info http://mj-rahimi.com

b) *Aiman Quraishi* – He has received Bachelor's in Technology in Mechanical Engineering from JNTU – Hyderabad in the year 2021.

c) *Mayur Ashok Sonawane* – He has received Bachelor's in Technology in Mechanical Engineering from Savitribai Phule Pune University, Pune, Maharashtra, India in the year 2020.

14. Reference

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10. https://github.com/gnea/grbl
11. https://github.com/martymcguire/inkscape-unicorn

15. Appendix

Google drive link: All the files, programs, codes, pictures, CAD file, G-codes, and etc are available in the google drive.

https://drive.google.com/drive/folders/1n1bUVdIGvhPVDfAwZ1R2MdOm4K6IxPrF?usp=sharing

The instructables website link: https://www.instructables.com/DrawRobot/