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UNIVERSIDAD INTERNACIONAL DEL ECUADOR

FACULTY OF TECHNICAL SCIENCES

SCHOOL OF MECHATRONIC ENGINEERING

Design and Construction of an Electrodeposition Based Metal 3D Printer with Polar Architecture

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MECHATRONIC ENGINEER
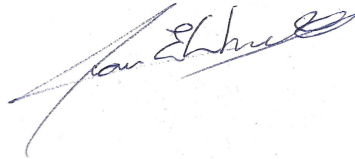
Juan Esteban Chiriboga

Supervisor: Luis Gilmour Andrade Acosta

D. M. Quito,

CERTIFICATE OF AUTHORSHIP

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Juan Esteban Chiriboga Muñoz

ACKNOWLEDGMENTS

I would like to thank my family for the constant support and sacrifice they made throughout these years to provide to me the education of the highest quality. I would also like to thank all my professors that guided me up to this point with patience and diligence.

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DESIGN AND MATERIALS SELECTION

1.   Electrodeposition

With the use of electrodeposition, copper can be deposited in a solid manner without the need of melting it. With an electrolyte solution, ions of copper travel with the help of an electric current and deposit in a conductive surface as seen in Figure 1. If the deposition is localized and controlled, a structure can be manufactured with the use of CNC equipment.
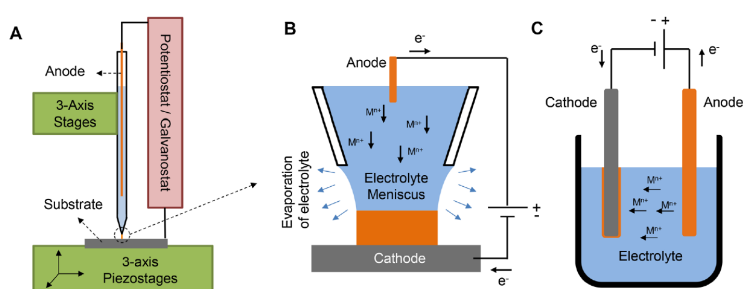
Figure 1. Localized electrodeposition of copper ions using a pipette and a current controller [1]

For the electrodeposition process, the electrolyte solution was copper acetate. Do to limitations in the obtainment of specialized and dangerous chemicals in Ecuador, a simple copper acetate is both easy to synthesise and low cost. The electrolyte solution must be prepared with the following quantities and materials as in Table 1 [4]:

Chemical	Amount
Copper metal	2g
Hydrogen Peroxide	20mL
Acetic acid	20mL
Sodium Chloride	0.5g

Table 1. Copper acetate solution for electroplating copper

To avoid the formation of dendrites due to too rapid deposition, a solution proposed by G. Devaraj and S.K. Seshadri was pulsed electrodeposition. As seen in Figure ‚ a pulsed electrodeposition with a frequency of 100 Hz at 80% duty cycle yields the maximum hardness while diminishing the number of pores [5].
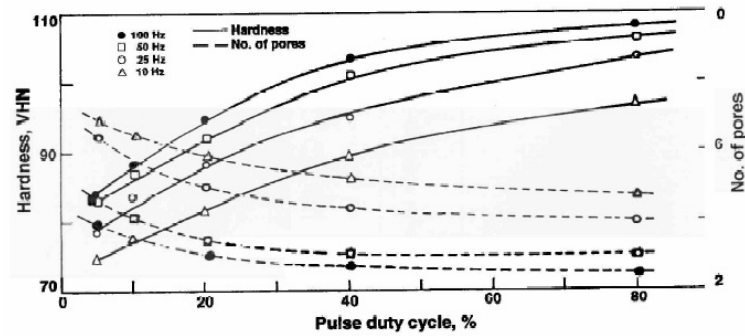
Figure 2. Effect on hardness and porosity of copper with pulsed electrodeposition at 2.5 A/dm^2 current density

2. Mechanical Design

2.1. Polar architecture

Polar 3D printers offer some advantages over the traditional Cartesian coordinates in the sense that these 3D printers are simpler to manufacture. This is due to the fact that it requires less mobile parts to achieve the same result. However, most slicing software for 3D printers require a Cartesian coordinate system, which in turn is easier to understand and modify. In order to use a polar coordinate system, it is necessary to convert from the Cartesian coordinate system to the polar coordinate system [6]. This means that the coordinates of (X, Y, Z) need to be converted to (r, θ, Z). This can me done by applying equations (1) and (2):

$$r = \sqrt{x^2 + y^2} \tag{1}$$

$$\theta = atan2(y, x) \tag{2}$$

It is important to take into account the quadrant in which the coordinates are given. This is because a different pair of coordinates can yield the same result if the quadrant is not taken into account. This can result in an erroneous angle. To avoid that, the function $atan2(y, x)$ takes care of determining the correct quadrant based on the sign of each of the coordinates [7]. As an example, a group of coordinates of (x, y) is given to create a square seen in Table 2 and illustrated in Figure 3 :

x	y
10	10
10	-10
-10	-10
-10	10
10	10

Table 2. Pair of (x,y) coordinates as an example to form a square
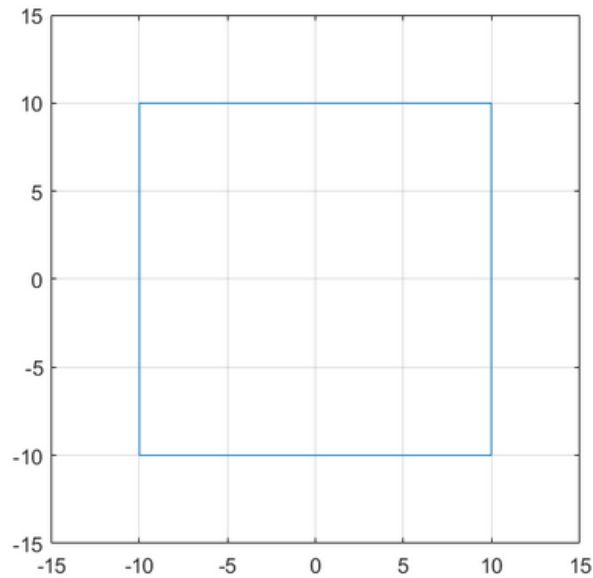
Figure 3. Cartesian coordinate system to form a square

Using equations (1) and (2),the corresponding values of the modulus and angle (in degrees) can be obtained as in Table 3 and visualized in Figure 4:

r	θ
14.1421	45
14.1421	-45
14.1421	-135
14.1421	135
14.1421	45

Table 3. Pair of (r,θ) polar coordinates as an example to form a square
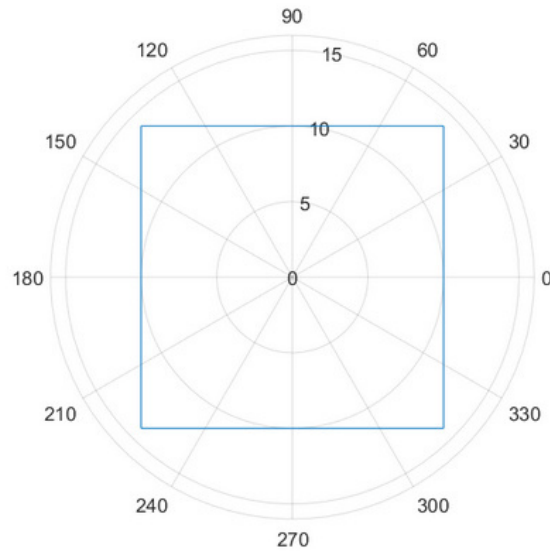
Figure 4. Square drawn on polar coordinate system

2.2.   Mechanism for X and Z axis

In order to achieve movement, a lead screw and nut mechanism was selected. This has the added benefit of increased torque and movement resolution at the cost of speed. The screw selected was an imperial unit 5/16" with 18 threads per inch. This type of thread was chosen over the metric threaded rod due to lower prices and the availability in stainless-steel material. More details about pricing and expenses can be seen in Table 10. Since most of the slicing software and 3D printing firmware require a unit of measure of mm/s, the following procedure was made in order to convert the imperial units to metric. Knowing that the threaded rod of diameter of 5/16" has 18 threads per inch, the pitch can be calculated as seen in the following equation (3):

$$\frac{1[thread]}{18[\frac{threads}{in}]} = \frac{1}{18}[in] \tag{3}$$

By having a lead screw mechanism, the calculation can be done to determine the torque that is necessary to raise or lower a load. In this case, the load is the horizontal axis assembly seen in the Figure 5:
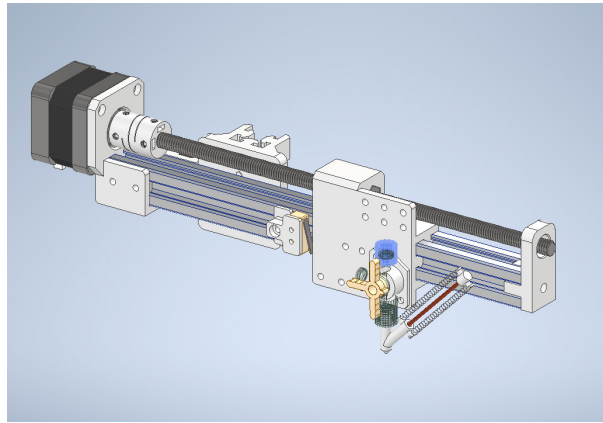
Figure 5. Horizontal axis assembly CAD model

Because the geometry of the assembly is considerably complex, it is wise to use the tools at our disposal to estimate the physical properties. The CAD model was designed using the software Inventor by Autodesk. In this software, the material for each part can be selected. This will result in a better estimation of the physical properties as seen in Figure 6:
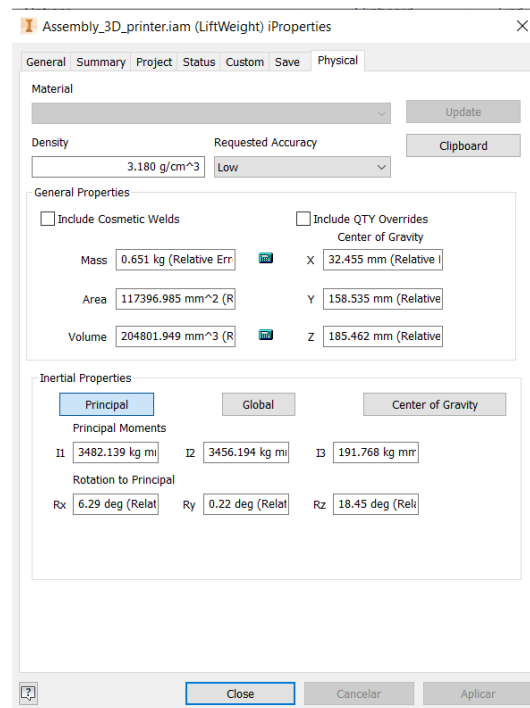
Figure 6. Physical properties inspector in Autodesk Inventor

The physical properties can help to simplify the model into a simpler 2D representation to better estimate the torque needed to raise the whole assembly like in Figure 7. Taking into account the weight of the assembly and the center of gravity, an approximation of the forces can be calculated.
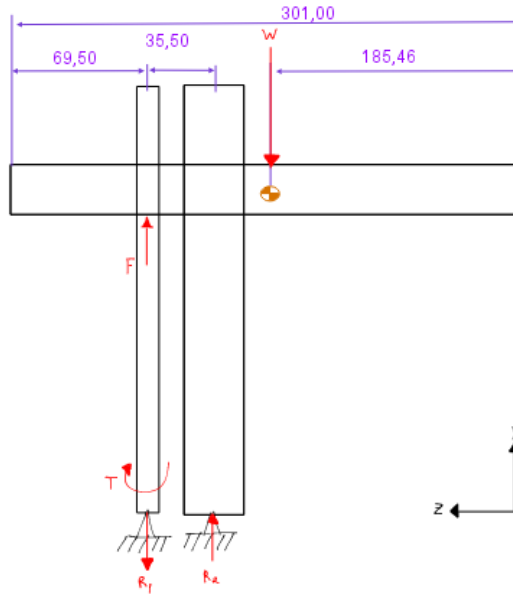
Figure 7. 2D representation of the horizontal axis assembly

The force W is the weight in Newtons, and can be easily calculated as in equation (4):

$$W = 0.651[Kg] \times 9.81[m/s^2] = 6.386[N] \tag{4}$$

Using the sum of forces equal to 0, the reactions at the base can be determined as in equation (5):

$$R_1 = R_2 + W \tag{5}$$

By knowing the position of the center of mass, a sum of moments can yield the result for one of the reactions. In this case, in order to determine the second reaction, it is useful to analyse the moments at the point where the lead screw and nut meet. So, by using equation we get (6):

$$R_1 \cdot 35.5[mm] = W \cdot 301 - (69.5 + 35.5 + 186,46)[mm] \tag{6}$$

$$R_1 = \frac{6.386[N] \cdot 9.54[mm]}{35.5[mm]} = 1.7161[N] \tag{7}$$

Using the value of R1 from equation (7), the other reaction R2 can be solved using equation equation (8) from equation (5). In turn, the reaction R2 can be solved like in equation (9:

$$1.7161[N] = R_2 + 6.386[N] \tag{8}$$

$$R_2 = 6.386[N] - 1.7161[N] = 4.6699[N] \approx 4.67[N] \tag{9}$$

In this case, the analysis will be made only for the Z-axis, due to the fact that it will be carrying a heavier load. To calculate the torque needed to raise the whole assembly, it is useful to have a factor of safety for the load. With a FOS of 10, it is assured that the motor will be able to manage most of the accelerations, disturbances, and external forces that may happen during movement. By using the formula for raising a load on a lead screw as seen in equation (10), the total torque can be determined [8].

$$\tau_{raise} = \frac{Fd_m}{2} \left(\frac{l + \pi\mu d_m}{\pi d_m - \mu l} \right) \tag{10}$$

Where:

- τ_{raise}=torque needed

- F=load on the screw

- d_m=mean diameter

- μ=coefficient of friction

- l=lead

Since the selected threaded rod contains only one thread, the pitch and the lead are the same. For obtaining the minor diameter, the formula is given by Shigley's Mechanical Engineering Design book:

$$d_r = d - 1.299038p \tag{11}$$

$$d_r = \frac{5}{16} - 1.299038 \cdot \frac{1}{18} = 0.2403[in]$$

Alternatively, using the ANSI B1.1-1974 table as seen in Figure 8, the minor diameter area can be found.

Figure 8. ANSI B1.1-1974 Unified Inch Screw Threads table [2]

For a 5/16"-18 external diameter screw, the minor diameter area is 0.0454 in^2. From the equation of the area of a circle, the minor diameter can be determined as in equation (12):

$$d_r = 2 \cdot \sqrt{\frac{A}{\pi}} = 2 \cdot \sqrt{\frac{0.0454[in^2]}{\pi}} = 0.2404[in] \tag{12}$$

Both equations (11) and (12) yield similar results. In this case, the value calculated from the ANSI B1.1-1974 table will be used. The mean diameter can then be calculated from the external diameter and the minor diameter as in equation (13):

$$d_m = \frac{d + d_r}{2} = \frac{5/16[in] + 0.2404[in]}{2} = 0.2765[in] \tag{13}$$

The threaded rod material is Stainless Steel as well as the nuts. The coefficient of friction for steel on steel parts are typically 0.25 [9]. Transforming inches to meters for a congruent answer we get:

- F=6.386[N]

- d_m=0.2765[in]=0.0070231[m]

- μ=0.25

- l=1/18[in]=0.0014097[m]

From equation (10), substituting all the variables yields equation (14):

$$\tau_{raise} = \frac{(10 \cdot 6.386[N]) \cdot 0.0070231[m]}{2} \left(\frac{0.0014097[m] + \pi \cdot 0.25 \cdot 0.0070231[m]}{\pi \cdot 0.0070231[m] - 0.25 \cdot 0.0014097[m]} \right) \quad (14)$$

$$\tau_{raise} = 0.07153[N \cdot m]$$

2.3. Mechanism for Rotary axis

For the rotary axis mechanism, a simple pulley system with a GT2 timing belt will work. In order to increase both the torque and the movement resolution, a reduction pulley system is designed. With a driving pulley of 20 teeth and a driven pulley of 120 teeth, the driving ratio is as in equation (15):

$$n = \frac{\# \ of \ driving \ teeth}{\# \ of \ driven \ teeth} = \frac{20}{120} = \frac{1}{6} \quad (15)$$

The final speed of the base will be 6 times lower, but will have 6 times more torque and will be able to have a better resolution per degree of the motor.

2.4. Motor selection

For this project, a NEMA 17 motor was chosen. The complete model of the motor is NEMA 17-HS3401, which was chose for its low price and high torque. From its Datasheet, the characteristics can be seen in Table 4:

Series Model	Step Angle (deg)	Motor Length (mm)	Rated Current (A)	Phase Resistance (Ω)	Phase inductance (mH)	Holding Torque (N-cm)
17HS3401	1.8	34	0.8	2.4	2.8	28

Table 4. Characteristics of the NEMA 17HS3401 stepper motor [3]

As seen in Table 4, the holding torque is 28 N-cm. To convert to N-m, it is necessary to divide by 100:

$$\tau = \frac{28[N \cdot cm]}{100} = 0.28[N \cdot m] \quad (16)$$

As seen in equation (16), the holding torque is more than 10 times bigger than the calculated theoretical raising torque. Additionally, it is important to take into consideration

that the moving torque is slightly less than the holding torque. However, based on the calculations, the NEMA 17HS3401 is sufficient for this application.

2.5. Steps per millimeter

3D printers commonly use NEMA 17 stepper motors in order to control the movement, and the mechanical characteristics of these motors can be used to determine the steps per millimeter. By using the stepper drivers A4988, micro-stepping can be achieved by configuring the MS1, MS2, and MS3 pins. The following configurations for the micro-stepping resolution can be seen in Table 5:

MS1	MS2	MS3	Micro-stepping Resolution
LOW	LOW	LOW	Full Step
HIGH	LOW	LOW	Half Step
LOW	HIGH	LOW	Quarter Step
HIGH	HIGH	LOW	Eighth Step
HIGH	HIGH	HIGH	Sixteenth Step

Table 5. Configurations for adjusting the micro-stepping resolution on the A4988 drivers

For this application, a quarter step was configured for all the motors. For the axes that have the lead screw mechanism such as the Z, X, and the extruder, the steps per millimeter are the same. Since the threaded rod in this case was fabricated in imperial units, it is important to calculate accurately to avoid misalignments. It is know that the stepper motor NEMA 17HS3401 rotates 1.8 degrees per step. By having a micro-stepping of a quarter step, each pulse on the A4988 driver will only rotate the shaft 0.45 degrees. To calculate the total steps per rotation it is necessary to divide the degrees in a full rotation by the degrees per step as in equation (17):

$$\frac{360[deg]}{0.45[\frac{deg}{step}]} = 800[\frac{steps}{rev}] \tag{17}$$

the pitch on the 5/16" -18 threaded rod is 1/18", meaning that each rotation will move the axis that exact amount. To know how much the shaft has rotated to move 1 millimeter, the conversion between millimeters and inches must be done as in equation

(18):

$$\frac{1[rev]}{1/18[in]} \cdot \frac{1[in]}{25.4[mm]} = 0.70866[\frac{rev}{mm}] \tag{18}$$

Next, to calculate the steps per millimeter, the result from equation (18) is multiplied with the result from equation (17) as seen in equation (19):

$$0.70866[\frac{rev}{mm}] \cdot 800[\frac{steps}{rev}] = 566.93[\frac{steps}{mm}] \tag{19}$$

For the rotary axis, as seen in equation (20) the quarter step and the reduction of 1:6 will result in each step rotating the bed by:

$$\frac{1.8[\frac{deg}{step}]}{4 \cdot 6} = 0.075[\frac{deg}{step}] \tag{20}$$

3.   Electrical design

3.1.   Power supply unit

To design a suitable power supply unit, it is important to know how much voltage and current the whole system will need. The different main electronic components and their electrical characteristics can be seen in Table 6.

Element	Quantity	Voltage	Current	Current subtotal
Nema 17HS3401	4	9	0.8	3.2
Arduino Mega	1	9	0.073	0.073
RAMPS 1.4 Shield	1	9	0.05	0.05
24 mm fan Brushless	1	12	0.06	0.06
Total current				3.383

Table 6. Total current draw estimate

The total current draw estimate of the 3D printer does not exceed 5 amperes. This means that a small power supply can be designed in order to minimize cost and space. To add flexibility, a variable voltage power supply was designed to fine adjust the output voltage requirements. For this, an adjustable linear voltage regulator LM317 was selected. However, due to current limitations on the LM317 of 1.5 amperes maximum [10], an additional element must be added to the circuit to increase the current draw capability. In this case, the transistor TIP41C can handle up to 6 amperes of DC

voltage [11]. For the power source, an AC to AC transformer capable of supplying 5 amperes at 12V was selected. The main part of the power supply circuit can be seen in Figure 9.
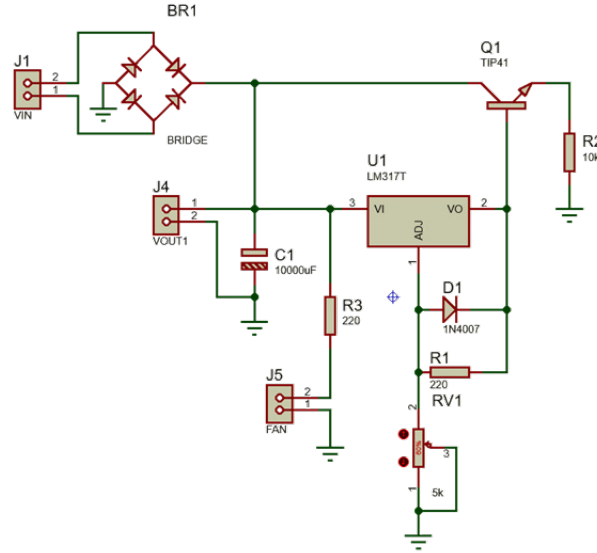
Figure 9. Adjustable LM317 voltage regulator with high current transistor

The transistor does not affect the voltage reference for the LM317, so the same equations for finding the required resistors can be used. To set the voltage regulator to 9V, the following equation can be applied:

$$V_o = V_{ref} \cdot (1 + R_{v1}/R_1) + (I_{adj} \cdot R_{v1}) \tag{21}$$

In equation (21), the current i_{adj} can be ignored as it is negligible. This means that the voltage reference can be calculated as a voltage divider as in equation (22). Additionally, the voltaje between R_1 and de Adj pin is always 1.25V which is adjusted automatically by the IC, making the voltage V_{ref} 1.25V too.

$$V_o = 1.25[V] \cdot (1 + R_{v1}/220) = 9[V] \tag{22}$$

$$R_{v1} = 1364[\Omega]$$

The variable resistor R_{v1} needs to be adjusted to have approximately $1.3k\Omega$. To prevent any danger of overvoltage to the microcontroller, an additional safety feature is included to cut via a relay the power if the voltage exceeds 12V as seen in Figure 10.
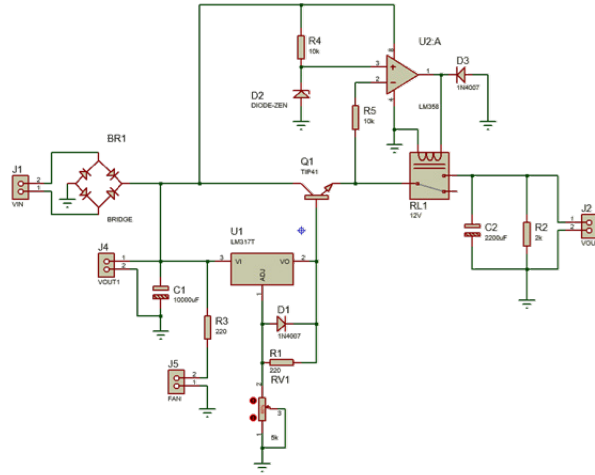
Figure 10. Power supply unit circuit diagram

3.2. Electrodeposition circuit

To control the current for a good quality electrodeposition, the current must be kept under $35mA/cm^2$ [12]. To be able to achieve this, a constant current source must be designed. An operational amplifier and a transistor can be a good option for low power constant current sources. The area in which the localized electrodeposition will take place can be calculated based on the nozzle diameter of 2mm:

$$Area = (0.2/2[cm])^2 \cdot \pi = 0.0314[cm^2] \tag{23}$$

To get the desired current for this configuration, the result obtained in equation (23) is multiplied with $35mA/cm^2$ like equation (24);

$$0.0314[cm^2] \cdot 35[mA/cm^2] = 1.099[mA] \tag{24}$$

The circuit seen in Figure 11 can be tuned to provide a maximum of 1mA to a variable load in order to control the electrodeposition quality. The current in this circuit is tuned by the equation (25). It is important to mention that less current will not affect the quality of the end result, just the speed at which copper deposits.

$$\frac{V_{ref}}{R_3} = \frac{5[V]}{5[k\Omega]} = 1[mA] \tag{25}$$
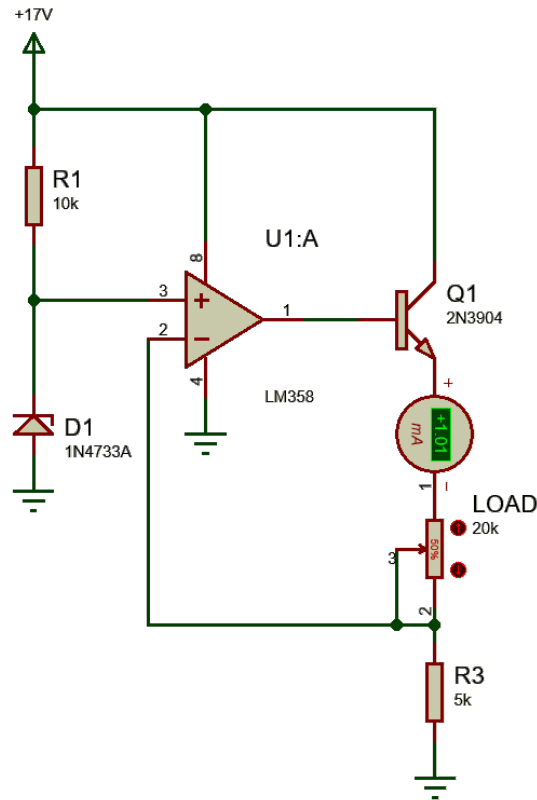
Figure 11. Constant current source circuit tuned to 1mA

Based on the data from Figure 2, a circuit capable of both controlling the current and generating pulses at the same time will increase the product quality. In order to produce a stable 100Hz square pulses, an integrated circuit NE555 was used. In order to produce such a frequency, the equations for an Astable operation in of the NE555 can be seen in equation (26) [13]:

$$T_h = 0.693 \cdot (R_1 + R_2) \cdot C_1 \tag{26}$$

If the desired frequency is set to 100 Hz, with an 80% duty cycle, the high time T_h has to be $\frac{1}{100[Hz]} \cdot 0.8 = 0.008[s]$. Assuming a capacitor C_1 0f $1\mu F$ and a resistor R_1 of $10k\Omega$, the resistor R_2 can be solved for in equation (27):

$$R_2 = \frac{T_h}{C_1 \cdot 0.693} - R_1 = \frac{0.008[s]}{0.693 \cdot 1[\mu F]} - 10000[\Omega] = 1544.01[\Omega] \tag{27}$$

The resistor R_2 yields to be approximately $1.5k\Omega$. The circuit in Figure 12 illustrates the complete electrodeposition circuit.
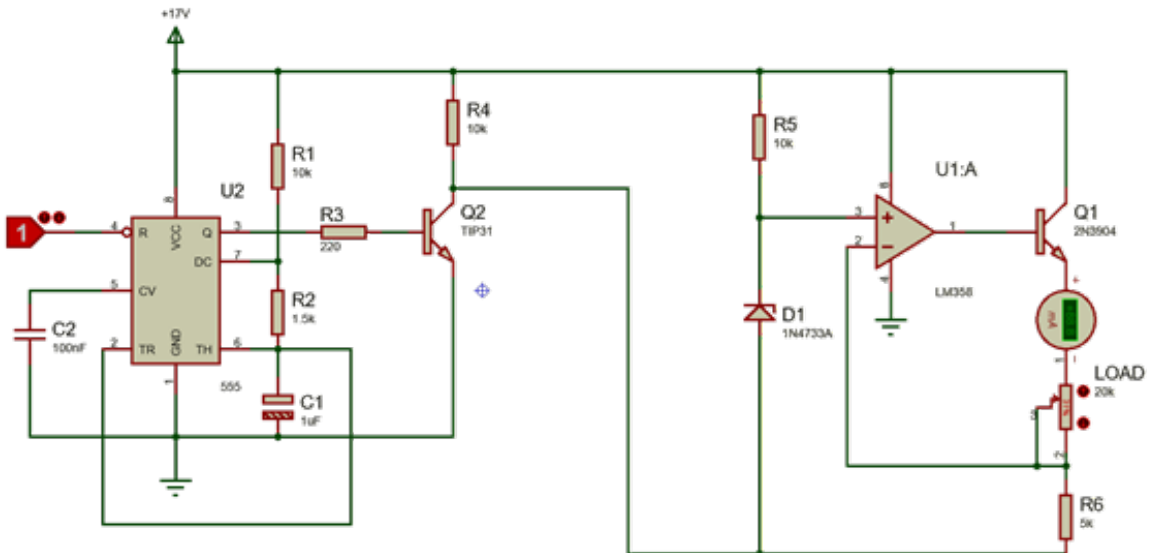
Figure 12. Electrodeposition current control circuit with pulse modulation at 100Hz at 80% duty cycle

The circuit in Figure 12 has a supply voltage of 17V, which is the rectified 12V AC from the transformer.

4.   Artificial Intelligence Component

A challenge with this technology is determining how much each layer grows over time. Due to some of the chemical aspects of this process being outside the scope of this paper and field, determining the layer height in this setup can be done empirically. To have a better estimation, a common practice is to use a machine learning algorithm for classification.

The data gathered mas measured using a caliper with a resolution of 0.1 mm. In total, 31 tests were made, each running from 0 minutes to 60 minutes in intervals of 2 minutes. The scattered points of data from Table 7 can be seen on Figure 13.

Minutes	Thickness	Minutes	Thickness
0	0	32	1.7
2	0	34	1.3
4	0.2	36	2.2
6	0.1	38	2.3
8	0.5	40	2.3
10	0.2	42	1.9
12	0.5	44	2.3
14	0.8	46	1.8
16	0.6	48	2.3
18	0.7	50	2.3
20	1.1	52	2.3
22	0.9	54	2.4
24	1.5	56	2.7
26	1.8	58	2.5
28	1.6	60	3.1
30	1.3		

Table 7. Data points gathered from performing measuring tests
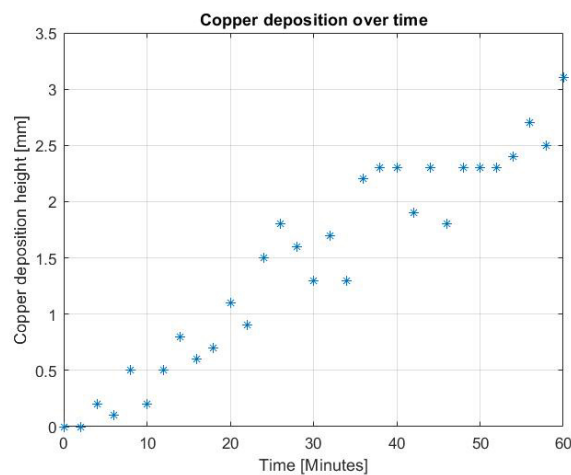
Figure 13. Tests for copper growth performed in increments of 2 minutes (stationary)

As seen in Figure 13, the points seem to have a positive correlation. With a positive correlation, the points can be adjusted to a line with Linear Regression [14]. In order to calculate the correlation matrix and facilitate the calculations, the software MATLAB can calculate automatically the correlation matrix with the command $corrcoef(x, y)$. In this case, the variable x is the time in minutes, while the variable y is the copper thickness. The correlation matrix is shown in Table 8:

	Minutes	Thickness
Minutes	1	0.9606
Thickness	0.9606	1

Table 8. Correlation matrix between time in minutes and copper deposition thickness

The correlation between the copper deposition thickness and time is 0.9606, which indicate a highly linear correlation. To adjust the data to a line, it is useful to perform the Least Squares method of regression. The equations for finding the regression line can be seen in equations (28) and (29) [15].

$$a_1 = \frac{n \sum x_i y_i - \sum x_i \sum y_i}{n \sum x_i^2 - (\sum x_i)^2} \tag{28}$$

$$a_0 = \overline{y} - a_1 \overline{x} \tag{29}$$

By again using the MATLAB software, the calculations for the coefficients a_1 and a_0 can be found to be:

```
X=Minutes;
Y=Thickness;
n=length(X)

n = 31

a1=(n.*sum(X.*Y)-sum(X)*sum(Y))/(n.*sum(X.^2)-(sum(X)).^2)

a1 = 0.0481

a0=mean(Y)-a1.*mean(X)

a0 = 0.0155
```

Figure 14. Coefficients for regression by least squares with the gathered data

As seen in Figure 14, the coefficients $a_0 = 0.0155$ and $a_1 = 0.0481$ can be used to form a line equation. However, since the coefficient a_0 is the intersection with the Y axis, in this application it must be 0. This is because the first point of the data will always be (0,0), as there will be no copper deposited if time has not started. So, the line equation (30) can be seen in Figure 15:

$$Y = a_0 + a_1 \cdot X = 0.0481 \cdot X \tag{30}$$
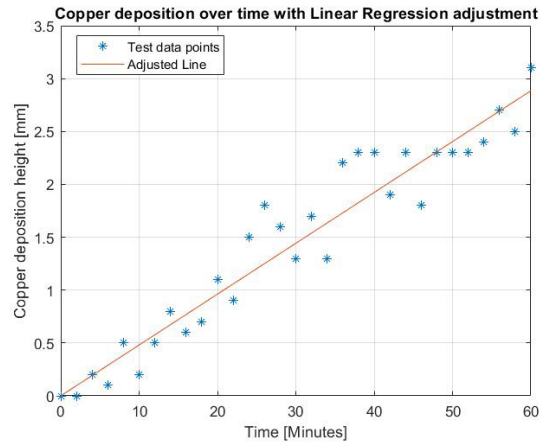
Figure 15. Line adjustment of the data with linear regression

The same coefficient $a_1 = 0.0481$ can be rounded to 0.05mm, which will be the layer thickness deposited per minute.

5. Manufacturing

For most of the custom designed pieces, 3D printing was the chosen method. This is because 3D printing offers a fast and reliable way to rapidly prototype pieces with complex geometry in a low cost manner. For this application, the polymer used was polylactic acid or PLA. This polymer has the added advantage of being reasonably stiff while providing an easy way of printing [16]. The mechanical properties can be seen in Table 9.

Properties	Unit	PLA
ρ	g/cm^3	1.21-1.25
σ	MPa	21-60
E	GPa	0.35-3.5
ϵ	%	2.5-6
σ^*	Nm/g	16.8-48.0
E^*	kNm/g	0.28-2.80
T_g	℃	45-60
T_m	℃	150-162

Table 9. Mechanical properties for PLA

6. Expense table

The following table includes an overview if the expenses that were made during the process of designing and manufacturing the project. Note that expenses such as manual

labour, electricity and miscellaneous components are not included.

Element	Quantity	Price/u	Shipping	Total
Aluminum Profile 2020 1m	1	9.5	3	12.5
Threaded rod 5/16" -18 1m	1	4	0	4
Nut 5/16" -18	6	0.2	0	1.2
M3*15 bolt	100	0.05	0	5
M3*15 nut	100	0.05	0	5
PLA 1Kg	1	20	3	23
TPU 1Kg	1	22	3	25
GT2 timing belt 1m	1	3.25	3	6.25
35ODx15ID Bearing	1	2.5	0	2.5
Syringe 20mL	2	0.2	0	0.4
Flexible Tube PU 1m	1	2	0	2
Three-way valve	3	0.25	0	0.75
Extension Spring	2	0.5	0	1
Copper wire AWG12 1m	1	2	0	2
Subtotal				90.6

Table 10. Mechanical components overview expenses

Element	Quantity	Price/u	Shipping	Total
NEMA 17 HS3430	4	4	3	19
RAMPS 1.4 Shield	1	11	2.5	13.5
Arduino Mega	1	25	0	25
A4988 Driver	4	3	3	15
Blank PCB A4	1	5	0	5
Switch KCD1-101	1	0.75	0	0.75
LED NTE3019	1	0.25	0	0.25
TIP41C	1	1	0	1
Relay 12V	1	1.5	0	1.5
Resistors	6	0.15	0	0.9
LM317	1	1	0	1
Terminals 2 Pin	4	0.2	0	0.8
1N4007 Diodes	2	0.2	0	0.4
Zener Diode 12V	1	0.25	0	0.25
OPAMP LM358	1	0.75	0	0.75
Capacitors	2	0.25	0	0.5
Bridge rectifier	1	0.75	0	0.75
Transformer 12V AC-AC	1	6.5	0	6.5
Connector JST	4	2.5	0	10
24mm fan brushless	1	3.5	0	3.5
Power supply cable 1m	1	2.5	0	2.5
Subtotal				108.85

Table 11. Electrical components overview expense

In total, the expenses for this project were less than 200$. The aim for this project was to make an affordable yet serviceable metal 3D printer.

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