**GNG5140 - Engineering Design**

**Prototype and Test Phase of 3D Electroplating Printer**



Submitted by

[3D Electroprinter]

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**Abstract**

The prototype and testing phase of this has been an extremely arduous process for the electroprinting team, but there have been several advancements in how the design has been handled. Firstly, some new design features have been identified, and previous high risk problems have been reduced to low risk due to new discoveries in the software that Ender 3 provides. There have also been massive leaps in the design of the electroplating system that governs nearly half of this project, with quantitative data in regards to the stability of the potentiostat, the resistor polarization curve, as well as some basic electrolysis testing that has been completed. The 3D printer has been assembled and is ready to be modified now that lab space has been found. The next coming week the team has an action plan to get back on track with the testing and integration of the system prototype so that by design day there is a minimum viable product to show.

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**List of Acronyms**

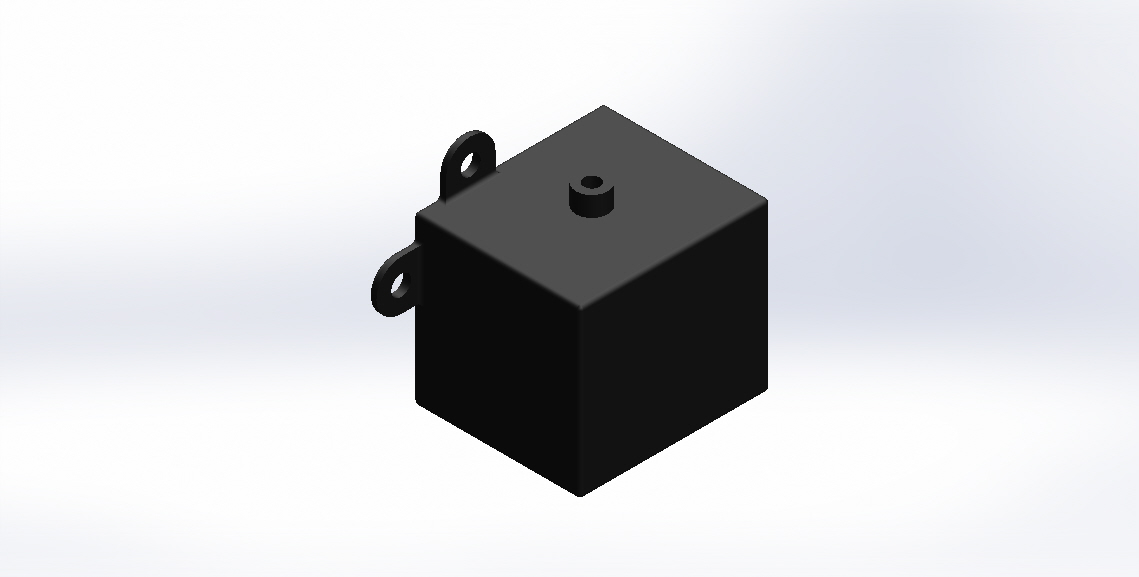
| **Acronym** | **Definition** |
| --- | --- |
| FDM | Fused Deposition Modeling |
| HBT | Hydrogen Bubble Templating |
| SLA | Stereolithography |
| PLA | Polylactic Acid |
| UI | User Interface |
| MOBO | Motherboard |
| DAC | Digital to Analog Convertor |
| CVC | Current to Voltage Convertor |
|  |  |
|  |  |
|  |  |
|  |  |

# Introduction

The prototyping and testing phase of our project has been moving along slowly, and we have hit quite a few roadblocks when moving through this phase. The team has finally procured a location to test, with help from Dr. Bruce, as well as Justine, who gave us access to the lab. Our goal for this phase was to have a prototype to test, a stretch goal to be the integrated prototype to start system testing in the subsequent phase. Due to a lack of labspace in the first week of this phase the full prototype and testing have not been completed. That being said, there have been several advances in the background that happened while waiting on this lab space. First, a few oversights that were discovered have been slowly worked on. These include a working connection mechanism for the anode onto the hot-end, the discovery that the 3D printer could work without any filament, and the file type for the prints has been decided. These three advances will be discussed further in section two, but overall these were small parts of the design process that weren’t foreseen until the actual prototyping phase, which is to be expected at times. The testing of the movement system, as well as the testing of the potentiostat system are also underway, as some of them have been partially completed, with new parts on their way as of the writing of this report. Lastly, the integration of the systems has been started, but this was rather simple as the two will undoubtedly not share a UI due to complications with the ender 3 software itself, and the lack of a software engineer on the team. Further risks will be discussed in the future work section found below.

# Global Solution and System Concept

Our design hinges on two major systems, the movement system and the electroplating system. This electroplating system primarily relies on the potentiostat, whereas the movement system is contained in a purchased commercial 3D Printer (Ender 3). As of now there is a design to hold the electrode to the print head, shown below.



The part itself will be 3D printed due to the low cost of production, easy access to a 3D printer and the low cost of the PLA used to print. This attachment point may weaken over time, especially in the presence of volatile chemicals such as electroplating solution. Ideally this part would be replaced with a corrosion resistant alloy such as chromium, nickel, or rhodium stainless steels which are common and relatively cheap alloys that have good corrosion resistance [1-3]. The manufacturing of these alloys is generally normal manufacturing, such as milling, but there have been quite a few advances in additive manufacturing in metals such as wire arc forming done on a corrosion resistant alloy such as C276 in the Qiu et al. paper “Microstructure and Mechanical Properties of Wire Arc Additively Manufactured Hastelloy C276 Alloy [4]. These advances would be best done in a later iteration of this project, but the resources have been added for future groups to use as branching points for design ideas.

Currently the prototype is in a more lab research phase than a commercial product. The prototype requires the user to have a very high level understanding of how to utilize a 3D printer already, because the prototype uses the STL and Gcode that is normally utilized by the printer. As of now the only way to get the printer to move is through this Gcode, which can be modified from the slicer itself, or through post processing. The only issue is that the printer would still believe that it is printing with PLA. One way around this is to leave the hot end on the printer, but attach an anode directly to the hot end itself. This anode could be at a comparable distance compared to the hot end to ensure it never touches the build plate, and would also make zero’ing the axis the same as if it was a normal print. This does not come without its own downsides though, while the hot end does not need to be turned on, it is a component that could cause confusion for new users as in the slicer there will be several settings relating to the temperature, nozzle diameter, etc. This would require an extensive user manual and oversight from monitors to set up a way for the new user to become trained on the machine. This is not a terrible solution, but future projects may want to elect to add a software engineer or similar background to the team to make a custom UI that would be more appropriately loaded onto the Ender 3’s MOBO.

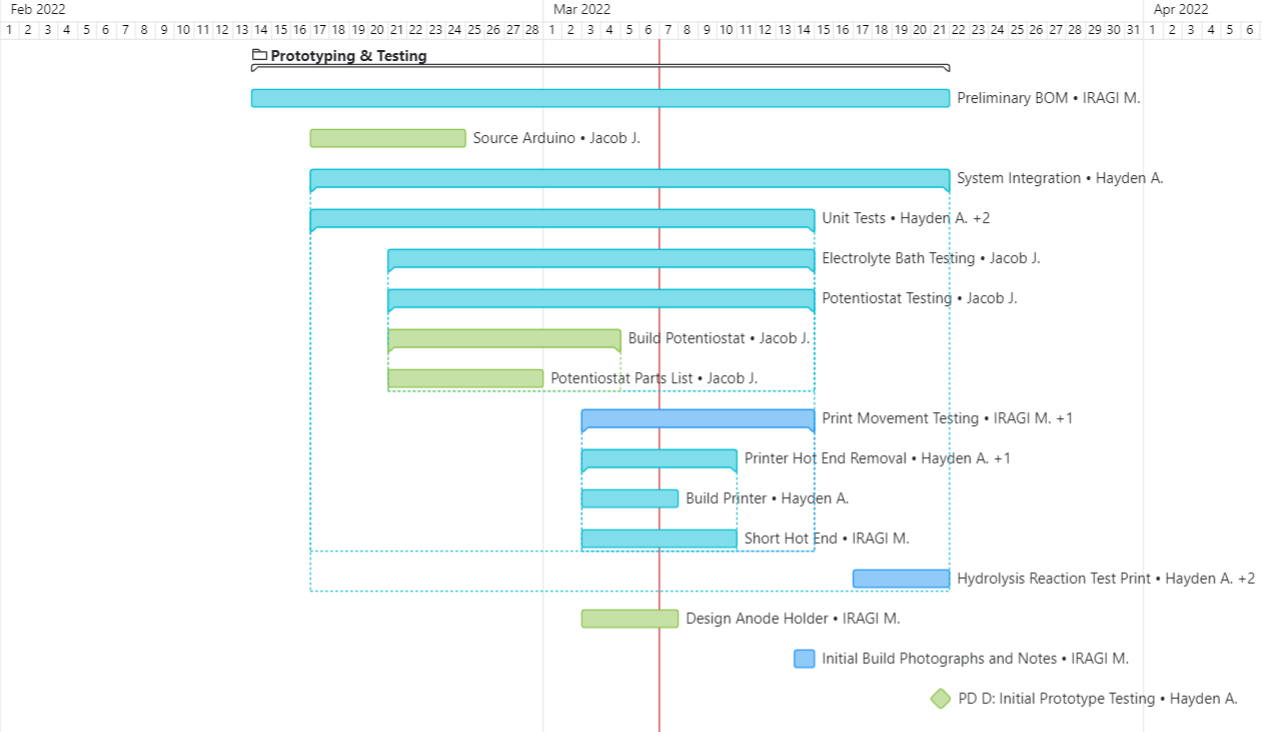


Figure 1: Gantt Chart

During the week our project deliverables have been pushed back due to a lack of testing space. This means that our project deadlines have been crunched down to a week of unit testing until March 14th, with Thursday through Sunday of that week performing the unit tests. With system integration and final testing needing to be completed by March 21st with enough time before design day to ensure the elimination of any bugs.

Lastly, the bill of materials that this project has used has also been kept up to date, with several new purchases since our last report. Most importantly would be all of the parts for the potentiostat that Jacob has created, which will be discussed in further sections. As of now, the final price for this prototype comes to $414.01 after taxes and shipping with the latest lead time being a full week. We are currently $85.99 under budget which is fortunate given that there are replacement parts that will need to be ordered from the potentiostat, as well as a few loose ends such as an electroplating bath that have not been shown here. We do not expect any reason to request an extension of the budget at this time, and foresee staying under budget.

| **Item #** | **Name** | **System** | **Price** | **Shipping** | **Tax** | **Lead Time** | **Received?** |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **1** | Creality Ender 3D Printer | Movement | $ 329.99 |  |  | 1 week | Y |
| **2** | Arduino Uno R3 | potentiostat | $31.48 | $ 8.00 | $ 4.74 | 3 days | Y |
| **3** | op amp TLV4110IP | potentiostat | $3.85 |  |  | 3 days | Y |
| **4** | op-amp MCP6022-E/P | potentiostat | $2.51 |  |  | 3 days | Y |
| **5** | Cables w/alligator clips | potentiostat | $3.44 |  |  | 3 days | Y |
| **6** | 2 uF capacitor | potentiostat | $2.73 |  |  | 3 days | Y |
| **7** | breadboard | potentiostat | $7.33 |  |  | 3 days | Y |
| **8** | 1Ω resistor | potentiostat | $0.15 |  |  | 3 days | Y |
| **9** | 10kΩ resistor | potentiostat | $0.14 |  |  | 3 days | Y |
| **10** | 1kΩ resistor | potentiostat | $0.14 |  |  | 3 days | Y |
| **11** | 9kΩ resistor | potentiostat | $0.14 |  |  | 3 days | Y |
| **12** | 20Ω resistor for testing | potentiostat | $0.14 |  |  | 3 days | Y |
| **13** | jumper cables x10 | potentiostat | $4.13 |  |  | 3 days | Y |
| **14** | jumper cables x30 | potentiostat | $3.44 | $ 8.00 | $ 3.66 | 3 days | Y |

Table 1: BOM of Current Prototype

# 3D Printer Prototyping

Due to a lack of physical prototyping space over the reading week there was very little advance when it came to the construction and testing of the 3D printer. One of the major advances was the acquisition of the makerspace lab space which allowed us to start building the 3D Printer and testing its capabilities.

## Building the printer.

We followed the building procedures provided by Ender in the box. The base of the printer came pre-assembled.

### Frame assembly

This consists of 2 long vertical aluminum extrusions that we assembled to the base (on left and right sides of the base) using 2 bolts each side. These provide the Z axis rail of the 3D printer.

Power supply: this was attached on the back-right frame of the printer with 2 bolts. After this, we attached the controller on the bottom-right side of the printer, in front of the vertical rail, using two small bolts.

### Axis Assembly

On the left frame, we fixed the Z axis switch, this limits the travel distance of the gantry while making Z movement. Two T-nuts were used for this purpose. Then in the back of the vertical frame we installed the Z motor. The X-axis is the horizontal aluminum extrusion that runs across the vertical frame. We started by installing the X axis motor on the left side of the extrusion, followed by the mounting of the extruder. This has rollers that slide in the extrusions of the horizontal frame. After installing the dual motor and the extruder, we installed the mounting bracket on the rear-right side of the X axis beam, then later, we installed the belt tensioner Infront of the mounting bracket using T-nuts.

### Belt assembly

After mounting all the parts on the X axis beam, we installed the belt that wrapped around the pulleys located at each end of the beam. Both ends of the belt were connected to the extruder.

While mounting the belt, we experienced some problems, the belt we received with the printer was of incorrect length as shown in Figure 2. This pushed us to go through some adjustments to get it in place. This belt cannot work for a long period, it needs to be replaced in the future.



Figure 2: Timing Belt Malfunction

After assembling all parts including the belt on the X axis beam, we positioned it facing front and letting the mounting bracket to slide into the extrusions of the right vertical frame while on the left side the lead screw of the Z motor being threaded into the gold bracket behind the X axis motor. Then we screwed the remaining horizontal beam on top of the two vertical frames to complete the process. Wiring was done after completing the building process. All cables were connected to the designed point as indicated on the connectors.

# Electroplating Prototyping

This project aims to implement a potentiostat based on the open-source Arduino-powered design presented in Gabriel M. Meloni’s 2016 paper.[5] Several modifications were made to account for the team’s limitations and requirements. Firstly the summing amplifier was entirely removed- it serves to scale the Arduino’s 0-5V voltage range to another range, but preliminary research suggested the 0-5 default voltage range was what the plating cell would be required to operate at anyway and thus the summing amplifier was unnecessary. Also at the time the team lacked the ability to supply a negative voltage such as was necessary for powering the transimpedance amplifier, and thus a simpler type of current-to-voltage converter (CVC) had to be used: A resistor connects the cell output to ground. By Ohm’s Law the voltage across this resistor will be proportional to the current through it. A 1-ohm resistor was used to minimize the additional resistance added to the system (since this resistor is in series with the electroplating cell it limits current through it which may not be desirable). This small resistance will create a small voltage across it, usually well below 0.5 V. The analog input to the Arduino has only a 10-but (1024 value) resolution so precision is lost if the input only occupies a small end of that range. To mitigate this the op-amp buffering the CVC output was converted to a non-inverting amplifier using a 9k and 1k ohm resistor to multiply the output voltage 10-fold. This gives the potentiostat a current measurement resolution of 0.49 milliamps. Lastly the reference electrode was removed; it added unnecessary complexity that was not necessary for simple electrodeposition or electrolysis. The electrochemical cell’s Op-amp was wired as a standard buffer amplifier.

Aside from altering the circuit topology, some components had to be resized. Preliminary exploration of the electronic system was done using Paul Falstad’s circuit simulation java applet (<https://www.falstad.com/circuit/>) and a major conclusion from that was that the 470 nanofarad capacitor Meloni used was grossly insufficient for precise digital to analog conversion of the Arduino’s PWM (pulse-width modulation) signal: even with the higher frequency 980 Hz signal provided by pins 5 and 6 of the Arduino Uno the real voltage would vary over 6% above or below the nominal output. Increasing the capacitance to 2 microfarads (about the limit of what could be found on Digikey at reasonable price and physical size) reduced this to less than 2%. The LM324 operational amplifier used by Meloni needed to be replaced; since we could not supply voltage below zero volts (ground) to the op-amp’s negative power supply, it was necessary to use amplifiers capable of “rail-to-rail” operation (meaning the possible output range includes the entire voltage span from negative to positive supply). For amplifiers other than that directly powering the cell the MCP6022 was found suitable. Since the potentiostat was expected to drive electroplating at currents substantially above the 30 mA maximum of the MCP6022, an amplifier capable of higher current was needed. The TLV4110, capable of 300 mA while still capable of rail-to-rail operation with a 5V supply span, was found suitable. Figure 3 depicts the circuit diagram of the finalized potentiostat design

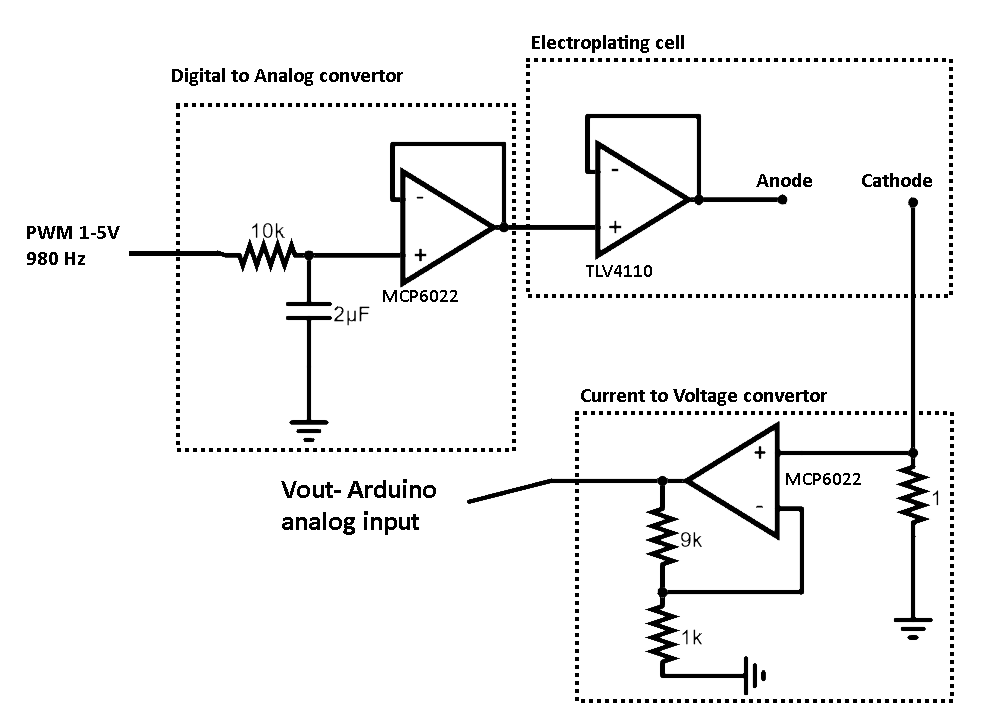


Figure 3:schematic of finalized potentiostat design (details of op-amp power supply omitted for simplicity)

Unfortunately after initial assembly it was discovered that the TLV4110 was defective and would not output any voltage. Replacement was ordered but would not arrive in time for testing. As an emergency fix it was removed from the design and the output of the ADC’s buffer amplifier was directly connected to the cell’s negative electrode. This limited the cell to the MCP6022’s maximum output current of 30 mA rather than the intended 300. Though this will not be able to achieve the current densities needed for hydrogen bubble templating it at least renders the potentiostat functional enough for basic performance testing to be done. Figure 4 depicts a diagram of this emergency revision as well as a photograph of the assembled potentiostat. Wires with alligator clips serve as ‘extension cords’ that will allow the potentiostat to connect to electrodes inside the printer in a future integrated prototype, as well as allowing resistors to be attached as testing loads.

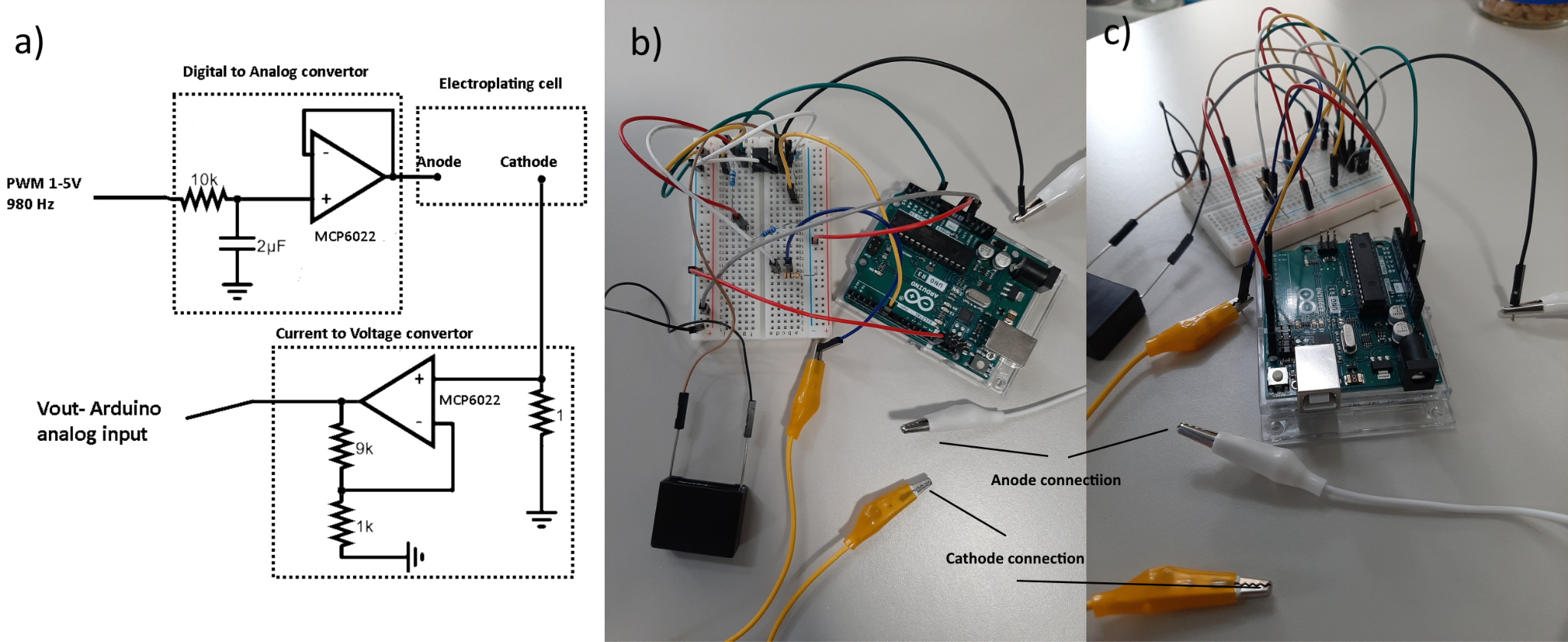


Figure 4: left (a): schematic of potentiostat as it was actually built. Right: top b) and side c) view of the constructed potentiostat (arduino power supply omitted for simplicity)

Work on implementing an actual electroplating basin is still only in the conceptual stage. However, immersing the ends of the alligator clips in a solution of sodium bicarbonate and setting the potentiostat to supply several volts did prompt the generation of bubbles and allow several milliamps of current to flow, showing that the potentiostat is capable of driving an electrochemical reaction.

The fundamental purpose of the potentiostat is to keep the current flowing through the cell at a target level. This is complicated by the fact that in the absence of mass transfer limitations the current through an electrochemical cell is an exponential function of applied potential so small adjustments to voltage can cause large change in current. Mathematically, the potentiostat must find the solution E to I(E) = T where I(E) is current as a function of voltage and T is some target current. The choice of algorithm used to solve this problem is not finalized, but the bisection method is currently the most likely candidate.

# Testing

The testing done has been primarily unit tests, with very little focus on integration of the systems together. As of right now the system acts as two different prototypes, but this may be something that is unavoidable in this iteration of the design. Due to a lack of software expertise, the creation of a unified UI will be unlikely to come to any fruition before design day, as this has been deemed outside the scope of this iteration.

## Movement Testing

The movement testing performed was very preliminary and does not reflect the movement testing that is coming in the next week. This is the basic qualification of the printer to run as intended, and does not include any modifications we will be making during the next week. We foresee that there will be another week of unit testing done on the printer before any meaningful data can be taken.

### Bed leveling

We started leveling the print bed, and we used a piece of paper for testing. We inserted the SD card in the controller, under option we selected the SD card then we ran the option Ender 3 bed leveling. The machine moved to the first leveling point. We passed a paper underneath the print head, then adjusted the thumbwheel of that point located under the bed. This was done until the paper could barely move. We positioned the print head at 5 points of the bed (4 points in the corners and 1 point in the center of the bed) . The process above was repeated at each point.

### First print

The printer needed to be verified as working as a 3D printer, and verify that all of the components were working as intended. The first prints can be seen in figure 5 below. As shown below there are two test prints given with the STL file, one is a test print to test adhesion and the other to test support. It became apparent that the adhesion test was actually too strong in some places, showing potential digging into the build plate that could cause issues with the movement commands. Due to the team working under the assumption that the 3D printer will “print” an STL file as normal but at an extremely reduced speed, it is necessary that the bed be extremely level because otherwise the chances of the counter-electrode being scraped across the surface become higher. This would be catastrophic and could hurt both the sample and be a potential safety concern should it break any of the equipment.

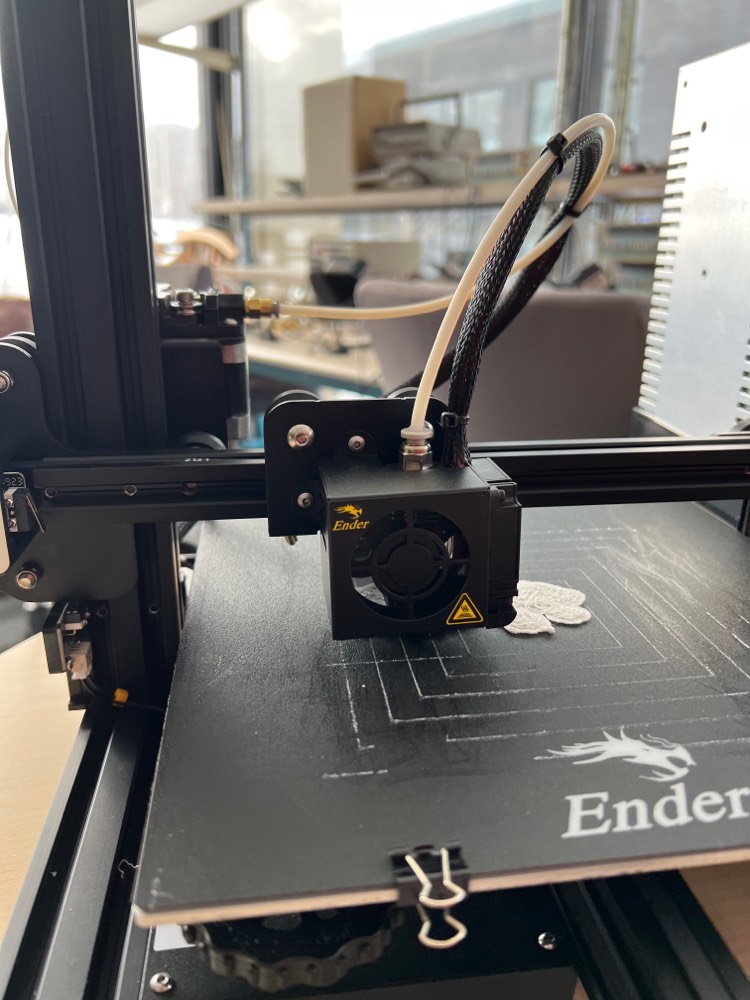
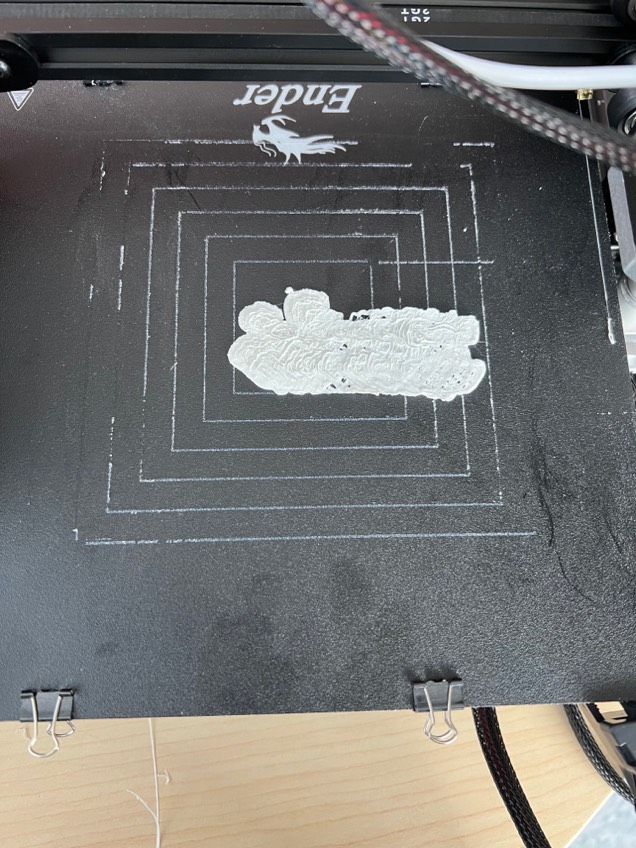


Figure 5: Top and Side View of a Sample Print given with the Ender 3

Due to these shortcomings of the first print, a few test prints, new PLA, and re-leveling the bed will take place before the movement tests can be performed. It was noted that there was a loud noise coming from the machine screw that controlled the z-axis movement which could explain the lack of z-axis precision in this case. During the build the machine screw was notably de-greased which could cause friction wear on the machine screw degrading it over time. White lithium machine screw grease has been procured at no cost to help alleviate this, and will be applied to test for any problems in the machine screw (a common malfunction other than the timing belt issue).

## Potentiostat Testing

The first unit tests on the potentiostat aim to confirm it can measure and generate current with reasonable accuracy. These tests were done with a 280 ohm resistor load connecting the two electrodes, meaning the total resistance to ground is 281 ohms when the current-voltage convertor is included. (original plans uses a 20 ohm resistor, but with the defective amplifier a higher resistance was used to allow sweeping across the potentiostat’s entire voltage range without hitting the current limit). The Arduino sketches used for these tests can be found in Appendix 1.

### Current stability investigation

The simplest test, the potentiostat was programmed to hold a static voltage for a few seconds while recording the flowing current twice a second. This was done at 1V (predicting 3.56 mA) and 4V (predicting 14.23 mA). This aims to evaluate how precisely the potentiostat can hold a current. Table 2 shows excerpts from the serial monitors of these tests.

| Output voltage | 4V | 1V |
| --- | --- | --- |
| Expected current | 14.23 | 3.56 |
| Serial printout | 16.13 mA, at 4.00 V  14.66 mA, at 4.00 V  14.66 mA, at 4.00 V  15.15 mA, at 4.00 V  14.66 mA, at 4.00 V  14.66 mA, at 4.00 V  14.66 mA, at 4.00 V  15.15 mA, at 4.00 V  14.66 mA, at 4.00 V  14.17 mA, at 4.00 V  14.66 mA, at 4.00 V  15.15 mA, at 4.00 V  15.15 mA, at 4.00 V  14.66 mA, at 4.00 V  15.15 mA, at 4.00 V  14.66 mA, at 4.00 V  14.66 mA, at 4.00 V  15.15 mA, at 4.00 V  14.66 mA, at 4.00 V | 3.42 mA, at 1.00 V  3.42 mA, at 1.00 V  3.42 mA, at 1.00 V  3.42 mA, at 1.00 V  3.42 mA, at 1.00 V  4.40 mA, at 1.00 V  3.91 mA, at 1.00 V  3.91 mA, at 1.00 V  3.91 mA, at 1.00 V  3.42 mA, at 1.00 V  3.91 mA, at 1.00 V  3.91 mA, at 1.00 V  3.91 mA, at 1.00 V  3.42 mA, at 1.00 V  3.42 mA, at 1.00 V  3.42 mA, at 1.00 V  4.40 mA, at 1.00 V  3.91 mA, at 1.00 V  3.42 mA, at 1.00 V |

Table 2 Constant potential testing results

At 4 Volts the measured current oscillates between 14.66 mA and 15.15 mA, both slightly above the predicted 14.23 mA. Occasionally it dips to 14.17 mA. Arduino documentation does suggest pins 5 and 6 can sometimes have higher than expected PWM duty cycles [6], which would cause higher than intended voltages. At 1 V the current mostly alternated between 3.91 mA (very close to the predicted value) and 3.42 mA, with occasional jumps to 4.40 mA. Again not entirely stable but not too bad. Given the potentiostat has a 0.49 mA current resolution, seeing the measured current never jump more than one such graduation above or below an average value is reasonable performance.

Using an external multimeter to measure the current across the test resistor with 4V potential yielded an oddly low value: only 13.57 mA. This is unnervingly low, and using the same multimeter to measure voltage across the resistor gave 3.99 V which should have corresponded to 14.21 mA. Most likely the multimeter is not functioning properly (it was quite cheap and old) but at least things seem to be on the correct order of magnitude.

### **Resistor polarization curve**

A more general test of the potentiostat’s accuracy, this was directly based on that done in Meloni’s paper: sweeping the voltage across a resistor and measuring the current at each voltage, to generate a polarization curve. This test used 0.1 V increments from 0 to 5 V. The code printed to the serial monitor the voltage and current separated by a semicolon, allowing this printout to be copy/pasted into a .txt file and opened in Excel as a semicolon-delimited document. Excel was used to create a graph and determine the line of best fit that has its intercept set to 0,0, shown in figure 6.

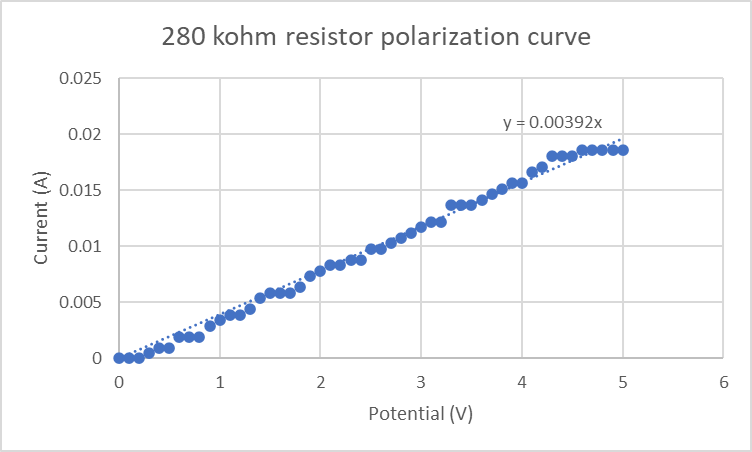


figure 6: Polarization curve of a 280 ohm resistor generated using the potentiostat

The graph’s frequent plateauing is an unfortunate symptom of the potentiostat’s low current resolution, since the CVC’s amplifier was designed with a 300 mA range instead of the 30 mA the defective main amplifier forced. For a resistor the polarization curve should be a straight line with slope equal to 1/R. Figure 6 is mostly linear, with the trendline’s slope being 0.00392 ohm-1, indicating a resistance of 255 ohms. This is 9% below the actual value. This inaccuracy is undesirable, but it is not a critical failure and can be compensated for, and the generally linear shape of the graph suggests the potentiostat has most of its expected functionality.

While the imprecise results of this test and the previous one seem to question the potentiostat’s applicability to high-precision electrochemical measurements like Meloni proposed, it seems to be generally functional and applicable to this project’s electroplating.

### Simple electrolysis testing

While the code to allow the potentiostat to find a target current is not yet implemented, a proof of concept that the system can hold steady current during an electrochemical reaction can be done. A saturated solution of baking soda was prepared in a glass, and the alligator clips meant to connect to the electrodes were dipped in it to tentatively serve as the electrodes. The same code as was used for the simple current stability testing was initially used, set for voltages of 2.5V and 3.0V. After the current revealed itself to be somewhat unstable it was modified to actively keep track of the time-average current. Table 3 shows excerpts from the resulting serial printouts.

| Voltage | 2.5V | 3V |
| --- | --- | --- |
| approximate average current | 3.7 mA | 14.9 mA |
| Serial printout excerpts | 3.91 mA, at 2.50 V  4.89 mA, at 2.50 V  3.42 mA, at 2.50 V  2.44 mA, at 2.50 V  3.91 mA, at 2.50 V  4.89 mA, at 2.50 V  3.42 mA, at 2.50 V  5.38 mA, at 2.50 V  3.42 mA, at 2.50 V  1.96 mA, at 2.50 V  3.91 mA, at 2.50 V  4.89 mA, at 2.50 V  3.91 mA, at 2.50 V  2.44 mA, at 2.50 V  3.42 mA, at 2.50 V  4.89 mA, at 2.50 V | 13.69 mA, at 3.00 V  14.66 mA, at 3.00 V  16.13 mA, at 3.00 V  15.15 mA, at 3.00 V  16.62 mA, at 3.00 V  14.66 mA, at 3.00 V  13.69 mA, at 3.00 V  15.64 mA, at 3.00 V  16.13 mA, at 3.00 V  13.69 mA, at 3.00 V  14.66 mA, at 3.00 V  16.13 mA, at 3.00 V  14.66 mA, at 3.00 V  16.62 mA, at 3.00 V  14.17 mA, at 3.00 V  14.17 mA, at 3.00 V |

Table 3: currents obtained from baking soda electrolysis

During both runs small bubbles could be observed forming at the electrodes, presumably hydrogen (at the cathode) and oxygen (at the anode) though equipment to try identifying the gasses was unavailable at the time. Figure 7 shows the electrodes with bubbles adhering to them. The current at 3 V is much higher than at 2.5 V, befitting of the expected exponential polarization curve. What is striking is how much noisier the signal is than when applying voltage across a resistor. The current varies in a range of almost 3 mA at 3.0 V and 3.5 at 2.5 V. Interesting is that while both signals are noisy, the higher voltage/current signal has a similar level of noise to the lower one This at least suggests this should not cause an escalating problem at higher currents, though it is still somewhat undesirable. Perhaps it is caused by bubbles briefly obstructing ion transfer to the electrode before breaking off. Thus far though the phenomenon is not severe enough to warrant investigation.

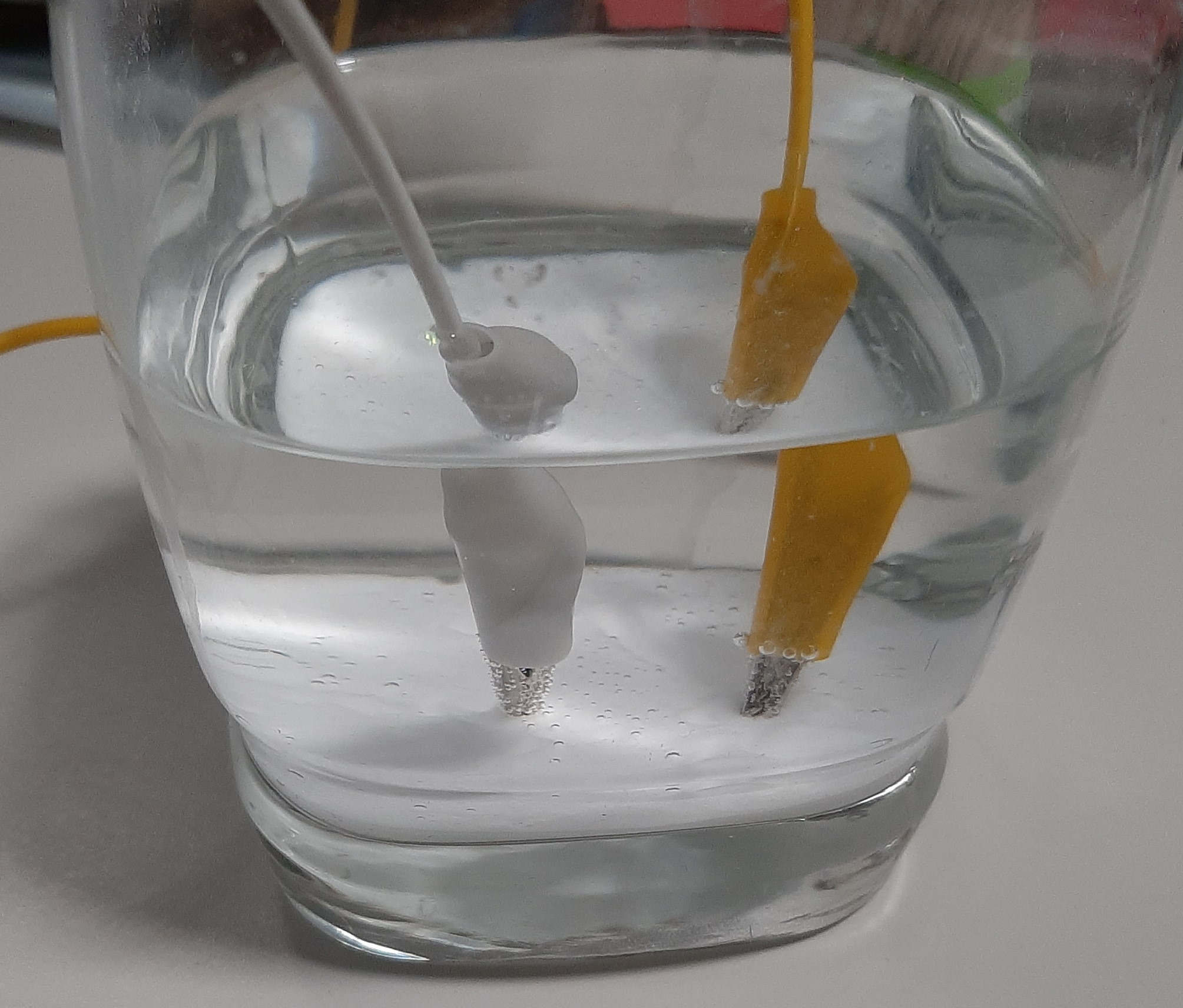


Figure 7: Simple Electrolysis Setup

# Conclusions and Recommendations for Future Work

As of now there is quite a bit of testing that needs to be done regarding the printer itself, as well as the building of an integrated prototype. These two things will be handled as according to the project plan that has been set out during our monday meeting. Which as shown outlines several tasks that have been moved up by about a week due to the lack of testing space. These tests are primarily the ones relating to the movement of the printer, as the potentiostat and electrolyte bath testing have already been started by the team. There are two tasks which are potentially redundant depending on the movement and integration testing we do, which are the hot end removal and shorting section, which may not be necessary. The team plans on meeting this thursday, March 10th with the client, as well as in the lab to start the print movement testing which has everything set up, with just the tests needing to be performed. Much of the data is qualitative currently, but more quantitative data will be coming in the following week. The project plan is to have all unit tests done by March 14th, with the system integration and final testing to be completed by March 21st such that the team is ready for any final design day requirements. Recommendations for future teams who may use this paper for advice is to always procure your testing space as immediately as possible, as this can take quite some time, especially during COVID-19. Even when there is lab space it is regularly restricted to certain days of the week, and as such knowing this ahead of time helps schedule team meetings around this lab space. It is strongly recommended to pursue this as soon as you know the requirements of the testing you will need to complete. This has been a valuable lesson for the team and we will move forward on a crunched timeline to ensure the project tasks get done.

# 

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# APPENDICES

## Arduino code

Current stability investigation

#define outputV 4.0

int output, value;

float outCurrent;

void setup() {

// put your setup code here, to run once:

Serial.begin(9600);

pinMode(6, OUTPUT);

}

void loop() {

output = (outputV/5)\*255;

analogWrite(6,output);

value = analogRead(A1);

outCurrent = 1000\*(value/1023.0)\*0.5; //writing the .0 forces it into float rather than integer division

Serial.print(outCurrent);

Serial.print(" mA, at ");

Serial.print(outputV);

Serial.println(" V");

//Serial.println(value); //for debugging

delay(500);

}

Resistor polarization curve

#define outputPin 6

float volts, outCurrent;

int output, input;

void setup() {

// put your setup code here, to run once:

Serial.begin(9600);

pinMode(outputPin, OUTPUT);

Serial.println("potential(V);current(A)");

}

void loop() {

// put your main code here, to run repeatedly:

for(volts = 0; volts <5; volts=volts+0.1)

{output = (volts/5)\*255;

analogWrite(outputPin,output);

delay(100);

input = analogRead(A1);

outCurrent =(input/1023.0)\*0.5; //writing the .0 forces it into float rather than integer division

Serial.print(volts);

Serial.print(";");

Serial.println(outCurrent,5); //print to 5 decimal places

}

Serial.println("end");

delay(10000); //gives time to stop and unplug

}

simple electrolysis

#define outputV 3.0

int output, value, n;

float outCurrent, averageI ;

void setup() {

// put your setup code here, to run once:

Serial.begin(9600);

pinMode(6, OUTPUT);

averageI = 0;

n = 1;

}

void loop() {

output = (outputV/5)\*255;

analogWrite(6,output);

value = analogRead(A1);

outCurrent = 1000\*(value/1023.0)\*0.5; //writing the .0 forces it into float rather than integer division

averageI = (averageI\*(n-1)+outCurrent)/n;

n++;

Serial.print(outCurrent);

Serial.print(" mA, at ");

Serial.print(outputV);

Serial.println(" V");

if(n%10==0)//only print the average every to measurements, less to edit

{Serial.print("moving average is ");

Serial.println(averageI);}

//Serial.println(value);

delay(500);

}