GNG5140 Report Template

Design Generation and Requirements of a 3D Electroplating Printer

Submitted by

[3D Electroprinter]

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Abstract

The focus of this stage is to start defining the design requirements and metrics that the team will be aiming to complete before moving on to the prototyping stage. We want to lay out a project plan that we will utilize moving through the project to ensure that the prototyping, testing, and design process move fluidly. The design requirements, basic prototype design plan and project statement have been prepared. The problem statement comes from our customer requirements, which have an extreme focus on HBT and antenna deposition. HBT requires an extremely precise and high energy system that is not feasible at a large scale, according to the work done previously by Dr. Bruce. Our solution intends to reduce the plating area by using commercial 3D printing technology mixed with electroplating technology to "print" plating compounds. The goal of this phase of the project is to create a printer that is able to move around an anode in an electrolyte bath while providing future improvements to the team that will continue this project. We have included several improvements and ideas for further design ideation for future iterations of the project.

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Acronym	Definition
FDM	Fused Deposition Modeling
HBT	Hydrogen Bubble Templating
SLM	Stereolithography

1 Introduction

In our previous report we spoke on the basic research and literature review conducted by the team on how 3D printing technology has been used in the space of electroplating to improve the process's speed, accuracy, or applications. While there are uses of 3D printing in the electroplating sphere, or printing being used outside of stereotypical materials, many of these applications did not seem to have much in common with our design other than the printing aspect [1] [2] [3]. This spurred the team to move into a different design process entirely, and it was decided that hands-on feasibility and prototyping would be necessary. Therefore, the team has already gone into the process of acquiring a commercial 3D printer to modify, which is on route now. The team has also been doing theoretical calculations to assist with the feasibility of the design, which has led to a design choice being made. Moving forward with a very simple prototype using an inert anode with no z-axis control of the anode other than the z-axis of the printer was chosen. This included no pumping of the solution or feedstock at all, with the only heating element being the resistive heater on the printer. This design is the intended outcome of this stage of prototyping, but not the future vision for the project we are setting out. Currently our goal is to make a 3D printer and electroplating system coexist and work together, such that future teams can work towards the same or similar goals. This will manifest in a 3D electroplating machine that can perform electroplating in a sodium bicarbonate bath as a first feasibility test. The exact tests of both our iteration and our visionary goal are outlined below. The goal of this printer would be to leave room to add functionality and iteration on future projects to reach the extended goals we set out further below.

2 Design Requirements

The following design requirements have been taken from the customer requirements below, these have been given relative priority and the priority of the system is based on both the functionality of the system as well as the customer's needs.

Label	Customer Requirement	Priority
C1	Nickel Plating Capability	5
C2	Precise Movements	5
C3	Hydrogen Bubble Templating (HBT)	5
C4	Easy to maintain	4
C5	Open Source	3
C6	Easy to make/maintain	3
C7	Environmentally Friendly	2
C8	Swappable Components	1

Table 1: Customer Requirements

Design Requirements	**Relation**	**System**	**Rating**
Utilize Existing 3D Printer	C2 C5 C4 C6	Movement	5
Accurate Current (2A/cm^2)	C1 C3	Plating	5
Contained solution	C6 C7	Pump	5
Precise plating current	C1 C3	Plating	4
Print Speed (X,Y)	C1 C2	Movement	4
Z- Precision	C1 C2	Movement	3
Thin anode and Feed stock precision	C1 C2 C3	Feeder	3
Bed temperature difference	C1 C3	Heating	3
Configurable voltage/current	C5 C8	Plating	2
Feed rate	C1 C4 C7 C8	Feeder	1
Pumping (Fluid out, clean solution, drain)	C4 C6	Pump	1
Bed temperature variance	C1 C3	heating	1

Table 2: Design Requirements

Associated with these design requirements are several metrics that must be achieved. The 3D printer model used must have stepper motors that can move the print head smoothly at speeds well below 1 mm/s. They must be able to deliver torque in the range from 20 to 60 newton-centimeters. The electroplating system must be able to achieve current densities of 2 A/cm^2 and hold them with minimal fluctuations in order for the HBT process to take place and create the desired hydrophilic nickel surface. It is estimated that the potentiostat must be able to deliver voltages of up to 5 Volts to reliably achieve this. Unfortunately, while it is known that raising the temperature of the electroplating bath will aid the speed of the plating process, the exact requisite operating temperature remains uncertain.

3 Design generation

Unfortunately, there are no true existing prototypes or products to use as starting points for designing a prototype for this project. While many papers have been published on HBT of nickel and other metals, and the surfaces that can be generated with them, they remain largely theoretical research with no commercial designs for devices meant to manufacture the sorts of porous metal structure HBT can generate. While the current 3D electroplating printer project is an outgrowth of earlier work done by ECRIT, as of yet they do not have a complete prototype themselves and as such this project is effectively a greenfield design. No other attempt at an electroplating 3D printer is known.

While the scientific papers published do not focus on the engineering of their processes, the way their electroplating system is constructed is worth analyzing to see what design elements are present, as this project aims to use the same fundamental process. The 2019 paper [5] that prompted this HBT project specified the distance between the working and counter electrodes as 5 mm. This will be a starting point for future prototyping, with other papers not listing their distance. Not all research work utilized parallel plate electrodes; a 2020 Thesis [6] used cylindrical rods for the reference and counter electrode while the working electrode was still a flat plate. So this project is fortunately not constrained to using parallel electrodes. The working electrode, or cathode, gets plated by the metal under investigation so its composition does not have a major impact though in most use cases starting with a plate of the same metal as the substrate is desirable.

The composition of the counter-electrode can vary. The 2019 paper used an inert material: platinum gauze. Other papers have also used platinum. This is appealing in its simplicity, but platinum is an expensive material. A much cheaper material for a relatively non-reactive electrode is graphite, but no paper found utilized it (though one paper [7] did use graphite as the counter-electrode while evaluating the generated Ni plating in water electrolysis) so it is uncertain how stable it will be in this electrochemical system. An alternative to an inert anode is an "active" anode made of nickel that dissolves during operation. This would prevent the concentration of nickel ions in the electroplating bath from dropping as the print proceeds. This has concerns associated with it due to meaning anode geometry changes during operations, however some papers [7][8] do use nickel counter electrodes. So, the electrode consumption is not automatically crippling, though with this project's aim to precisely control the plating area it may still be a small issue.

The reference electrode material is highly variable. Saturated Calomel (mercury chloride) [5], silver chloride [7][9], and mercury oxide [6]. None is obviously superior in the lab, but the health risks of mercury suggest silver chloride would be more suitable for the printer- if a reference electrode is used at all. Though most potentiostat designs call for one, some papers [8] have managed to perform effective research using only a two-electrode system lacking a reference electrode. Whether this project will use one remains uncertain.

Last is the composition of the electroplating solution. The 2019 paper [5] used 0.1 M $NiCl_2 * 2H_2O$, and 2 M NH_4Cl. Other papers have used slightly different compositions such as a higher $NiCl_2$ concentration of 0.2 M [6][7]. In the case of an inert anode, using the higher concentration is tempting as it increases how much can be plated with a given volume of solution. However, the exact impact of plating bath concentration is uncertain. The objective given to the project team was to create a device that could plate a chosen area with the porous Ni surfaces described in [5], and as such and given lack of time for very detailed testing the decision was made to use the same electrolyte concentration that paper used to minimize variables.

This moves into the actual design process which comes after the rigorous work to research past designs and build requirements. The design generation process itself is open-ended, with several designs being proposed by different team members. The first step that was taken was to come up with as many ideas, even if they were at a base level not feasible for our team. This design generation stage led to several designs which were not explicitly going to be used as the final design, but helped the team in identifying the systems, and subsystems of the design. This also helped to identify possible futureproofing that will need to be done for such a new prototype.

System	**'Cheap'**	**'Deluxe'**	**'Large'**	**'Precise'**
Movement	3D Printer (Ender)	Custom w/ stepper motor	Industrial 3D printer	3D printer (Prusa)
Plating	Passive/graphite	Passive/inert metal (Pt)	Ni cylinder	Ni wire
Feedstock	z-axis movement	Solution feed stock	Belt movement of anode	Geared wire feed
Pumping	none	3-cycle + shower	Constant circulation	Simple 1-cycle
Heating	resistive	Piping + insulation	Resistive + insulation	Insulated Tank

Table 3: Initial Design Generation

This stage of design identified 5 major subsystems that would be necessary in the final design, with three of the subsystems being identified as “out of scope” for this stage of the prototype. Those three systems being the feedstock system, the pumping system, and the heating system. The two systems that this design will focus on are the movement system and plating system.

3.1 System Breakdown

Each system can be broken up into its own subsystems, and special attention has been given to how the systems interact with one another, to reiterate, the only two systems of this project stage that will be fully planned out are movement and plating, with the other systems being left to future design projects.

3.1.1 Movement System

The movement system is broken down into two different subsystems which work closely together, one is the XY plane movement, and the other is the Z-axis movement. The X and Y movement are primarily dependent on stepper motors, as are the Z-axis movements. There were several design choices considered, which may have made these different. One is the addition of machine screws for the Z-axis movement which help stabilize the Z-axis and reduce jog. While these are extremely interesting for our use-case they both get in the way and cost much more than simpler designs offered by the Ender3 that was being considered. The focus of the movement system itself though should be to be extremely precise and accurate and not fast. This is because the plating process itself is extremely slow and does not require high print speeds (unlike those found in metal sintering, SLA or plastic-FDM).

3.1.2 Plating System

The two subcomponents of the plating system are (1) the electroplating bath and (2) the potentiostat. The electroplating bath is the basin that is filled with an aqueous solution of ammonium and nickel salts that will respectively provide the hydrogen and the nickel atoms for the nickel HBT procedure. A flat metal plate is to be positioned horizontally in the bath, which serves as the cathode on which nickel will be deposited. The counter-electrode or anode will likely be cylindrical or the needle, and be mounted on the 3D printer's print head, moved by it to determine where plating occurs. The design will most likely also include a "reference electrode" that will be kept at constant potential without current passing through it.

The potentiostat is the power source that will drive the electrolysis of the dissolved salts and the precipitation of nickel. What separates a potentiostat from a simple voltage source is its use of operational amplifiers to ensure the voltage across a load such as the electroplating system remains constant when the load changes, allowing the voltage or current (as desired) to be controlled with a great deal of precision. The potentiostat for this project aims to be a low cost open-source design based on that proposed by Meloni [4], adapted to operate at the high currents required of electroplating.

3.1.3 Feedstock System

While the feedstock system is not being explored in this project it is important to lay out the overall through process that was explored while making the initial prototype. The goal of the feedstock system would be two-folk, (1) to control the z-axis precision by a metric other than the printer's motors, and (2) to allow for the addition of an active feedstock to aid in deposition. This means that the printer would have a belt-fed or gear-fed feedstock (if solid) that would be fed into the solution either to be degraded as electrolyte, to control Z-axis precision, or both. Another way to utilize this would be to use a liquid solution or gel solution feedstock but this was quickly deemed outside the scope of this course.

3.1.4 Pump System

Pumping would be an extremely well utilized system in this design, as the focus of the pumping system was to take in clean electrolyte solution into the system and to rid old electrolyte solution. Ideas were explored where pre-heated or refreshed electrolyte solution could constantly be put into the system to maintain a constant electrolyte molarity and temperature. In addition to the idea of washing down the substrate after plating was explored. The primary goals of the pump system would be to move electrolyte through the system (clean in, old out), wash the substrate after plating, and to have a regenerating heater for the solution. This was quickly deemed out of scope due to a lack of experience and time to dedicate to an additional solution.

3.1.5 Heating System

While important, the heating system was also deemed outside of this course, but as discussed in the pumping section, the team did explore regenerative electrolyte solution heating, as well as utilizing the heating system to aid in the plating process. Currently the heating system will remain as the resistive heaters in the base Ender3 model, with additional insulation as necessary for the speed. The goal of the heating system would be to both speed up the speed of plating, as well as to assist the pumping system in keeping a regular and healthy flow of electrolyte solution into the plating process.

3.2 Final Design Decision Matrix

Given the design requirements laid out previously, and the system breakdown, the following final design matrix could be created and utilized to determine the most appropriate course of action for the prototyping phase.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	Cost	Weight
D1 Hot Feedstock	0	+	-	-	0	0	+	0	0	+	0	0	-	-8
D2 Passive Feedstock	0	+	0	+	0	0	+	0	0	+	0	0	-	10
D3 Active Pumping	0	+	-	+	0	0	+	0	0	+	++	0	--	-5
D4 Passive from below	_	+	0	+	+	+	0	-	0	0	0	+	-	6
D5 Simple Feedstock	0	+	-	-	0	0	+	0	0	+	+	0	-	-7
D6 Simple Graphite	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CHEAP	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Weights	5	5	5	4	4	3	3	3	2	1	1	1	3	

Table 4: Design Decision Matrix with “Cheap” as a baseline

The cheap design was laid out previously, with the other designs being laid out in the group meeting. D1, D2, D3, and D5 all utilized an Ender3 style printer, with the major differences being in feedstock, existence of pumping or not, and the type of feedstock.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	Cost	Weight
D1 Hot Feedstock	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D2 Passive Feedstock	0	+	+	+	0	0	0	0	0	+	0	0	+	18
D3 Active Pumping	0	+	0	+	0	0	-	+	0	0	++	+	0	12
D4 Passive from below	_	+	+++	+	+	+	0	-	0	0	0	+	0	14
D5 Simple Feedstock	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D6 Simple Graphite	-	+	+	-	+	0	0	0	0	0	0	0	-	2
Weights	5	5	5	4	4	3	3	3	2	1	1	1	3	

Table 5: Design Decision Matrix with "D1 Feedstock" as a baseline

D1 intended to hot work a wire to keep it straight, utilizing the cannibalized hot end of the printer, with no pumping of the solution. D2 utilized a passive feeder to control Z-depth. D3 utilized an active anode, like D1 but cold-worked instead. D4 utilized a set level z-axis to help with precision with a larger bath to avoid pumping. These differences were what led to these plus and minus in the chart, which could be seen as "better or worse" than the baseline chosen.

4 Testing

There are two types of testing that need to be done on the system, unit tests and system tests. The unit testing can be described as subsystem testing, which will see to testing the movement and plating systems, whereas system testing will try and navigate how each of these subsystems interact. Any tests regarding feedstock, plating, or pumping have been left out due to scope creep.

4.1 Unit Testing

The following test plans have been drawn up as preliminary unit tests for the different subsystems of our design.

4.1.1 Print Precision

One of the more crucial parts of this design because the minimum speed is extremely important for the plating process. The print precision will determine whether the speed will be slow enough to print at a desirable rate. Electroplating requires slow movement because the plating process is slow. The step motors of the printer will have a minimum degree turn on the movement, which will associate to a minimum X & Y speed. This X and Y speed can be measured using a camera setup with checkered background to denote distance. A Logitech camera can be set up facing the printer against this checkered background, and the printer will then shift at its lowest possible speed, this distance will be measured over time and a minimum speed can be found. This speed will relate to the lowest possible rotation angle of the device, and thus give a realistic expectation of the XY precision of the device.

4.1.2 Z-axis Precision

Similarly, to print precision, a test can be set up that has the step motors go down a singular step. The Z precision requires two different values to be known. One would be the job (how much the printer will be over-corrected), and the other would be the actual distance traveled. The test for print precision will still apply here, but instead of just a constant speed, the printer will also be stepped down to get a measurable jog of the device. The overall precision of the X-axis will also depend on the inclusion or exclusion of a feedstock. For this project it is assumed that the feedstock system may be outside scope, and as such the Z-axis precision will need to compensate for a lack of a feedstock subsystem.

4.1.3 Potentiostat testing

The first step to verifying the functionality of the potentiostat is to perform the same validation test Meloni used in their paper [4]. The potentiostat should be used to measure the current versus voltage curve of a resistor of known specifications. The resulting curve should be linear with a slope of 1 over the resistance. Generating such a slope accurately demonstrates the potentiostat is providing voltage and measuring current appropriately. The next test will be to perform a basic electrochemical operation such as electrolysis of water at relatively high current (>0.5 amps) over a longer time period (exact length to be determined as circumstances allow) to prove the device can supply the requisite power for this project across an extended period of time.

4.2 System Testing

These unit tests can now be combined to form system tests that will help describe the action and precision of the system together. These are preliminary system tests, and as the prototyping process continues, more will be added.

4.2.1 Contact Angle

As the aim of this project is to produce a plating with the hydrophilic characteristics that make a suitable electrode for water electrolysis, the confirmation of presence or absence of this property in critical. As in the paper the material was originally described [4], this is done via Contact Angle measurement. To do this, the plate should be positioned at the edge of a flat surface, and a syringe or pipette should be used to place a single drop of water (in the range of a few hundred microliters or less) on the plate's surface. A camera should view the surface from a completely horizontal angle so that the drop can be clearly captured in profile. The photography area should be backlit with diffuse white light to aid the picture's clarity. From the picture, the angle the edges of the drop make with the plated surface can be measured (either manually or via image recognition software)

4.2.2 Electroplating functionality:

Multiple tests must be performed on the electroplating system at different levels of integration. Firstly, after the potentiostat and associated wiring is mounted on the printer, it should be run with a relatively innocuous solution filling the electroplating bath such as a solution of sodium bicarbonate (baking soda). The print head should move around during this. This electrolysis is to confirm that the potentiostat can deliver power to the bath effectively in this configuration and it neither impedes nor is impeded by the mechanical functions of the 3D printer. Next, the bath will be filled with the intended electroplating solution (0.1 M NiCl2 * 2 H2O and 2 M NH4Cl), however the print head will not be moved. This will confirm that nickel is getting plated and will inform the team how wide the plating area under the anode is as well as what range of voltages it requires. This test will be performed with the anode at different heights above the cathode to determine how that parameter impacts the plating and what the optimal height would be. Finally, once the height is chosen, the plating will be performed with the print head moving as per expected final design as a final test of functionality. The quality of the resultant plating will be evaluated by methods described in the other sections.

4.2.3 Plating Quality

There are several plating quality tests that we need to make, specifically cross section test, hardness test, and adhesion test. These tests are running under the assumption that some electroplating will occur for this project. As stated previously, this may be outside the scope of this prototype, and as such these are being included in the report as future proofing for future work that may be done on this project.

The cross-section test will be utilized only if electroplating can occur. The process is taking a recently electroplated part from the bath, washing it with a solvent that will wash away the electrolyte solution but not the recently plated surface (such as isopropyl alcohol), then utilizing a band saw these substrates can be cut by their width to reveal the plating layer. From this the substrate can be put under a microscope and inspected for cracks, corrosion artifacts, or delamination. Due to not having access to an SEM or TEM machine, the thickness of the plating can only be determined relatively, and as such will be considered outside the scope. The current prototype will simply be looking at the quality of the coating from a visual point of view. The minimum “n” for this trial should be n =3, so that a relatively useful sample size can be gathered, to avoid any error.

For hardness testing, the substrate and coating should be flushed with a solvent to clean the electrolyte solution off. Afterwards, three separate samples can be prepared for a Rockwell hardness C test. These will be conducted according to International Standard ASTM B578-21 which outlines microhardness for electroplated parts.

An adhesion test can be conducted using a standard pull test on the coating layer. This can be done by welding or soldering a plug to the coating layer and conducting a pull test. The strength of the weld is crucial to this, and due to a lack of experience this may also be considered outside the scope of this prototype. This has been included simply as future proofing for future designs which intend to electroplate.

5 Conclusions and Recommendations for Future Work

The biggest thing that can be taken from this is to ensure that scope creep does not cloud future judgment. When it comes to working on a newer greenfield-like project, it can become very easy to bite off more than a team can handle. One of the issues confirming the design requirements for this project is the fact that many of the deliverables and prototypes the team can promise are relatively qualitative; “Does it print?”, “Do the systems talk to each other”, etc. This is because we are working on the very first stage, and as such we’ve included a plethora of notes for future teams to work from when it comes to the heating, pumping and feedstock systems. We hope that this work inspires future teams to think further than we could and enable them to have a solid ground in the future. As of now, our certainty in delivering a project ends at getting an Ender3 3D Printer to successfully speak to an electroplating system, and to have the two of them work synchronously to electroplate over an area.

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APPENDICES

1. APPENDIX I: Rough design example.

This is an example of a rough design created as part of the team's design generation. This design was ranked well in terms of fulfilling design objectives but was considered impractical due to requiring Z movement controlled from below, which our ordered 3D printer model did not provide.