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Low Profile Home Speaker: Evaluation of Production Methods for Reduction of Eddy Currents and Increased Production Efficiency of Magnetic Stator Assemblies

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Evaluation of Production Methods for Reduction of Eddy Currents and Increased Production Efficiency of Magnetic Stator Assemblies

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Abstract

This Major Qualifying Project aims to improve upon previous efforts to develop a low-profile planar home speaker system. This subproject focuses on evaluating methods to produce a moving magnet transducer with reduced eddy-currents and improved production efficiency. The team developed procedures to analyze two commercial methods and one in-house method of production of a low eddy-current-loss stator assembly. The group also redesigned, fabricated, and improved a filament extruder and devised an experimental process to improve the system.

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Executive Summary

Previous Major Qualifying Projects have attempted to create a low-profile home speaker capable of producing low frequencies. These past projects had successes in creating their low-profile speaker. However, they have had to deal with certain downfalls. The transducers within the speaker were made of singular pieces of metal instead of the standard laminated core designs found in modern speakers. This was done to save space in the design, however without the laminations, the speakers were prone to heating due to eddy currents.

The team worked to investigate whether 3D printing could be used to create a stator assembly that would be less affected by the eddy currents produced by the speaker. 3D printing is an interesting field and provided the team with a way to produce complicated parts easily and quickly. By using additive manufacturing techniques, we hoped to lower the heating induced in the stator assembly.

To do this we used resources from another previous project. Our first and primary objective was to produce ferromagnetic 3D printable filament in order to create parts needed inside the low-profile speaker. In order to do this, we used a filament extruder, known as a Filastruder, to begin combining PLA and metals such as iron and neodymium. We successfully created a filament combination of 85% PLA and 15% iron filings. Our attempts with neodymium were not as successful as our PLA/iron hybrid.

The iron and PLA material was magnetic but was brittle and its diameter was inconsistent. Our attempts to use it in 3D printers only caused clogs in the printers available to us. After our failures at producing usable filament, we attempted to use commercial products available to us. We were able to find a ferromagnetic filament known as Protopasta and a soft magnetic powder known as Somaloy.

We were able to successfully print a magnetic stator assembly using the Protopasta filament. This success shows that it is possible to produce the parts for the speaker using 3D printing.

We attempted to press the soft magnetic powder on multiple occasions. We needed to create our own press molds in WPI’s Washburn Shops. The presses available to us on campus were unable to provide the heat and pressure output necessary for the material to be shaped correctly. Because of this, we needed to design our own press, and purchase heating elements to be used. Due to the quarantine our design was not able to be tested.

Due to our in-house filament’s issues, the team redesigned and created our own filament extruder. We recycled some of the old Filastruder given to us at the start of the project, using it’s motor, shaft and other pieces to design a linear, yet modular filament extruder, which we dubbed the ‘Modular Filament Extruder’. The modular aspect of the redesigned extruder permitted far more variability during the extrusion process and therefore enabled us to test different variables to help develop the highest quality filament.

With the modular filament extruder design completed, the plan then shifted to achieve the goal of consistent filament. To do so, we devised a design of experiments procedure using the modular capabilities of the filament extruder to test six different factors that were identified as potential influencers of the extruded filament's consistency. The six factors suspected of having influence were: nozzle type, motor speed, temperature set point, temperature profile, nozzle/screw distance, and iron to PLA ratio. Per DOE procedures, each factor had predetermined levels to be tested and the response of which was to be measured and recorded. Due to the coronavirus outbreak, the experiment was not able to be carried out, but we created procedures for the experimental process and a means for data collection. The end objective of the design of experiments, when conducted, will be to identify the optimal settings on the modular filament extruder to produce the most consistent iron/PLA combination filament.

Our second objective was to test and prove whether ferromagnetic 3D printed parts did reduce eddy currents. To do this, we designed an Arduino based test bench that will automatically stress test these 3D printed parts. The Arduino would generate a range of sine waves at different frequencies to see how the material would react. In order to create eddy currents, a test coil was created to induce a magnetic field in the material. Two amplifiers of different classes and output power were compared to see the performance of the material under different conditions. One amplifier heated the material too slowly, whilst the more powerful amplifier seemed to have created a heater out of the coil which saw more heating from I^2R, creating inconclusive results. However, promising results may have been realized through power consumption. The 3D printed filament drew less power when being excited by the weaker amplifier versus pure steel. This opens an avenue for greater research in the production of eddy currents in the material, as lower power means a weaker field and overall less eddy currents.

The recent novel coronavirus outbreak caused an abrupt ending to project proceedings. To cope with the situation the team outlined specific recommendations for the future of this project. The recommendations, outlined below, address various aspects of the project like the modular filament extruder, the extruding process, and the testing procedures.

- **We recommend the Design of Experiments be carried out.** Even after the successful print of the iron/PLA combination filament, the filament remains inconsistent and brittle in nature. The DOE will lead to optimal settings which, hopefully, when used in combination with the extruding procedures will produce consistent filament robust enough to print in all 3D printers.
- **We recommend the modular filament extruder prototype be expanded on.** In its current state, the modular extruder is primarily constructed from 3D printed parts. So to improve design, these parts should be machined using the preexisting 3D models. Similarly, the extruder wiring needs to be enclosed with a housing. The team was not able to design a housing for the unit due to time constraints and the pandemic, but the extruder would benefit from the design of a housing.

- **We recommend that the filament extruder be coupled with another device to improve the quality of the filament after being extruded.** When the project was passed onto us, the Filastruder and its Filawinder were passed along as well. The Filastruder served as the basis of the modular filament extruder, but the Filawinder proved virtually useless. The Filawinder, had it been functioning, would have helped create more consistent filament while also spooling it. As a recommendation, the group suggests that the winder is fixed. Alternatively, a practice with growing popularity is coupling a filament extruder directly with a 3D printer.
- **We recommend that a lower gauge wire be used in the eddy current tests.** Testing was tainted in some instances due to heating of the test sample of filament. At temperatures of 60-65C the filament enters into its glass transition zone, which means the material begins to deform. Decreasing the gauge of the wire coiled around the test sample will effectively decrease the resistance per unit length of wire. This could help to determine what factors may cause the system to heat as quickly as it did, whether the source was eddy currents or I^2R.
- **We recommend that the arduino code be debugged.** The Arduino Due's DAC output seemed to struggle creating frequencies above 1kHz, though this can possibly be rectified by changing the clock speed of the processor. Thermocouple accuracy was another error that was encountered as false values would be read by the Arduino, possibly due to electrical interference. These errors could be resolved by creating a more efficient code as well as adding an external ADC to acquire more precise readings from the thermocouple.

As a result of our work on this project, we are confident that 3D printing with magnetic filament is an inexpensive, easily accessible and effective alternative to traditional laminated designs for the production of speaker transducers. With further experimentation and research, we believe that both commercial and homemade magnetic filament can be used within speaker assemblies to reduce heating as a result of eddy current production.

Chapter 1: Introduction

Speakers have been around for the past century and have been evolving since their conception. Just as speaker technology has grown and advanced, so too has the global speaker market. In fact, the global speaker market size is expected to increase by $42.67 billion during the period 2018-2023 (Technavio Research, 2019). The first loudspeakers were developed in the late 1800s and have since inspired headsets, earbuds, Bluetooth speakers, and many more advancements. A disparity in the speaker market has been a discrete speaker capable of producing low frequencies (Technavio Research, 2019). A Major Qualifying Project (MQP) was created to fill this gap in 2016-2017. Since that initial project began, teams have continuously taken on the project to further refine subgroups of the low profile home speaker system. One subsystem being the moving magnet transducer (MMT) within the speaker. The MMT teams of the past were focused on reducing the profile of these transducers within the speaker system to help achieve the overall speaker's desired dimensions. This past project successfully reduced the size of the MMT, but inefficiencies still remained.

Another project, focused on 3D printing with magnetic filament, served as another predecessor to our project. This project worked to combine nylon and neodymium to create consistent 3D printing filament. Stemming from their successful procedures, our team identified this manufacturing method as an opportunity to address the inefficiencies in speaker transducers. As a result, our team decided to further refine the moving magnet transducers of the low profile speaker by coupling theories of these past projects. Our project will be focusing on improving efficiency and simplifying manufacturing.

The low profile speakers used in previous projects had the tendency to begin heating. This is because of ohmic losses due to the circulation of eddy currents. Eddy currents are currents induced in electrically conductive bodies due to varying magnetic fields, according to Faraday's Law. Because of the small size of the planar speaker, it is particularly susceptible to the heating this generates. We hoped that by using 3D printed magnetic material, the induction within the magnetic stator assembly (MSA) in the moving magnet transducer (MMT) would be lessened and therefore the heating would be countered.

We began working on the project with the clear goal of reducing eddy currents in the stator assembly of the moving magnet transducer. We started work on producing our own magnetic filament that could be used to print the stator assembly. Following several issues with our filament extruder, we began to evaluate different commercial products that may also achieve the same goal. We designed our own way to test and compare these materials by creating eddy currents through magnetic induction. Simultaneously, we redesigned and fabricated our own filament extruder to make the best possible filament to achieve the primary goal of the project.

Chapter 2: Background

2.1 Eddy currents

When an electrically conductive body (whether magnetic or nonmagnetic) is subjected to a time varying magnetic field, this field induces an electromotive force (EMF) in the conductor according to Faraday's law of magnetic induction. This induced voltage will produce a current within the electrically conductive body, called Eddy Currents, which can be beneficial or detrimental depending on the application. In the case of an moving magnet transducer (MMT), this formation of eddy currents is destructive as the conductive properties of the stator will create a closed-loop, increasing the energy and temperature of the stator. This leads to a loss of efficiency and can cause deformation due to heating. A coil of wire excited by an alternating current will produce an alternating magnetic field within the iron. This coil is wound around the stator of the MMT, inducing the magnetic field in this conductive body which consequently induces current within the stator. Current flowing through a conductor increases the heat of a system through ohmic losses which is not ideal for a low-profile system such as this. This was specifically a problem in the previous iteration of the low-profile system as the body of the stator was constructed from a single block of steel. This large conductor body created a lot of eddy currents which heated the MMT in an undesirable time period.

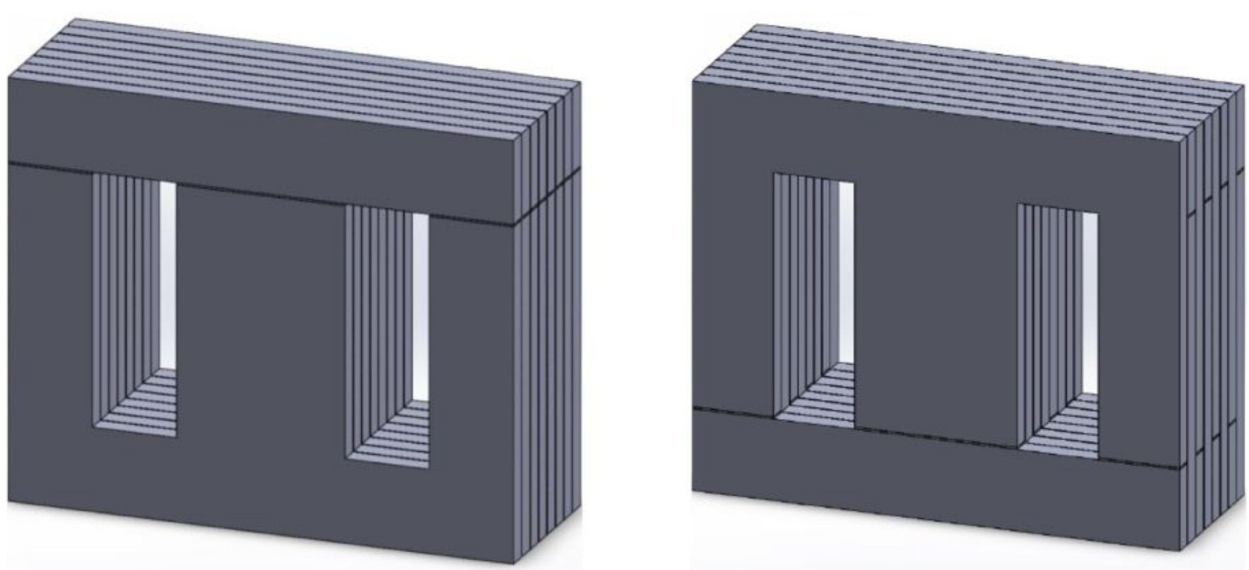

Figure 1: Laminated Core Example

Ways that eddy currents have been reduced in modern times is with the use of laminated cores. Laminated cores essentially "slice" the body of a stator into thin sheets which are then insulated from each and are placed parallel to the flux which, effectively, reduces the amount of eddy currents circulating within this system, see Figure 1. This method of eddy current reduction has been used in the industrial construction of electromagnetic machines for decades and is the most common method of eddy current reduction.

2.2 Transducers

The most common transducer is a moving coil or voice coil transducer shown in Figure 2.

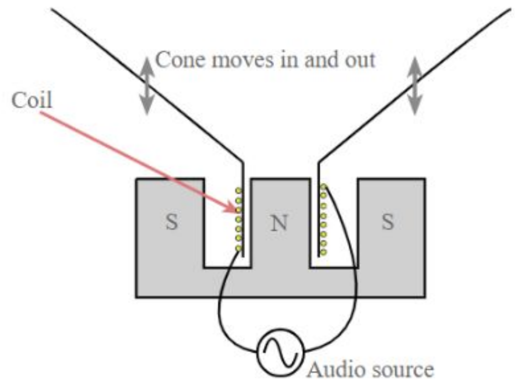

Figure 2: Voice Coil Transducer

This form of transducer consists of a strong magnet that surrounds the coils, and when a current is passed through the coil which is in a magnetic field, a force is generated. This force is perpendicular to both the force and the magnetic field which causes the coil to move up and down and thus causes the cone to move in and out, creating sound.

2.2.1 Moving Magnet Transducers (MMTs)

A Moving Magnet Transducer, shown in Figure 3 and 4, consists of coils mounted to the body of the transducer and a permanent magnet mounted to a diaphragm. This magnet mounted to the diaphragm is the component of the transducer that vibrates to drive the cone, making sound instead of the coil vibrating. The magnetic field flowing across the permanent magnet, which is called magnetic flux, exerts a force on the existing magnetic field. The strength of the force causes physical displacement, or excursion, of the magnet, which translates as the amplitude of the speaker’s vibration. The excursion of the magnet induces the diaphragm attached to the magnet to vibrate at the same frequency as the magnet. The frequency of both the magnet and diaphragm varies with the given input signal. The motion of the diaphragm then translates to the surrounding air both in front and behind, matching the frequency. This, in turn, is what creates sounds of various pitches. Due to the mass of the magnet, these transducers are tuned for lower (bass) frequencies.

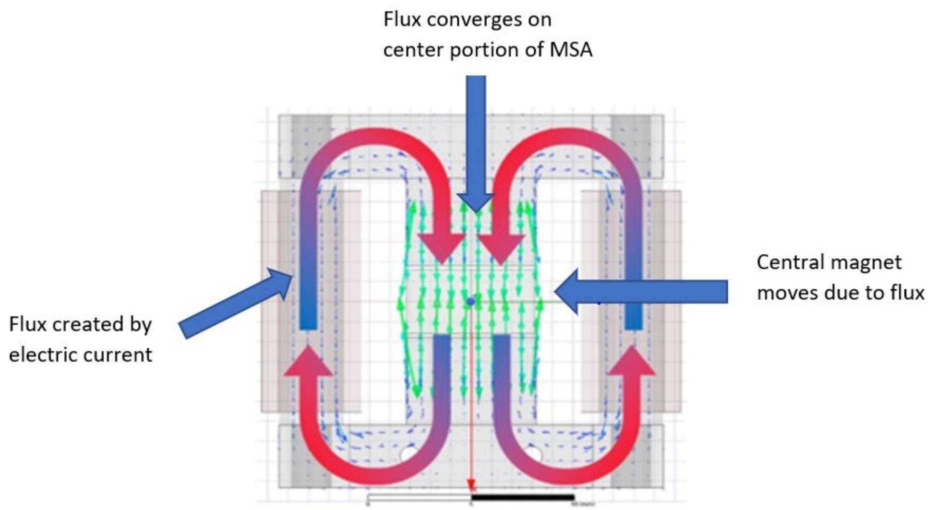

Figure 3: Moving Magnet Transducer Flux Illustrated

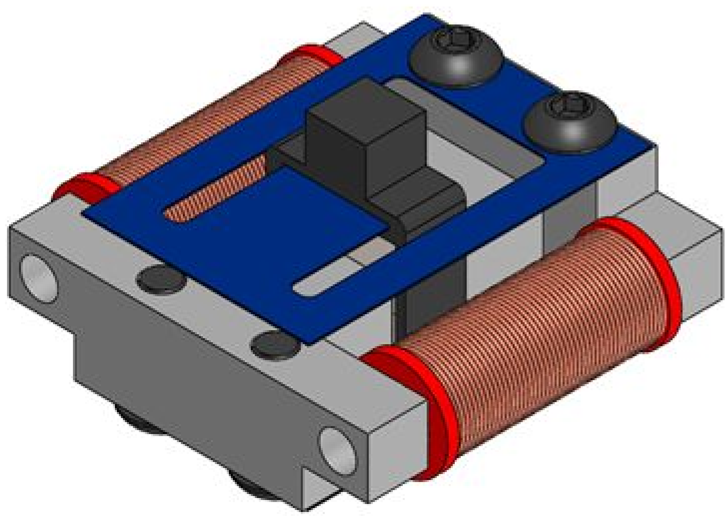

Figure 4: Final Assembly of MSA used in Low-Profile Home Speaker Project

2.3 3D printing

3D printing is a rapidly growing industry that provides interesting opportunities for experimentation. 3D printing technology has advanced into filaments composed of various combinations of materials. Filaments can be created from a combination of metals, wood, and plastics among others. These advancements led the team to believe that by using 3D printed pieces made from ferromagnetic filament, we would be able to produce the complex parts needed in a MMT as well as reduce the subsequent heating due to eddy currents.

The term 3D printing refers to the action of fabricating a physical object from a three dimensional digital model through the process of additive manufacturing. 3D printing typically consists of "printing" many thin layers of a material in succession. The 3D printer collects data from a digital file which is derived from the three dimensional digital model. This data describes the printing path to add the filament layer by layer. The printing process itself consists of an extruder, which is part of a larger component used to print as shown in Figure 5.

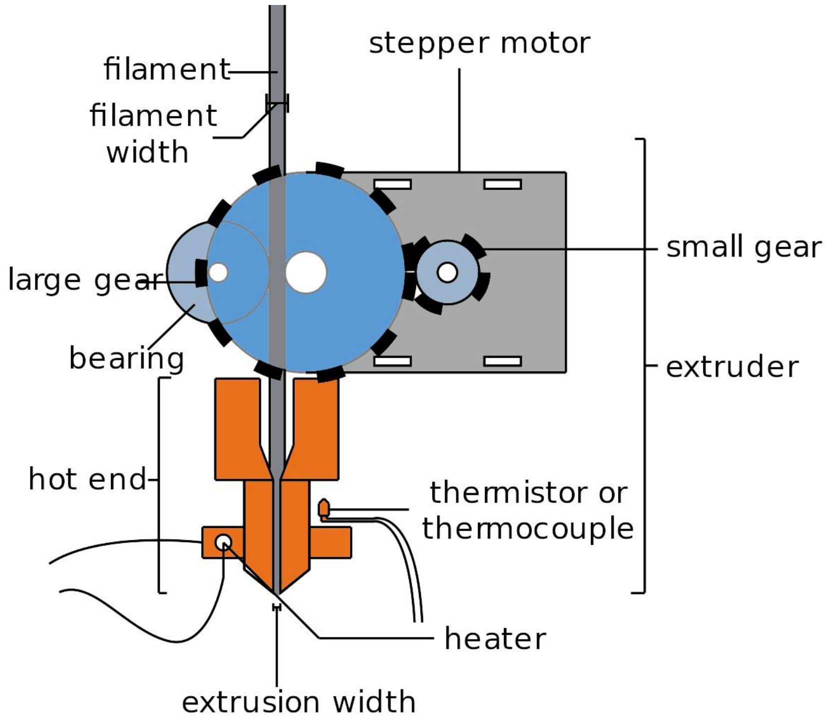

Figure 5: "Hot End" of 3D Printer (Mathematics Stack Exchange, 2018)

Our project is NOT working with an extruder for printing. We instead are working with an external extruder for producing filament.

The feedstock material for 3D printers is a type of thermoplastic known as filament. The filament used in these printers are made of specialized polymers. The filament is melted by the extruder and added layer-by-layer to make the product. The most common types of filament are PLA, ABS, and PET (ALT, LLC, 2020). Polylactic Acid (PLA) is common because of its biodegradability and the fact that it is produced from corn and other biomaterials. PLA can also be reinforced with other fibers. For example wood fibers can be added to increase strength and provide desirable aesthetic qualities (ALT, LLC, 2020). Acrylonitrile Butadiene Styrene (ABS) is used due to its higher strength and higher melting point (ALT, LLC, 2020). Polyethylene Terephthalate (PET) filament is used for water bottles and is known for its recyclability (ALT, LLC, 2020). This project will be using PLA because of its simplicity and the ability to embed other materials into the plastic.

2.4 External Filament Extruding

Any filament for printing comes in a wire-like form. These materials are made into wires through an extrusion process. Filament extrusion has been commercialized as long as 3D printing has been around. However, as 3D printing technology has advanced and become more accessible, so too has filament extrusion.

As mentioned earlier, filament comes in all different shapes and forms depending on its application, but before the filament is loaded into a printer, it must be extruded. Filament extruders take pellets of filament material, for instance ABS or PLA pellets, and extrudes them into wire-like filament (Obudho, 2019). The extrusion process starts with the pellets fed into the system through the feed hopper. From there the pellets enter the shaft where a rotating screw passes the materials forward along the shaft, passing through the heating elements in the process. While being exposed to the heating elements, the plastic pellets begin to melt. The molten plastic, still being pushed forward by the screw, now reached the end of the extruder. At the end, the molten plastic is extruded through a nozzle into its final wire filament form. Outside of the extrusion unit the filament is then left to cool and the process is complete (3devo, 2019). Figure 6 shows this process.

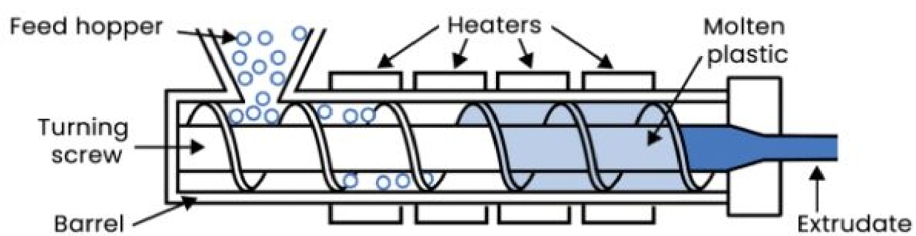

Figure 6: Filament Extrusion Process (3devo, 2019)

Extruding magnetic filament follows the same extrusion process. Magnetic filaments are typically made by infusing finely ground iron powder with a base thermoplastic material. This process allows 3D prints to be made which act much like metals in terms of their response to a magnetic field. Prints using magnetic filaments are described as ‘ferromagnetic’, meaning they are attracted to magnetic fields (Flynt, 2018). For our project, we explored two combinations of magnetic filament: Iron with PLA and Neodymium with PLA. We used the iron/PLA combination for the manufacturing of the stator assembly. The neodymium/PLA mixture was for another project team, to print a “muscle”.

2.5 Filastruder

Figure 7: Filastruder Filament Extruding Unit

Entering this project, we received a Filastruder which was passed on to us by previous groups exploring extruding their own filament. The group previously explored combining neodymium and nylon. Shown in Figure 7 is the Filastruder filament extruding unit. Filastruder is a small company that started in March 2013 (Filastruder), with the help of a kickstarter campaign that had the goal of creating a robust and inexpensive filament extruder. Filastruder's idea was to make something that would help people get into the 3D printing space with ease and enjoyment whether it be students, at-home hobbyists, or professionals. The company has also grown to become a distributor of accessories and filament.

2.6 Electrical Discharge Machine (EDM)

In order to create our new filament extruder, we designed a tapered nozzle to hopefully allow for a more consistent flow of melted PLA. The original nozzle had a flat entrance for the melted PLA and was prone to clogs. In order to prevent clogging and promote easier flow of the filament out of the extruder, we decided to redesign the original flat nozzle of the Filastruder to a tapered, elongated version for the modular filament extruder. Our tapered design could not be made using traditional machining methods. Instead, however, we needed to use the facilities at Washburn Shops, specifically the new Electrical Discharge Machine (EDM) to create the smooth conical (tapered) section we desired. The EDM is a special device that uses electric current to cut away material (Weeks, 2019). In order to use the machine, an electrode must be made out of a conductive metal and in the shape of the desired incision. This will act as the cathode. Once this is done, the stock is fixtured and submerged in a dielectric fluid. The stock acts as the anode in this operation (Weeks, 2019). A current is then ran into the electrode and it is lowered into the stock to cut the desired shape. This process allows for more complex operations than can be performed with traditional machining options. Refer to Figure 8 for an EDM process diagram.

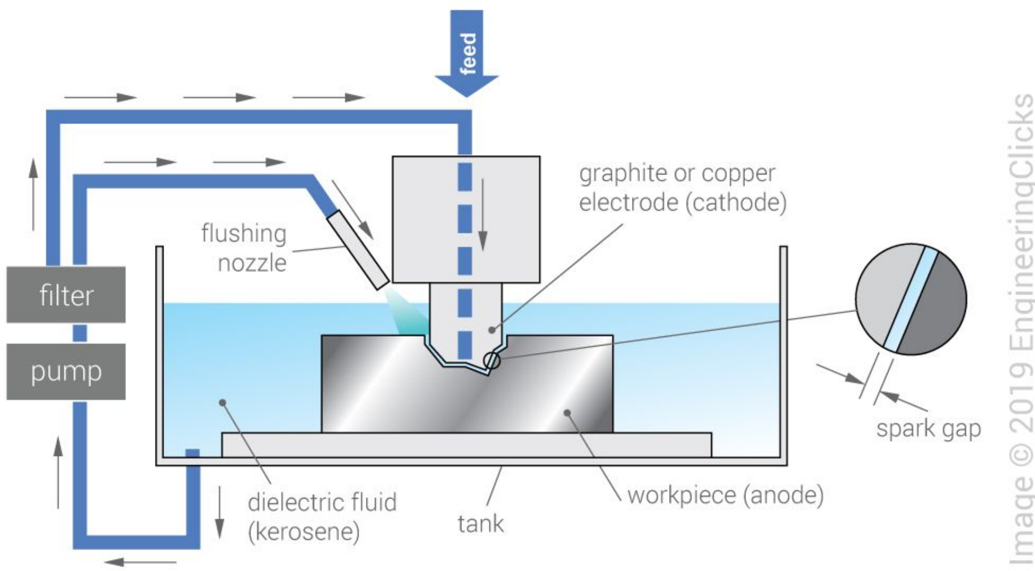

Figure 8: EDM Process Flow Diagram (Weeks, 2019)

2.7 Design of Experiments (DOE)

An essential ingredient to any successful product development or continuous improvement process is experimental design using statistical analysis. The statistical design of experiments, DOE, provides an efficient and scientific approach to finding valuable information (Anderson & Whitcomb, 2010). DOE allows teams to identify which process inputs have significant influence on the output. From these findings, an optimal target level of those input factors can be developed to achieve a desired result (Anderson & Whitcomb, 2010).

As aforementioned, designed experiments follow a structured flow of steps in order to build a sound study. A flow of the DOE process is presented below in Figure 9. This diagram outlines nine distinct steps to complete the design process, ranging from initial problem definition to additional spinoff experiments to further investigate hypotheses based on the results found.

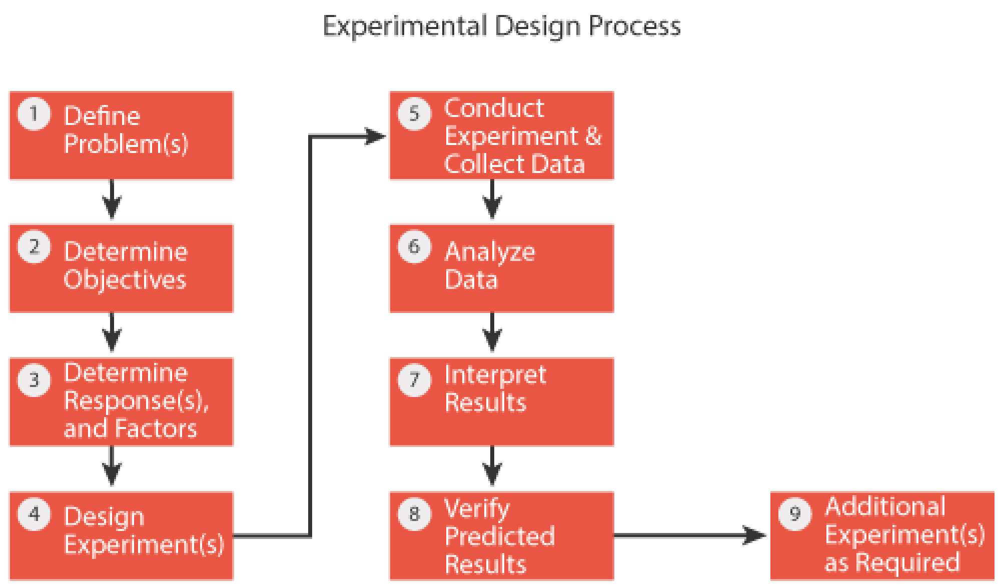

Figure 9: DOE Flow Diagram

Mainly, there are three components to successful designed experiments. The three aspects that are analyzed are factors, levels, and responses. Factors are characterized by the process inputs. Factors, or variables, can be separated into two subgroups: those that are controllable and those that are not (MoreSteam, 2020). Factors that can be controlled are useful when designing an experiment. This type is easily manipulated and is controlled through the use of different settings. Contrastly, uncontrollable variables are not as easily controlled. Instead experiments implement safeguards such as randomization and blocking to mitigate, or even eliminate, any bias or unmanageable variable influence (MoreSteam, 2020).

Levels are characterized as the settings of each factor (MoreSteam, 2020). These settings can be either qualitative or quantitative in nature, depending on the factor they control. Furthermore, levels can be based on intervals of measurement spanning a range. For example, as related to this project, the temperature set point of the extruder's heating element spans the range of PLA melting point (170 C) to the element's maximum temperature (260 C). The level is the temperature set point, whether it follows intervals across the entire range or focuses on a smaller segmented range is to be determined by the testing group - whichever is most appropriate. The factor that the set point controls is the filament extruder's heating element.

The third, and final, component is the response of the system. The response, or commonly referred to as the outcome, is the result of the different combination of levels contributing to the system's input (MoreSteam, 2020). Responses are typically measurable outcomes which are potentially influenced by the factors and their respective levels - the purpose of the experiment is to recognize this influence. One response, for our experiment, is the measurement and analysis of the consistency of filament diameter in the samples of each trial run. Each trial, with its specific combination of levels, will produce different samples as a response. In turn, these response variables will tell experimenters the optimal combination of settings for the desired outcome (MoreSteam, 2020).

In contrast to traditional vary one-factor-at-a-time (OFAT) experimentation, design of experiments permits the changing of variables together. This allows experimenters the ability to identify and evaluate reactions between inputs (Anderson & Whitcomb, 2010). Therefore, it is best to use DOE over other experimental methods when there is suspicion of multiple inputs having influence over the output of the system. For instance, trying to identify the optimal settings (inputs) of an extruder to produce consistent printable filament (output).

Chapter 3: Methodology

3.1 Initial Goals

The initial goal of the project was to develop magnetic filament which would then be used to 3D print a magnetic stator assembly (MSA) to be used in an moving magnet transducer (MMT). We would then begin eddy current testing to hopefully prove that the 3D printed MMT would have reduced eddy current heating compared to last year's design.

To begin, we took the filastruder left behind by the previous group, and did a full tear down analysis and cleaning. The pictures from this process can be found in Appendix K. We began a controlled test using just PLA pellets and the vertical set up used by the previous year, seen in Figure 10. After the screw became continuously dislodged from the motor during extrusion, we decided to abandon the vertical set-up and begin using the filastruder horizontally. We cleaned the clogs left over by the vertical configuration, and after another test with PLA, the team confirmed that the horizontal configuration was best.

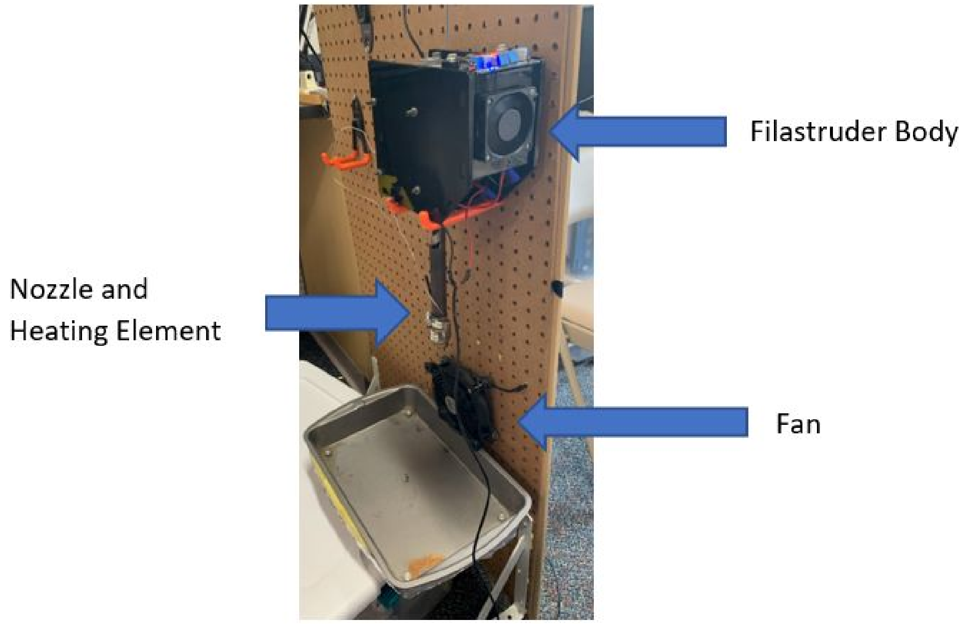

Figure 10: Prior Project Team Vertical Configuration of Filastruder

3.2 Extruding Magnetic Filament

The next step was to incorporate magnetic material into the filament. To do this, we began testing with iron filings, with the intent to move on to neodymium, the material generally used in speakers. The team once again decided to use the information given by the previous group. We began with a mixture ratio of 15% Iron filings to PLA by weight, based on procedures laid out by the previous team.

We took the combination and inserted it into the filastruder via a newly designed hopper as seen in Figure 11. The material traveled through the shaft as the screw turned and melted by the heater present at the end of the device, which was heated to 170C. This act combined the two parts and pushed the mixture through the nozzle becoming filament. We also cooled the exiting filament, using a fan, to help it retain shape. Sometimes, the filament needed to be pulled out of the extruder with pliers. The extrusion was successful; however, the metal material was not evenly dispersed among the filament. To counter this, we took the extruded filament and cut it into small pieces and ran it through the filastruder multiple times in order to evenly distribute the metal. Following the completion of this process, we produced a gray magnetic filament that we believed could be used in 3D printing. After our initial successes with iron filings, we began to test with neodymium as the magnetic material. The process was the same as discussed above. A step-by-step procedure can be found in Appendix H.

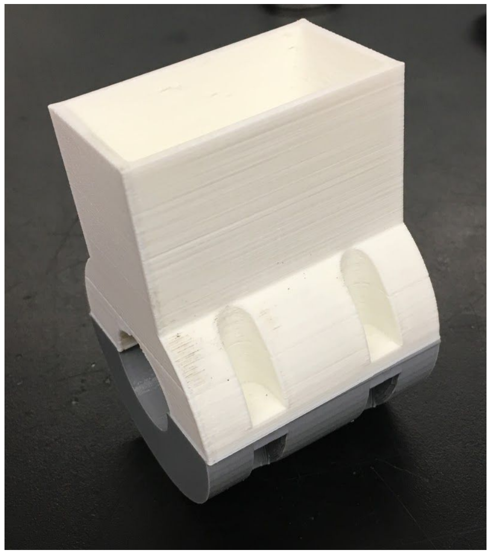

Figure 11: Redesigned Feed Hopper

We identified several issues with the filastruder during this time. The process was incredibly slow and was prone to clogging if used too often without cleaning or too much material was inserted into the device. We had to clean large clogs several times.

Figure 12: Cleaning a Clog from the Filastruder

We attempted to test our filament in the Prusa 3D printers available to us in the MQP lab. In doing so we discovered one of two major flaws with the filament produced by the original filastruder. When the material was taken into the Prusa, it broke and clogged the Teflon tube that feeds into the printer's extruding head. We had learned that our filament was very brittle. The clog took at least a week to fix and required a complete dismantling of the printer in order to solve it.

We worked this project in conjunction with another MQP team advised by Professor Stabile. The team would use our magnetic filament to test their own 3D printer in hopes to use it to produce a 3D printable "muscle." However, when they began to examine and prep our filament, they discovered the biggest flaw in the original Filastruder's filament, its diameter is incredibly inconsistent. This inconsistency forced us to reevaluate the filastruder as a viable option for this project.

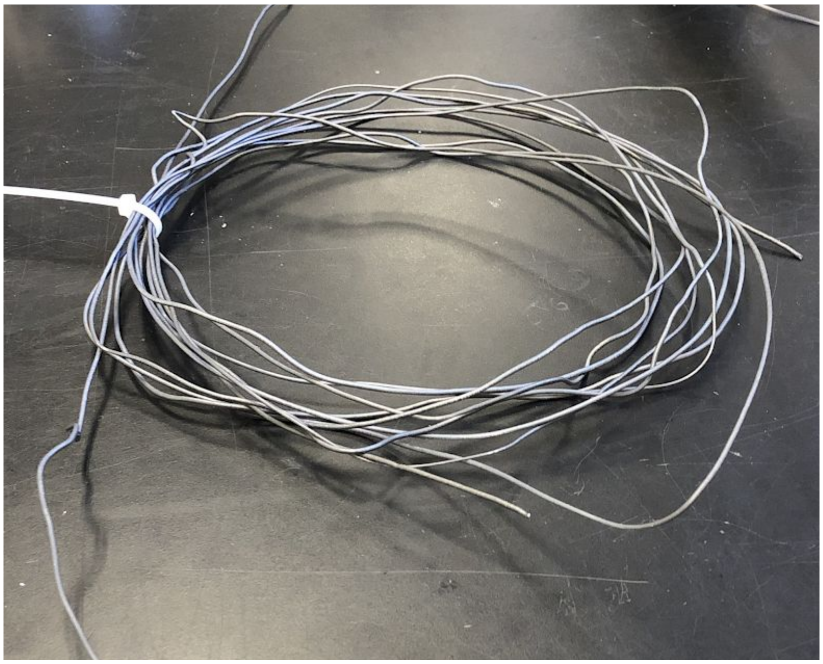

Figure 13: Iron/PLA Extruded Filament (15% by wt.)

We first attempted different ways to extract the filament from the filastruder. For example, we attempted to fix the winding system left behind by the previous team; however, it was not able to be fixed due to issues with the code and motor. It was passed to another MQP team which hoped to use the parts for different purposes. Another method we tested involved allowing the filament to fall off the table and using gravity to pull the remaining filament at a semi-constant speed. The filament was allowed to pool on the floor and was eventually wound onto a standard filament spool. While this method did markedly improve the consistency of the filament, it was still not good enough to be used in the 3D printers. A full step-by-step procedure can be found in Appendix H.

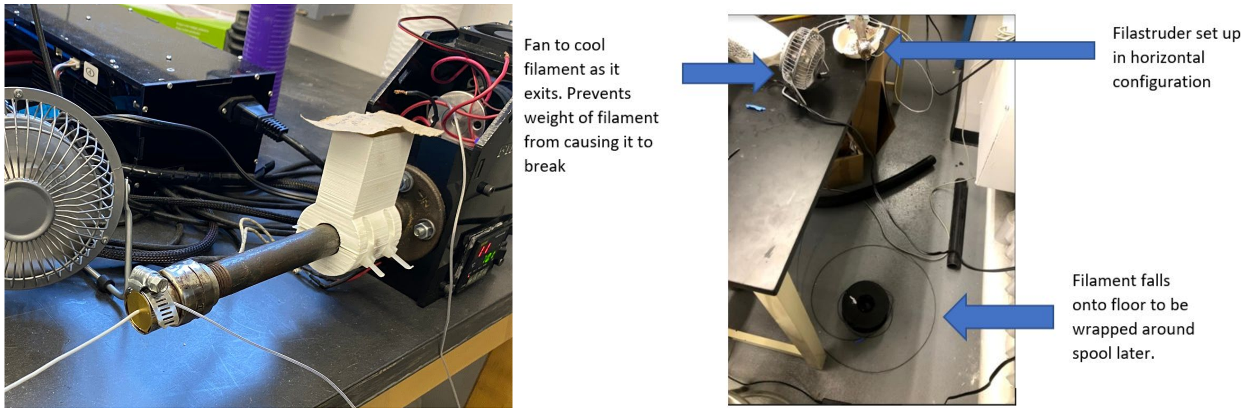

Figure 14: Horizontal Extruding Setup & Spooling Procedure

3.3 Changing Goals

The team decided to begin exploring other options to achieve the primary goal of the project. In order to not waste time while we explored different solutions to the filament problems, we looked at commercially available products that we hoped would lower eddy current heating in the MMT.

3.4 Commercial Products

The first product we examined was an iron and PLA mixed filament created by the company Protopasta. The Protopasta filament was created similarly to ours and was a mixture of iron and PLA. However, their production techniques were not publicly available to be studied. However, we know that their ratio was around 45% iron fibers to PLA. A public safety data sheet of the material can be found in Appendix E. The second material we investigated was a soft composite magnetic powder called Somaloy. Soft Magnetic Composites (SMC) are pressed and thermally-treated powder metal components with 3D magnetic properties. SMC materials, like Somaloy, are composed of encapsulated iron powder particles that are compacted to form uniform isotropic components with complex shapes in a single step. The SMC material is manufactured by a company called Symmco. The use of these materials makes innovative electrical machine designs technologically viable. By heating and putting it under pressure, the powder is capable of forming structures. Somaloys typical applications range from electric motors to fast switching actuators and power transformers. See Appendix F for more information about Somaloy from the company.

In order to test the effect of eddy current heating, we decided to test these materials against the rods of last year's MMT as shown in Figure 15. We used the Prusa printer to print several cylinders of Protopasta with varying diameters and finally the diameter of 4mm to compare against the Somaloy powder and traditional MMT.

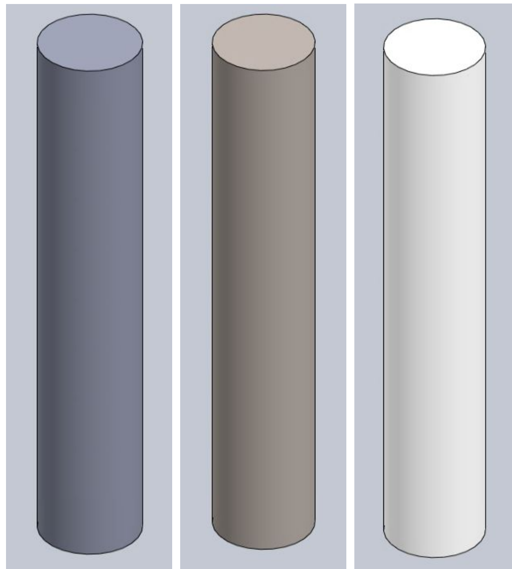

Figure 15: CAD Models of Steel, Iron/PLA,
& Neodymium/PLA Rods (In order)

Once we felt comfortable printing with the Protopasta, we used Solidworks to CAD the stator assembly that makes up the framework of the MMT. We decided that since the stator is symmetrical, we could save time by taking the piece in half and printing it. By doing this it took only 11 minutes to print a complete magnetic stator assembly. A screenshot of the settings used for tolerancing can be found in Appendix J.

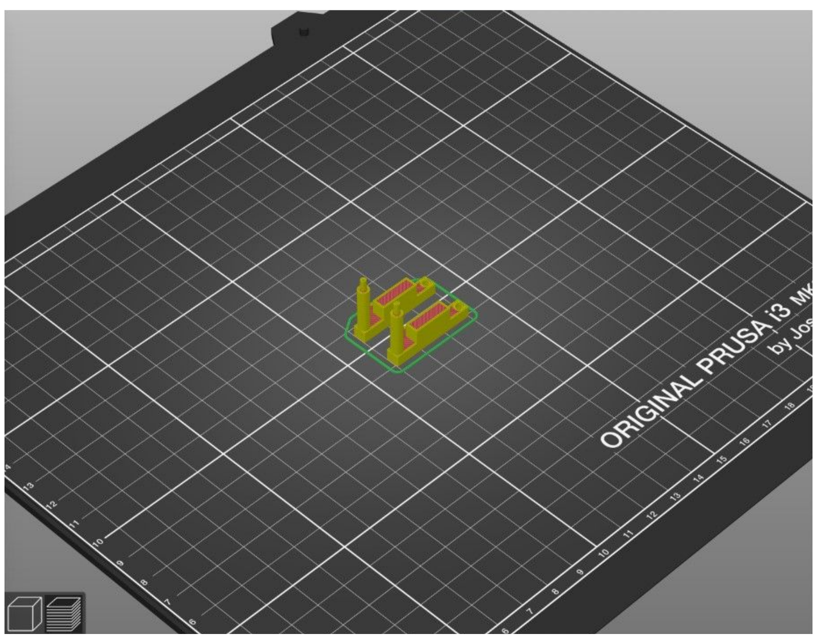

Figure 16: 3D Print Slicer (PRUSA)

By using the slicer program available to the Prusa, we would be able to print as many as 44 full stators in one print. However, the Protopasta material ran very dirty and was prone to clogging the nozzle of the 3D printer. In order to stop this, we had to replace the nozzle several times on the printer until we discovered that purging with non-Protopasta (pure PLA/ABS) filament afterwards helped to clean the nozzle.

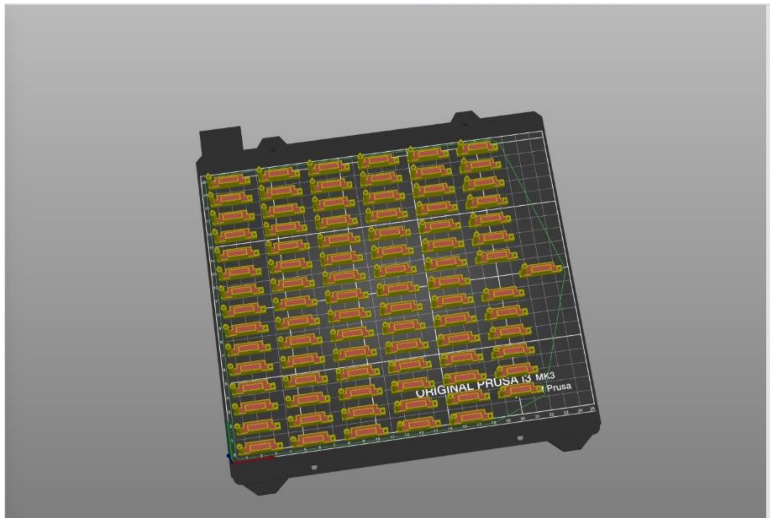

Figure 17: 3D Print Slicer Maximum Production

3.5 Somaloy and Press Molds

After receiving our Somaloy powder from Bud Jones, the Vice President of New Technologies and Business Development at Symmco Inc., we began to investigate pressing the material on WPI's campus. The Somaloy material was difficult to work with. Mr. Jones told us that we needed to heat the material to 140 F and press with a force of 45 TSI. See Appendix F for more information on the material. We spoke with Professor Torbjorn Bergstrom at Washburn Shops in order to discuss creating our first iteration of press molds.

Shown in Figure 18, our first iteration was a cylindrical die with a hole in the middle that was toleranced to produce the correct diameter for our eddy current testing, 4mm. The punch was created by using a cap made of machined aluminum and a drill bit of the correct diameter, broken off in the top. Finally the bottom was capped using a lid made of machined aluminium with holes cut and threaded to keep it sealed.

Figure 18: First Iteration Punch and Die

To press with this first design we used the tools available to us in Washburn Shops. We heated the press molds and powder using a camp stove available to us. We also used a thermal gun to measure the temperature. However, the device was incredibly inconsistent and would not give us an accurate read on the temperature. We also had to use an old hand press with no readout on the force applied. We calculated the mechanical advantage of the machine and found that we needed to apply approximately 45lbs of force on the lever of the machine to produce the correct tonnage. After we were confident the mold had reached a temperature above 140F we took the mold to the press and attempted to keep a constant force of 45lbs on the lever for 1 minute. During the pressing action, the drill bit snapped and broke off in the press mold. Because of the lack of lubricant we were unable to remove the bit from the die piece. Our first test was ultimately a failure as we could not remove the final rod from the mold. Reference Appendix L to see pictures of the press process and the aftermath.

We needed to redesign press molds that would help prevent this from occurring. We ended up settling on the design shown in Figures 19 & 20. It would allow us to vary the amount of powder we put into the die and it would separate easily even after being pressed. For a punch, we decided to test just using a single rod purchased from McMaster-Carr at the appropriate diameter. We hoped this would allow the force to be applied as focused as possible.

Creating the second design took more time than the first as it involved several complex machining methods. We took a large piece of aluminum available to us and began by cutting it to the desired length of 2.5in. Following that, we shaved the surface to make it flat and clean, then cut the desired dimensions of the mold. Once that was complete, we used a ⅜in. endmill to cut the correct diameter into the press mold. Following that, we drilled two holes into the piece at the depth of 0.5in to make sure that it would go all the way through the piece. Following this, we flipped the piece over and performed another surfacing operation to cut away the leftover stock pieces. We then created a chamfer along the edge to prevent any cutting or burs. We then repeated this operation with the only change being switching the holes locations so they would line up. We then pressed in two metal dowel pins in order to line up and connect the two pieces. James Loiselle was instrumental in this process and helped us every step of the way. Pictures of the process can be found in Appendix I.

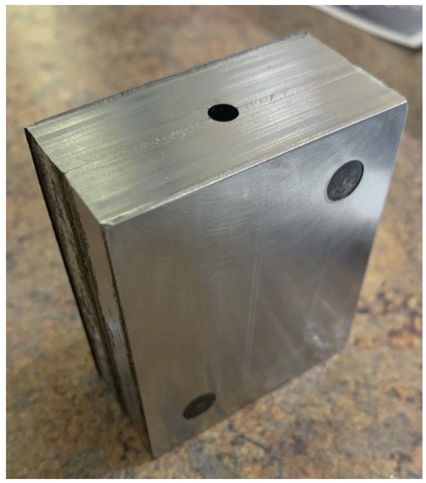

Figure 19: Final Punch and Die Design

Figure 20: Separated Press Molds

After we finished fabricating the molds we made another attempt at pressing the Somaloy material. We used a press that was created by graduate students in Higgins Labs. The machine had heated beds and an air canister with a gauge that provided the pressure. We attempted to press using this machine. However, during our trials we learned that the pressure read out gauge was broken, and the temperature indicators were incorrect.

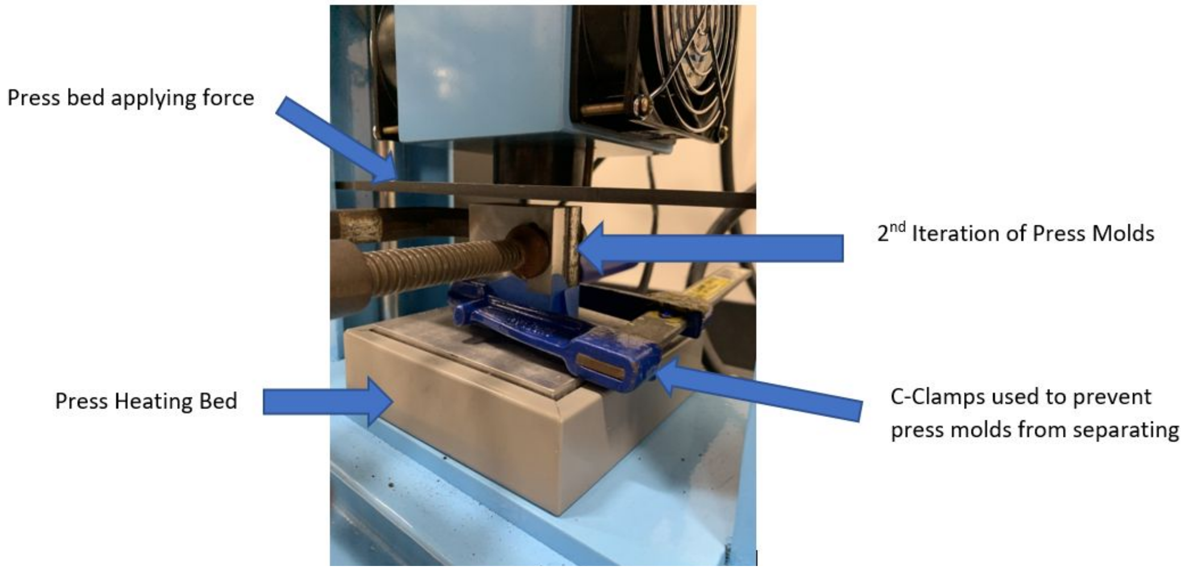

Figure 21: Heated Press in Higgins Labs

Following this failure, we decided to design our own press. We utilized standard U channels and created a frame for the press. We intended to use a bottle jack that Professor Stabile had at his home. We also ordered heaters that could be applied directly to the die and could be measured easily. We were going to attempt to make the press and begin testing in D Term of 2020, but due to the COVID-19 quarantine and the cancellation of classes, we were unable to make the press ourselves. Professor Stabile has created the press we designed with his own tools at home, see Figure 22. He took the standard U channels and cut them to the lengths specified in our CAD. He also attached the bottle jack and strain gauges to measure the force output.

Figure 22: Newly Designed Press

3.6 Modular Filament Extruder

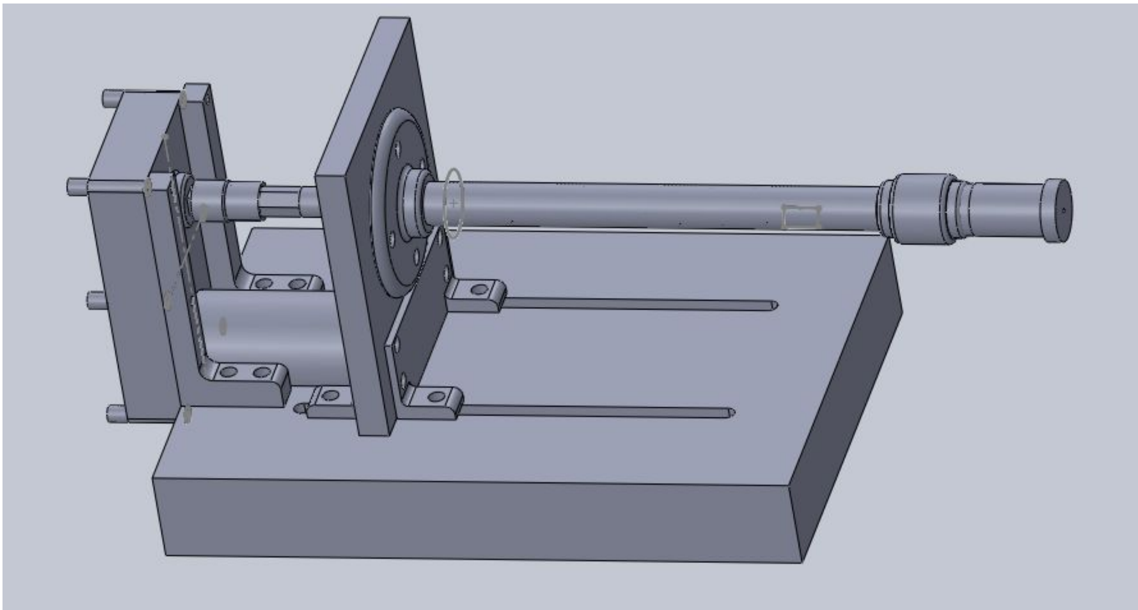

Figure 23: Modular Filament Extruder Assembly with New Nozzle

As we continued to evaluate the commercial products, it soon became clear that the team needed to redesign the filastruder. The objective of the redesign would be to create a linear, and modular filament extruder that is designed to permit variation with the goal of finding the ideal setup through testing. For simplicity in fabrication, we kept most of the usable components of the Filastruder Kit. These components include the shaft, extrusion screw, motor and the socket as a coupling between the screw and motor all shown in Figure 24. Therefore, the redesign needed to incorporate each of these components while also permitting for linear variation in the shaft and screw.

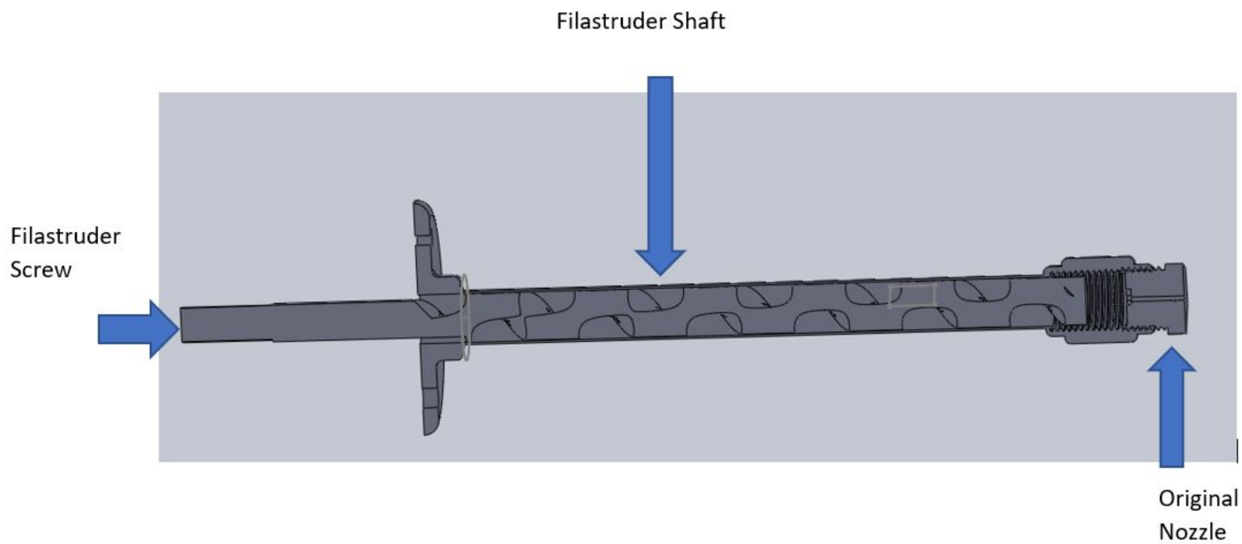

Figure 24: Extrusion Screw, Shaft, & Original Nozzle Subassembly Filastruder Kit (Section View)

While keeping the shaft, extrusion screw, motor and the socket does simplify fabrication, it does restrict us to design around these. We needed to develop a base and fixtures that would be able to hold the motor and the shaft, while allowing the extrusion screw and coupling to rotate freely. The motor needed to be fixed to one location, while the shaft needed to be capable of moving horizontally to permit variation. Unfortunately, the motor contains a large cylindrical portion that needs to be designed around. This creates a need for a significant notch in the base to fit the motor into as shown in Figure 25.

Based on these requirements and constraints we developed a modular filament extruder that would secure the shaft using L brackets to a base. These brackets are then secured to a track at the desired length using a nut and a bolt, this whole assembly is shown in Figure 25 and 26. The shaft is then bolted to a rectangular fixture containing a hole at the same diameter as the shaft, permitting the extrusion screw to rotate within the fixture without issue. The extrusion screw itself is then entered through the shaft and the circular clamp ring is applied and tightened onto the screw at the desired length as shown in Figure 25. This is essential to prohibit the screw from moving forward into the shaft during extrusion, but the clamp can be adjusted as needed. The motor is then secured to the end of the base using two more L brackets as shown in Figure 26. The screw is then connected to the motor by the socket used as a coupling as shown in Figure 26. Finally, one of the most difficult portions of the redesign was the nozzle, as the intention was to manufacture a nozzle with a long taper to promote easier flow through. We developed a profile of the nozzle in CAD with the desired taper length and angle as shown in Figure 27.

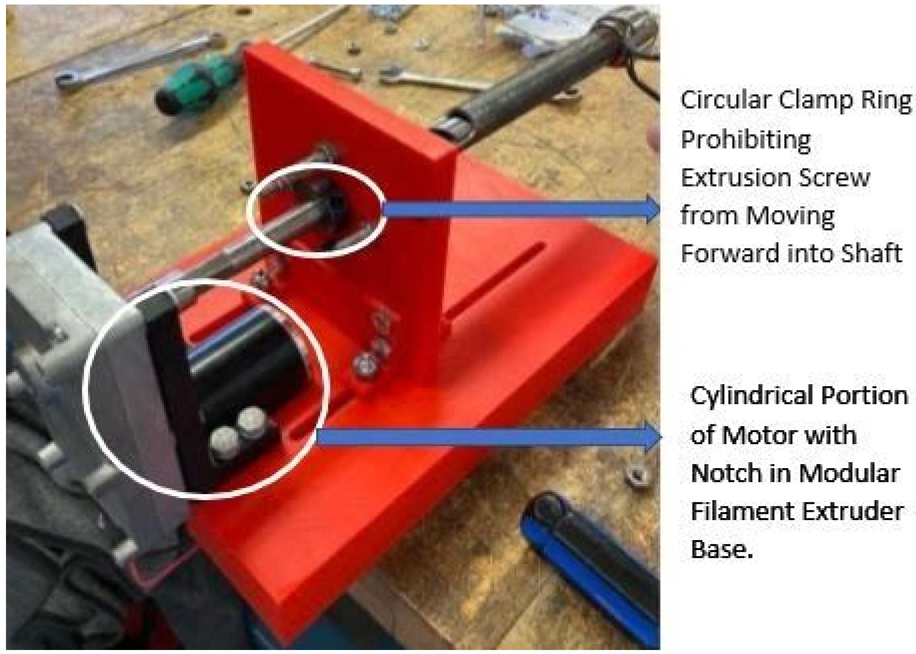

Figure 25: Modular Filament Extruder Full Assembly

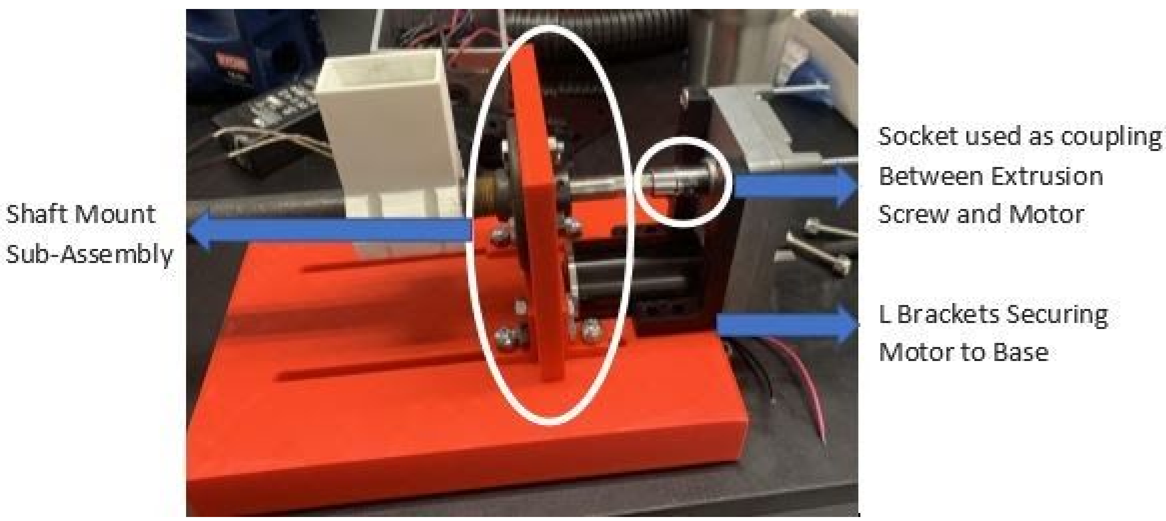

Figure 26: Modular Filament Extruder Full Assembly Side View

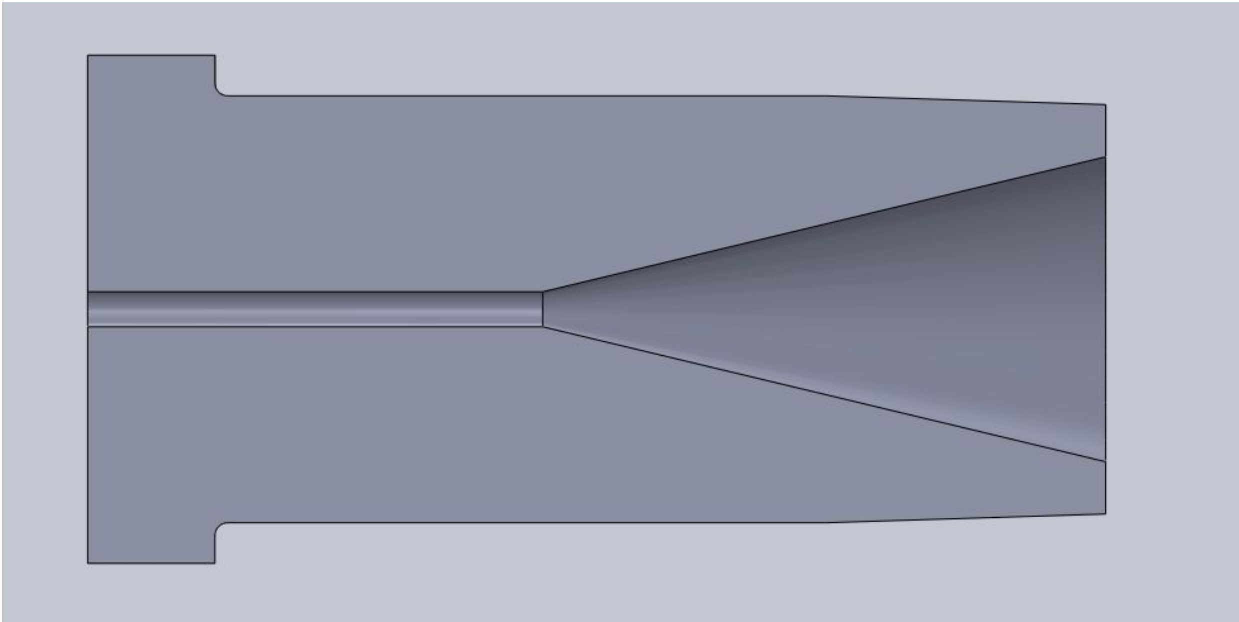

Figure 27: Section View of Tapered Nozzle

In order to create the nozzle, we returned to washburn shops. Because of the desired size of the nozzle and the limitation of the tools available to us, the fabrication would have to take place in two parts. The first part would be a lathe operation that would create the shaft and the outer section of the tapered portion of the nozzle. The lathe would then be used to create the correct threading on the nozzle so it would mate with the shaft of the filament extruder. A cutting operation separated the stock from the lathe. From there it was taken to a mill where various sizes of end mill bits were used to cut into the conical section of the nozzle. This was done to make the second part of fabrication easier. The result of this operation can be seen in Figure 28. From there a small drillbit of diameter 1.75 mm was used to cut into the top of the nozzle. The final operation faced the top of the nozzle making it smooth. Finally the six edges were added to the top of the nozzle to make the nozzle hex shaped in order to make assembly and disassembly easier.

Figure 28: Nozzle Conical Section before EDM

Figure 29: Machined Tapered Nozzle

The second part of the fabrication required the use of the new EDM unit in Washburn. First, we used a lathe to create an electrode using brass. The lathe cut the stock to proper dimensions for the conical section of the new nozzle. We inserted the electrode into the machine and began the setup procedure. After fixturing and submerging the unfinished nozzle in the dielectric fluid, the machine started to run current through the electrode. The machine was programmed to lower into the material intermittently until the desired dimensions were acquired. After the operation was finished, the nozzle was removed and inspected to make sure it met all design requirements. This process took hours and required constant supervision to make sure there were no fire hazards. After the completion of the first nozzle, James Loiselle requested that we determine through our testing methods if it was worth the effort to create more nozzles.

Figure 30: Nozzle After EDM Operation is complete

Finally after the fabrication of the new nozzle and the 3D prints were complete, we created the new modular filament extruder. As you can see in Figure 31, the base and supports of the extruder are made of red or black PLA. The motor, shaft, screw, and heating element were all taken from the original filastruder.

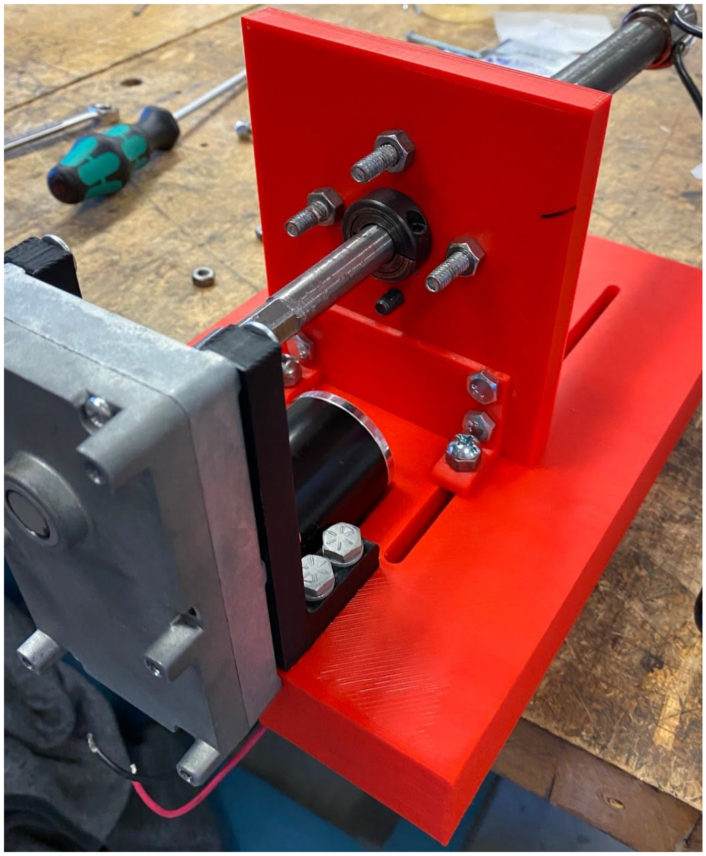

Figure 31: Modular Filament Extruder Assembled

3.7 Design of Experiment (DOE)

After abandoning the Filastruder and committing to a redesign of the modular filament extruder, our team began designing an experiment to evaluate the success of our redesign. To conduct our experiment we decided to take a systematic approach. Our approach would need to make this procedure as simple and repeatable as possible. Eventually, this experimental process would lead us to optimal operation settings for the filament extruder to produce consistent filament. In order to accomplish this goal, we turned to the concept of design of experiments (DOE) (MoreSteam).

DOE is a branch of applied statistics which deals with planning, conducting, analyzing, and interpreting controlled tests to evaluate the factors that control the value of a parameter or group of parameters. The advantage of a DOE is its ability to allow for multiple input factors to be manipulated and tracked throughout the procedure. Manipulating multiple variables at the same time can identify important interactions which may be missed when experimenting with one factor at a time. This is why our group chose DOE over the more commonly used "one factor at a time" method (Anderson & Whitcomb, 2010). DOE is defined by its systematic approach which is outlined earlier in Figure 8. We used this flow to navigate our DOE process. See Figure 32 below for our project specific flowchart. In alignment with our goals, we follow the flow structure of the design of experiments process, but eliminate some aspects as they were not essential in the scope of our task. As a time constraint, our team was forced to eliminate any future experiments stemming from the results of our initial DOE. Likewise, the evaluation of specific hypotheses is not applicable in our case because this step often helps design further experiments. Whereas our goal was merely to identify the best combination of settings for the modular filament extruder to produce the most consistent filament.

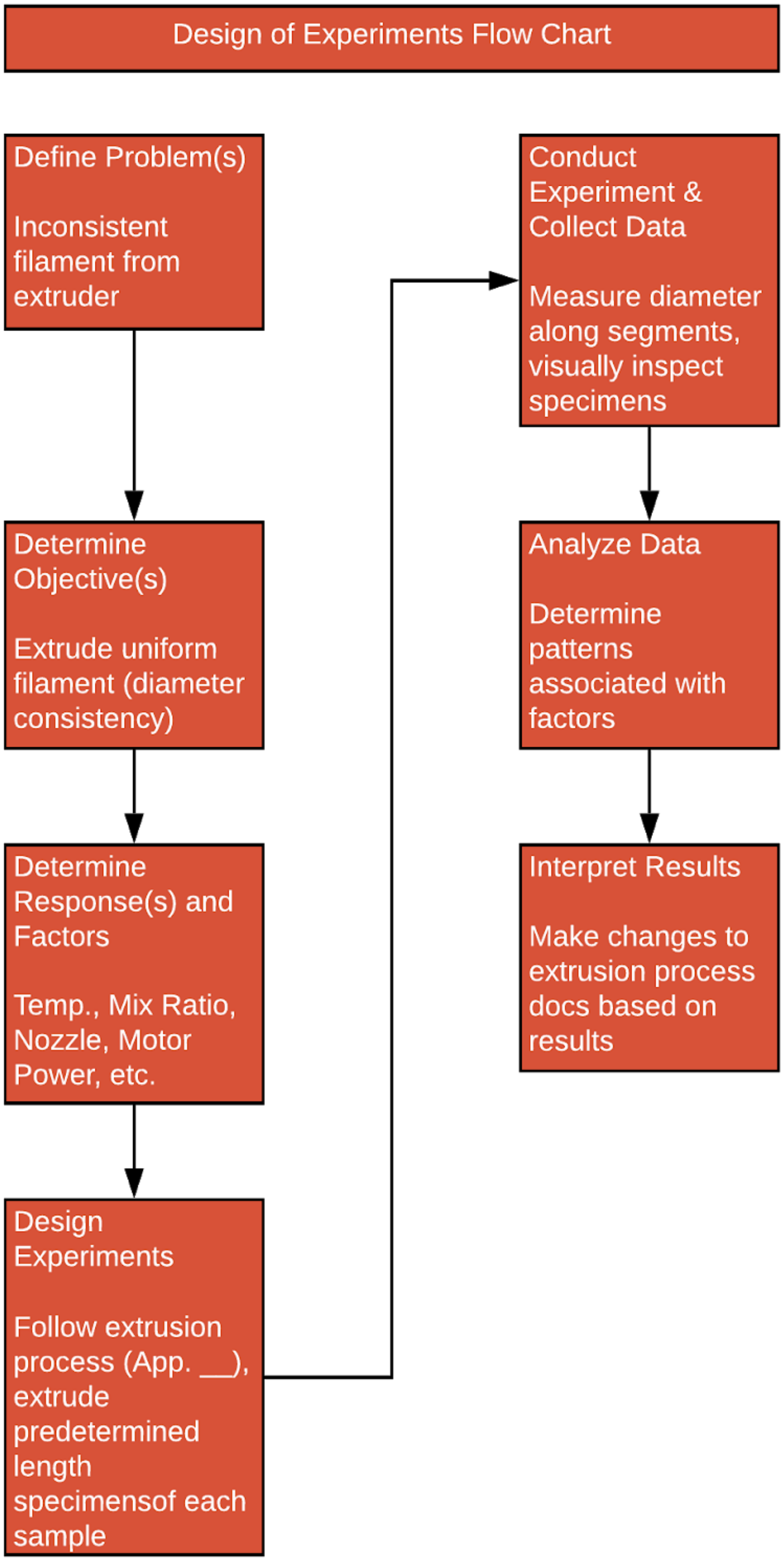

Figure 32: Project Specific DOE Flowchart

In developing our DOE, we first needed to identify which factors, or inputs, our experiment would focus on. For the purpose of testing our modular filament extruder, our factors would all be controllable. The next step in the design of the experiments process was to identify the levels, or settings, associated with each factor. Levels could be anything from the temperature set point to voltage supplied to the motor. The following table (Table 1) shows all of the identified controllable factors related to our experiment design as well as the levels associated with each factor. Again, these factors and levels were determined to help the team reach the optimal process output, consistent printing filament.

Table 1: Factors and Levels of DOE

Controllable Factor	**Levels (Control Method)**
Nozzle type	Flat Nozzle (Original) Tapered Tapered
Motor Power	Voltage supplied to motor (controller added to extruder circuit)
Temperature Set Point	Target temperature of the extruder (Minimum ≈ 170C)
Temperature Profile	Original heating element (Point Source) Additional elements distributed across shaft (Distributed Source)
Nozzle/Screw Distance	“Modular” aspect of the extruder - distance from the end of the screw to the nozzle
Metal to PLA Ratio	Starting at 15% by weight (Increasing intervals)

With all of the factors and levels determined, the DOE continues, like all experiments, with the development of hypotheses. In experimental design, this is also known as predicting the response, or output. The key is to determine how this is measured. For our design of experiments, the response will be a measurement of the diameter of the specimen of produced filament from the trials of the experiment. Consistency of the diameters on each strand of filament and across the batch marks the success of the experiment. Thus, revealing the optimal settings on the modular filament extruder.

3.8 Eddy Currents Testing

To investigate the effects of eddy currents on different forms of filament and the newest MMT, a test bench was created to log the results of the materials. The initial idea was to create a test coil that could be placed over a 4mm diameter 3D printed cylinder made from magnetic filament. This would then be excited by an audio amplifier, through a range of frequencies for a few seconds to log the temperature difference before and after excitation.

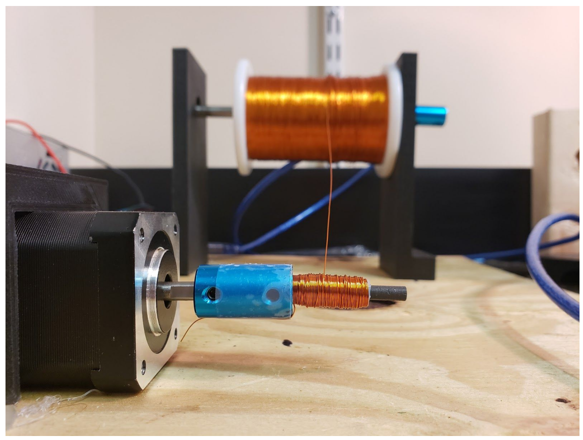

Figure 33: Stepper motor winder and test coil

This system, as shown in Figure 34 was controlled by an Arduino for the sake of automation and better testing precision.

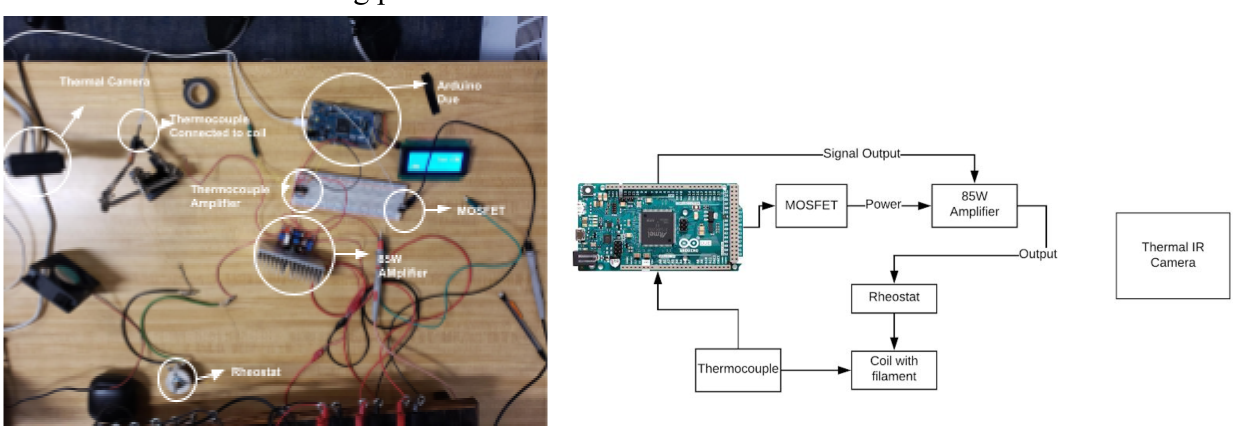

Figure 34: Arduino test bench layout

The final system contained the components:

Table 2: Arduino test bench component list

Category	**Name**
Microcontroller	Arduino Due
Temperature Acquisition	Type K Thermocouple Thermal IR Camera
IC	AD595AQ Thermocouple Amplifier
MOSFET	P30N06LE
Audio Amplifier	TDA7498
Rheostat	10-Ohm Rheostat

This choice of the microcontroller was due to the Arduino Due's built in Digital to Analog Converter (DAC) that will serve as the input of the amplifier. The Arduino will output periodic (Sine) waves at varying frequencies to investigate what frequency range gives the highest temperature gradient. The Arduino Due will also receive the output of the Thermocouple amplifier and recorded in the serial monitor/plotter.

A thermocouple was decided as the main source of temperature logging due to a thermocouple's size, ease of use, and temperature range. A Type K thermocouple was utilized with an AD595AQ thermocouple amplifier to receive accurate temperature measurements from the surface of the filament. While being cost effective, a type K covers a temperature range of −200°C to 1260°C (328°F to 2,300° F) which is more than suitable for the task at hand. A thermal IR camera was utilized as a secondary source of temperature acquisition. The camera was chosen as this device can monitor the coil and filament simultaneously while undergoing testing.

An amplifier of suitable power was needed to drive the test coil to produce adequate results for this test. From the devices easily accessible, A class AB 85W TDA7498 amplifier was used as a substitute to our initial 5W amplifier. It was found that the 5W class-D spark fun amp initially used for testing was of inadequate power and could not energize the coil to the results needed. To limit the amount of current going to the coil, a 10-ohm high current rheostat was used in series with the coil.

3.8.1 Operation

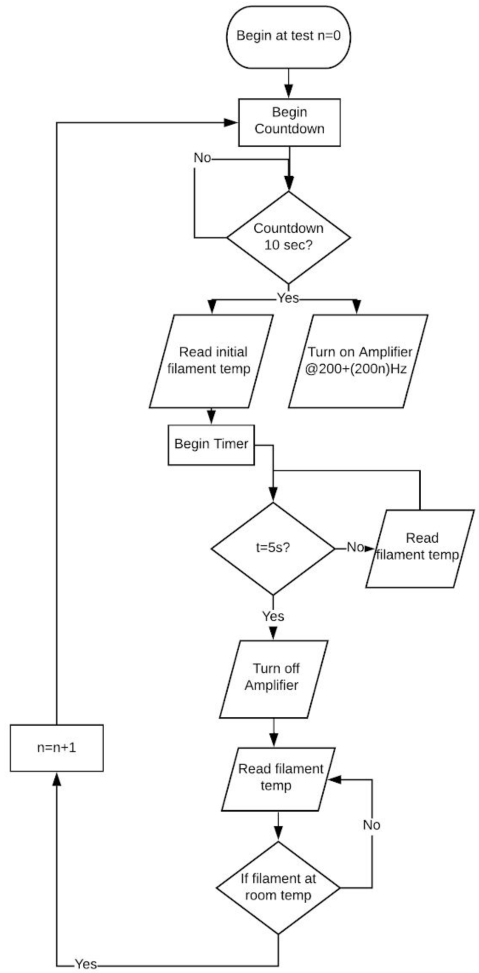

Figure 35: Arduino test bench flow diagram

The Arduino Due conducts different thermal tests at frequencies ranging from 200Hz to 2000Hz. This was done to see the frequency response of the filament when excited for a few seconds. The information acquired from this test would then be used to attenuate different frequency ranges. This task would be completed through a purpose-built equalizer to potentially slow the heating curve and extend the lifetime of the components.

The Arduino counts down till the beginning of the first test, which begins at 200Hz, turns on the MOSFET connected to the amplifier which excites the coil. The amplifier would then be turned on for 5 seconds with the Arduino logging the temperature throughout this time period. After 5 seconds have passed, the Arduino turns off the amplifier and turns on a cooling fan to get the filament back to room temperature. After the thermocouple reads room temperature for a few seconds, the Arduino counts down to the beginning of the proceeding test, increasing the frequency by 200Hz. The test repeats itself till the final test at 2000Hz. Whilst the Arduino continually runs, the thermal camera, through a separate software on a PC, records the thermal image of the coil and filament throughout all tests. Source code of this test bench can be found in Appendix M.

Chapter 4: Results

4.1 Original Filastruder

During our use of the filastruder, we were able to create several spools-worth of magnetic filament. However, while the machine did work, the filament it produced was very inconsistent in both diameter and magnetic strength. By cutting up and recycling the filament, the magnetic properties became more uniform; however, there was no change in the diameter variation.

The filament that we produced was ultimately brittle and very inconsistent. The material did not often print perfectly straight and varied in diameter in many locations. Attempting to use the filawinder did not work at fixing this inconsistency. Letting the filament fall off the table did markedly improve the consistency of the filament, but it was still not good enough to be used in the 3D printers available to us.

Figure 36: 1 Spool of Iron and PLA (Note the inconsistent diameters)

When we began testing with neodymium, the filament came out much different than the iron and PLA. After analyzing the neodymium/PLA combination filament, it appeared that the filament was stiff, brittle, and not nearly as magnetic as the iron filings filament. We believe that the neodymium filament is less magnetic due to the powder's tendency to stick to the screw and pipe of the filastruder. The lack of magnetic strength is most likely due to the powder not properly mixing with the PLA, creating a "weaker" magnetic filament. Without a proper way of verifying this, it was difficult to say if enough powder was making its way into the filament to be effective. We were never able to create the same amount of filament with the neodymium as with the iron filings. Once the team decided to redesign the filament extruder, neodymium testing became less of a priority.

4.2 Commercial Products

The Protopasta filament was ultimately our best result. By using it in the Prusa printers available to us, we were able to print full size stator assemblies as seen in Figure 37. The filament was much more magnetic than the filament we produced using the original filastruder. The stator assembly we produced was fully magnetic and, as you can see in Figure 37, was structurally sound enough to be drilled into and have a flexure attached without any sort of deformation. By using the slicer software for the printer, we were able to print multiple stators at a single time. The production was easy and effective. With proper setting manipulation, the tolerancing on the prints were able to fit together perfectly.

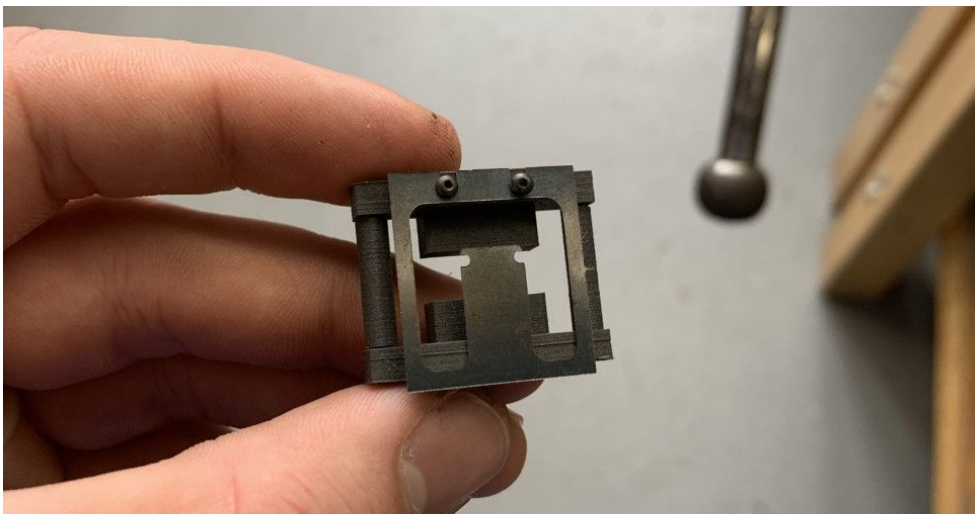

Figure 37: Printed Stator Assembly Equipped with Flexure

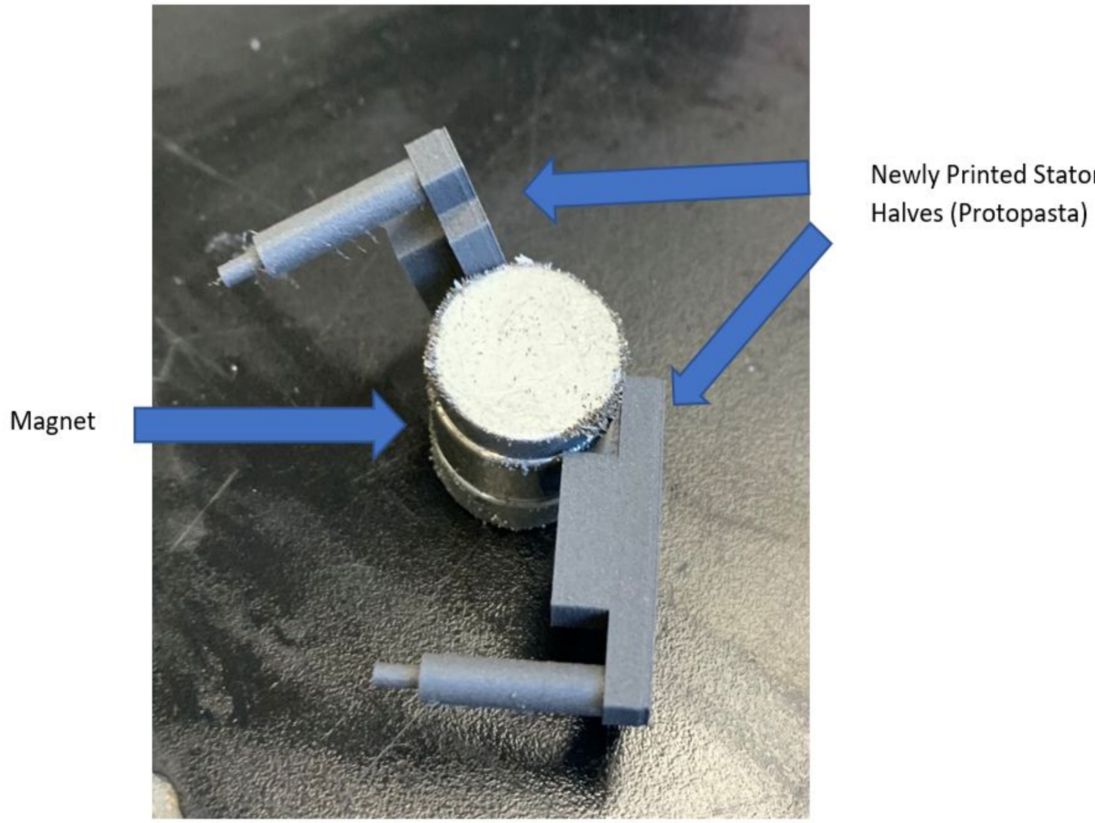

Figure 38: Protopasta Printed Stator Assembly Attracted to a Magnet

The Somaloy material was never fully able to be tested due to the difficulties established in the methodology. The first iteration of test molds was never able to be opened, so we cannot definitively say that the rod was not created as we expected.

Likewise, during the tests with the second iteration of press molds, we were unable to get the powder to form into the correct shape. After each test, the rod would hold shape until removed from the molds and it would disintegrate back into the soft powder.

Figure 39: Failed Somaloy Press Attempt

Due to the quarantine and the limited resources, we were unable to get a final Somaloy product to test the eddy currents of. However, with the creation of our newly designed press assembly, we are hopeful that future attempts can be made to compare the powder to the other materials.

4.3 Modular Filament Extruder

After all of the design and fabrication, we were able to fully assemble and produce our own modular filament extruder. After rewiring and fully assembling the extruder, we were able to begin limited testing of the device. The plan was to continue experimentation into D-term to determine the best configuration.

Because of the quarantine, we were unable to implement the DoE as discussed in the methodology. Our one and only attempt was in a low power configuration and created a blockage that needed to be cleared. We do expect that after performing the tests required of the DoE that we can determine the optimal configuration for the filament extruder to be used in. During our testing in SolidWorks Flow Simulation, we obtained Figure 40. This image shows the conical effect that we hoped to create with the new nozzle. By continuing the DoE, we are confident that we can produce consistent filament to be used in 3D printers.

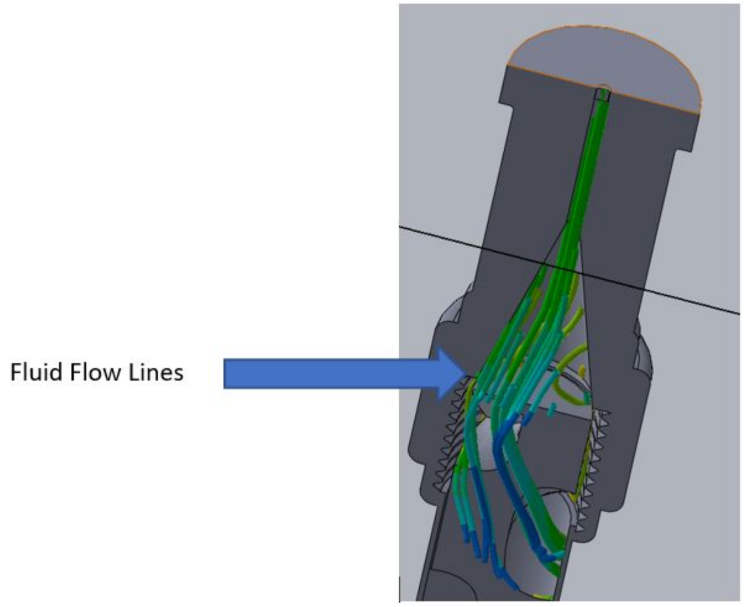

Figure 40: Solidworks Flow Simulation Through Tapered Nozzle

4.4 Eddy Current Testing

Multiple eddy current tests were conducted throughout 2 consecutive terms. However, the eddy temperature tests were inconclusive as it could not be fully determined if heating was due to eddy currents or the I^2R losses of the coil, due to the coil essentially acting as a heater. The thermal camera may have pointed to this as shown in Figure 41. The center of the coil is the hotspot whilst the ends of the coil show the Protopasta rod which is not as heated.

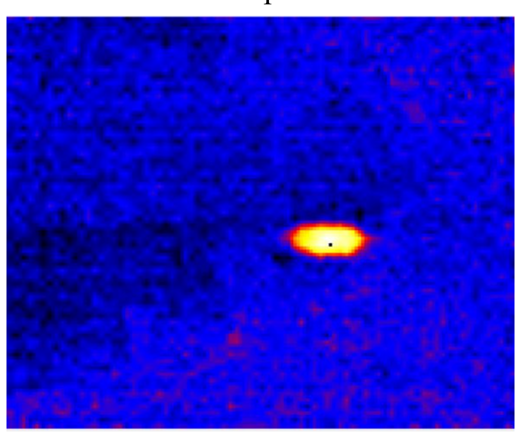

Figure 41: Thermal Camera Capture During Thermal Testing

When conducting eddy current testing, a base material (1800 steel) was used to simulate the previous effects of eddy current heating in previous projects. The base material was used to ensure proper operation of the amplifier and test coil, as well as give a heating reference for the materials under test.

Through both tests of an 85W and 5W amplifier, it was inconclusive whether the heating was due to eddy currents or I^2R heating. However, it was noted through tests of the 5W class D amplifier, there was significantly lower power consumption when testing a 4mm rod of magnetic 3D filament versus a steel rod. The test results can be found in Table 3.

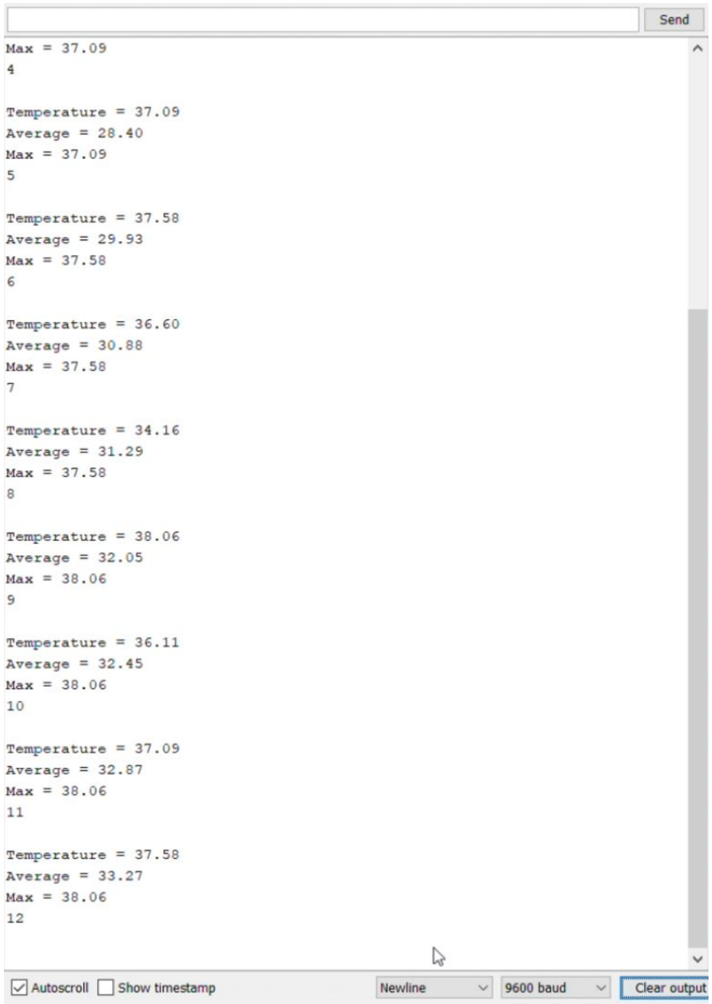

Figure 42: Sample Arduino test bench output (85W)

Table 3: Eddy Current Testing Results (5W Amp)

TEST 1	**1800 Steel**			**TEST 1**	**Protopasta**		
Starting Temp	22.94	Voltage (V)	0.58	Starting Temp	23.42	Voltage (V)	0.446
Heated Temp (2 min)	39.53	Resistance (Ω)	1.366	Heated Temp (2 min)	41.48	Resistance (Ω)	1.366
Delta	16.59	Current (A)	0.425	Delta	18.06	Current (A)	0.327
Average	33.22	Power (W)	0.246	Average	38.24	Power (W)	0.146
TEST 2				**TEST 2**			
Starting Temp	27.82	Voltage (V)	0.596	Starting Temp	22.45	Voltage (V)	0.45
Heated Temp (2 min)	41.48	Resistance (Ω)	1.366	Heated Temp (2 min)	49.29	Resistance (Ω)	1.366
Delta	13.66	Current (A)	0.436	Delta	26.84	Current (A)	0.329
Average	36.07	Power (W)	0.260	Average	38.66	Power (W)	0.148
TEST 3				**TEST 3**			
Starting Temp	24.4	Voltage (V)	0.573	Starting Temp	22.45	Voltage (V)	0.431
Heated Temp (2 min)	39.04	Resistance (Ω)	1.366	Heated Temp (2 min)	49.29	Resistance (Ω)	1.366
Delta	14.64	Current (A)	0.419	Delta	26.84	Current (A)	0.316
Average	32.33	Power (W)	0.240	Average	42.01	Power (W)	0.136

However, the average power consumption of the amplifier was reduced by up to 57% when Protopasta was used instead of steel. This can be due to Protopasta's makeup of iron and PLA, therefore less of this body is conductive in comparison to a cylinder of 1800 steel. This could be the reason for the reduced power as there will not be as great magnetic induction in the stator, since a suitable percentage of the stator is made of non-conductive material. This in turn means that there isn't as great of a demand for excitation current for the stator, reducing the overall power consumption. However, due to a decrease in magnetic excitation, this will create a weaker induced EMF in the body of the stator, therefore reducing eddy currents.

Chapter 5: Recommendations

Even with reduced time on campus, the team managed to cover a lot of ground and had some promising results. However, there are many different things the team was unable to try due to the quarantine and cancellation of class. Continuing these efforts may yield more results and eventually lead to a fully in-house produced and 3D printed stator for an MMT.

The team strongly recommends continuing with the DOE on the modular filament extruder. Hopefully, by conducting the planned DOE discussed in the Methodology chapter, specifically focusing on getting the right configuration for consistent diameters in the filament. Once this issue is solved, the filament can be tested in actual 3D printers to test for its production effectiveness. If it is comparable to the Protopasta filament, this result could drastically change how stator assemblies and ultimately MMT's are made.

With respect to the newly created modular filament extruder, there are many ways to continuously improve it. We would recommend that all parts of the extruder, with the exception of legacy materials, be machined instead of 3D printed. Doing this will improve the overall appearance of the device as well as improve the tolerancing and the longevity of the device. Adding a fan at the end of the nozzle provided success when attempting to improve the original filastruder, and may prove beneficial at making the diameter of the filament more consistent.

Finally, we recommend testing ways of removing the filament from the device. The original filastruder came with a winding device that would take the produced filament and attach it to a spool to be used later. However, the winder was broken when we received it. We were unable to fix the device and eventually gave it to another MQP group so its parts could be repurposed. We would recommend that another winding device be fabricated or purchased. Hopefully, the constant tension from the device would help the filament to properly form into the right diameter. Another method to attempt would be running the filament extruding in tandem the newly extruded filament directly into a 3D printer while it is performing an operation. However, this requires matching the timing between the two devices and can become very difficult.

During eddy current testing, one major issue was the plasticity temperature of PLA, which has a glass transition 60–65 °C. This means that the filament will begin to deform when it approaches these temperatures, which was an issue during a few tests. Since it could not be determined if the heating was caused by eddy currents or I^2R heating, a suggestion for teams willing to continue this project would be creating a test coil with a smaller gauge, decreasing the resistance per unit length of wire. This could help to determine what factors may cause the system to heat as quickly as it did. Furthermore, another factor of I^2R heating is the current, which is caused by the amplifier. Due to the availability of only a 5W amp (which was too weak) an 85W amp was used but lacked an internal potentiometer for current control. This means the output could not be ideally controlled. In the continuation of this project, a “volume control” system can be created for this amp.

The Arduino Due’s DAC output seemed to struggle creating frequencies above 1kHz, though this can possibly be rectified by changing the clock speed of the processor. Thermocouple accuracy was another error that was encountered as false values would be read by the Arduino, possibly due to electrical interference. These errors could be resolved by creating a more efficient code as well as adding an external ADC to acquire more precise readings from the thermocouple.

Chapter 6: Conclusion

During our time working on this project, we have come to believe that this is a viable way to improve the production of loudspeaker transducers. 3D printing has several advantages, such as its cheapness, widespread availability, and speed of production. These advantages could prove to make this method of manufacturing MMT a viable alternative to traditional laminated designs. With continued research and experimentation, the team is confident that self-produced magnetic filament can be used within a speaker assembly to reduce heating due to eddy currents. If successful, this project could drastically change the production of speakers.

Update

Nearing the end of the project, the team was informed by Professor Stabile that the 3D Printed "Muscle" team successfully printed using the 15% iron/PLA filament. Although this news had no effect on this particular project itself, it serves as a step in the right direction to completing a fully 3D printed ferromagnetic stator assembly for use in a reduced eddy current MMT.

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Appendices

Appendix A: Modular Filament Extruder CAD

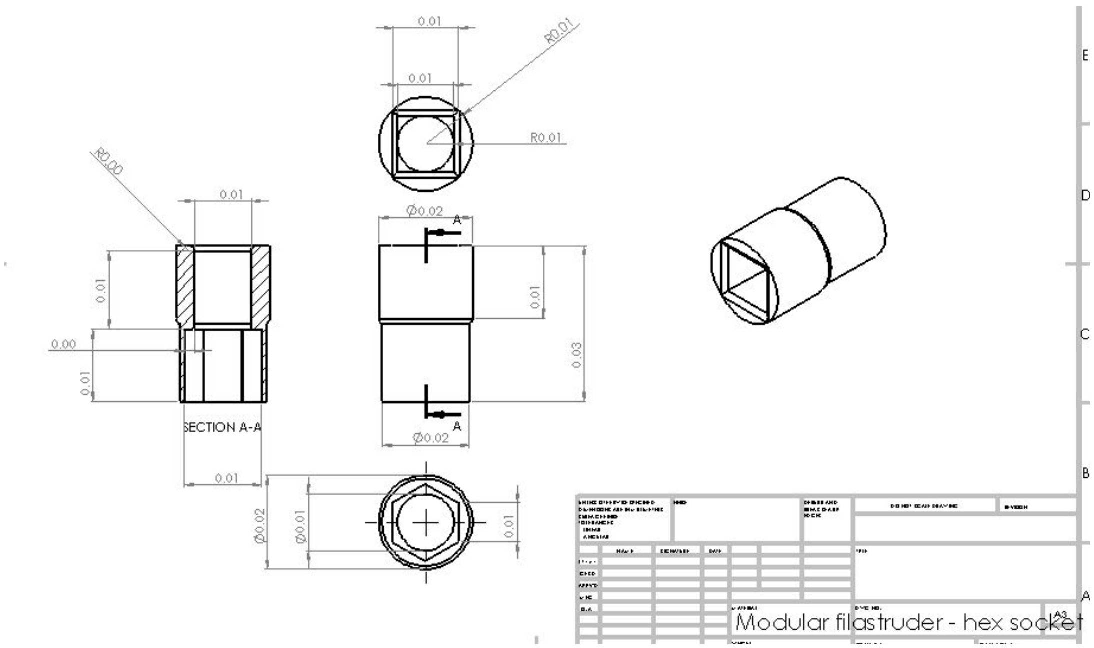

Figure 43: Screw/Motor Connection Coupling Drawing

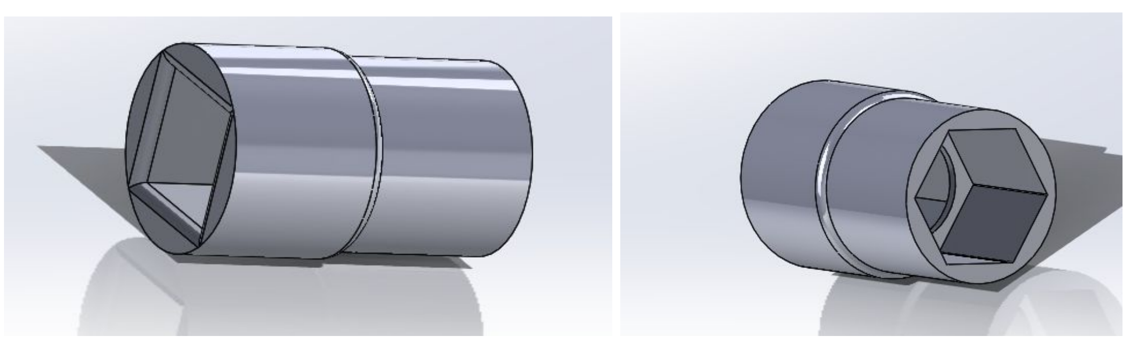

Figure 44: Screw/Motor Connection Coupling Isometric Model

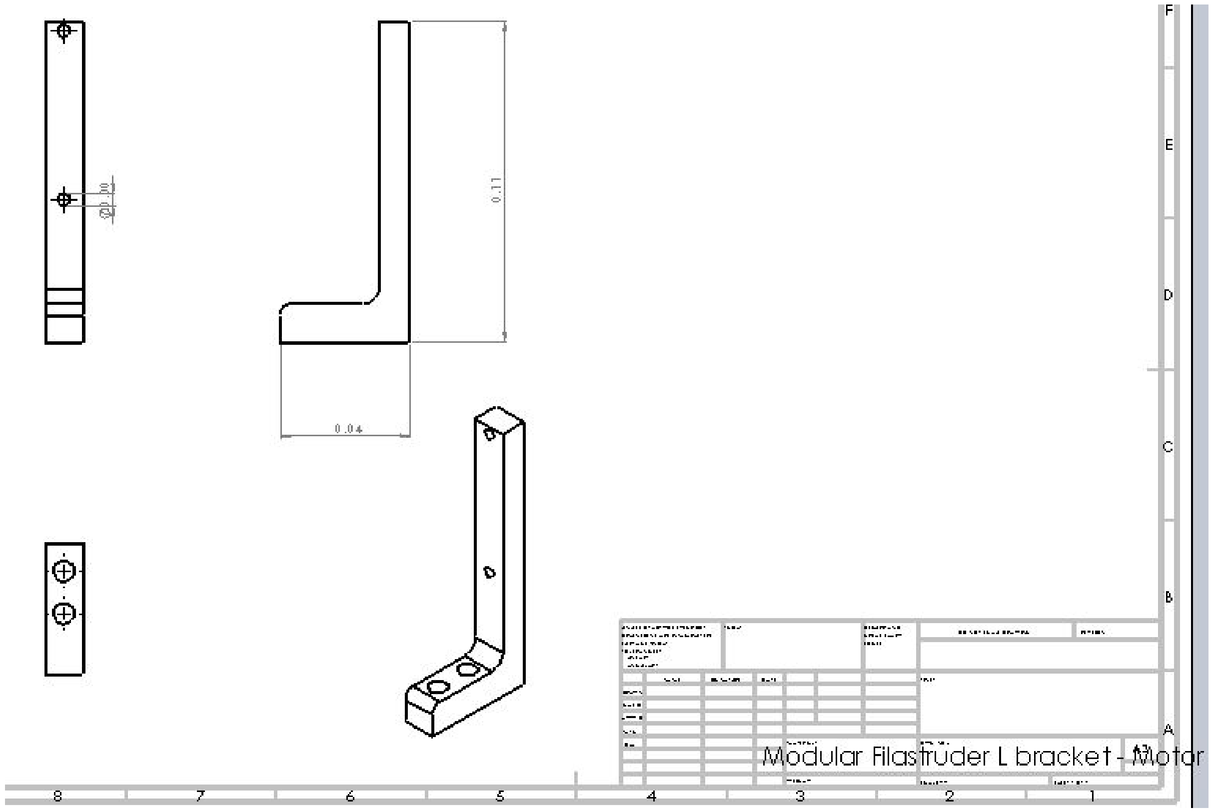

Figure 45: Motor L Bracket Drawing

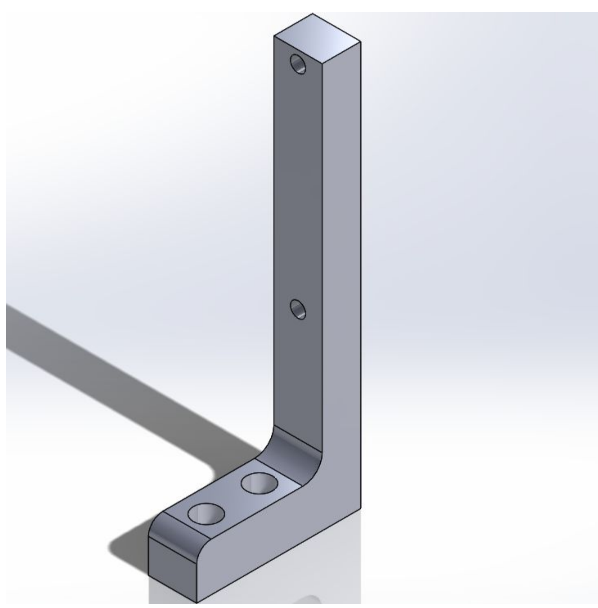

Figure 46: Motor L Bracket 3D Model

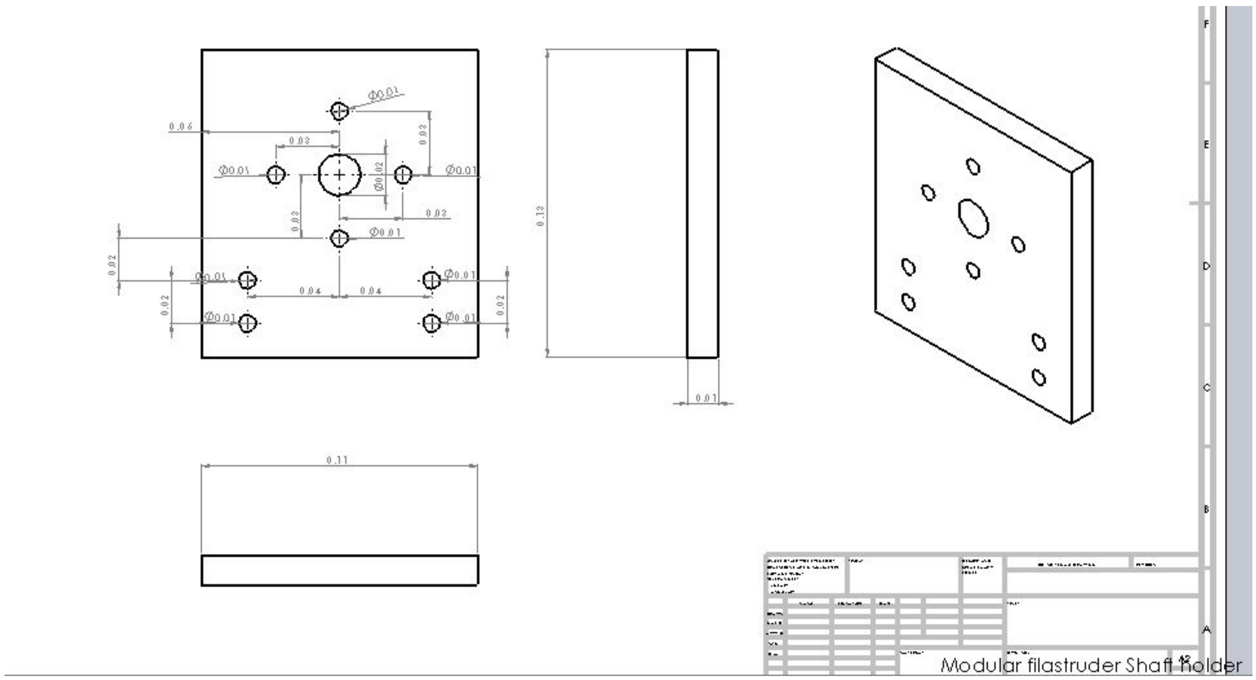

Figure 47: Extruder Shaft Fixture Drawing

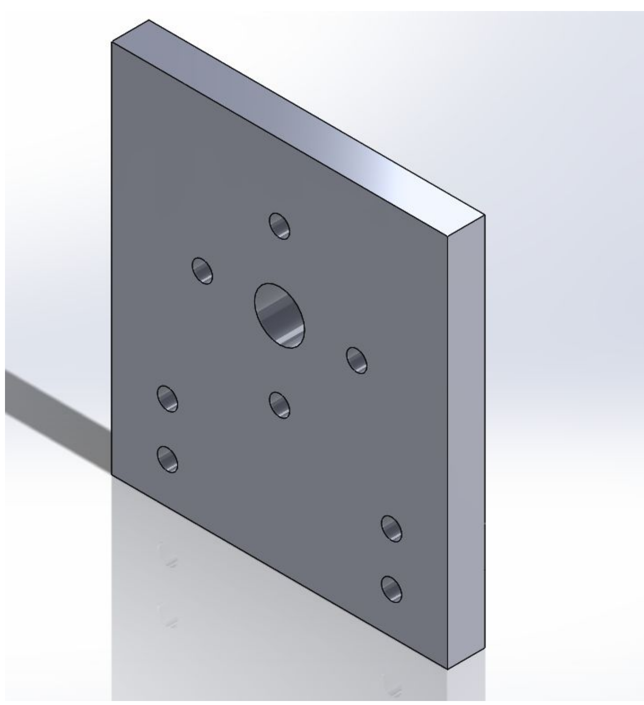

Figure 48: Extruder Shaft Fixture 3D Model

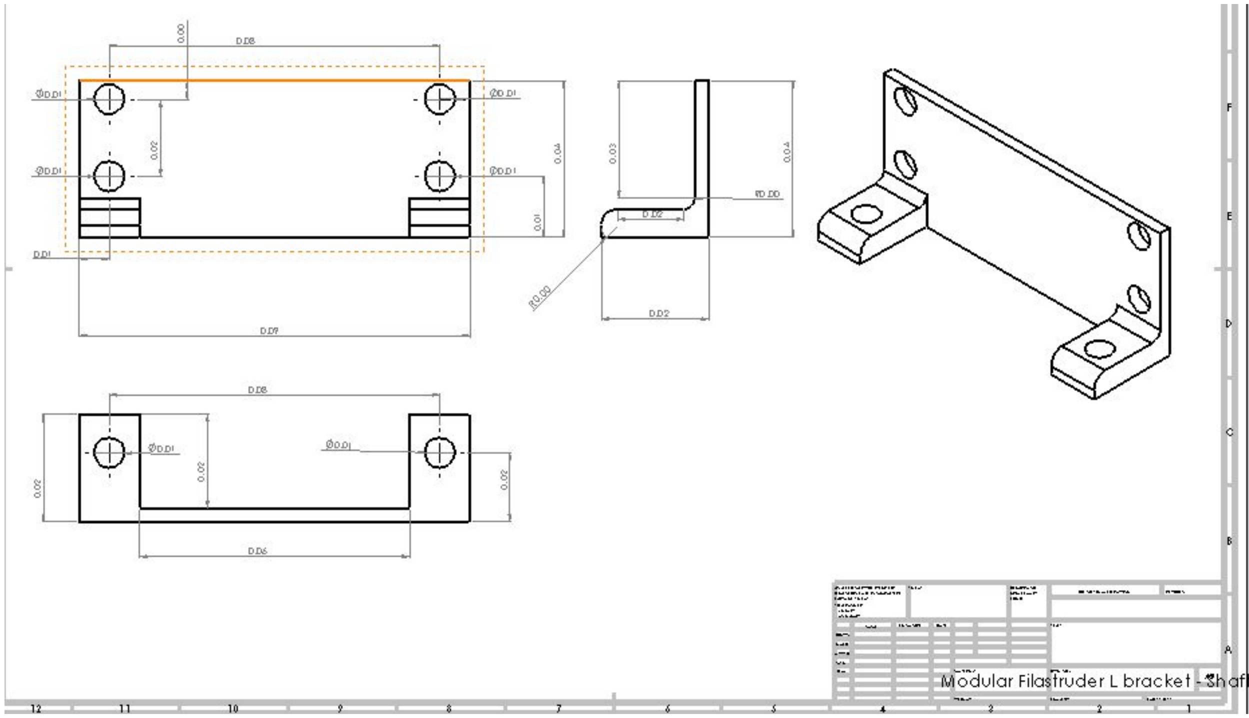

Figure 49: Extruder Shaft Fixture L Bracket Drawing

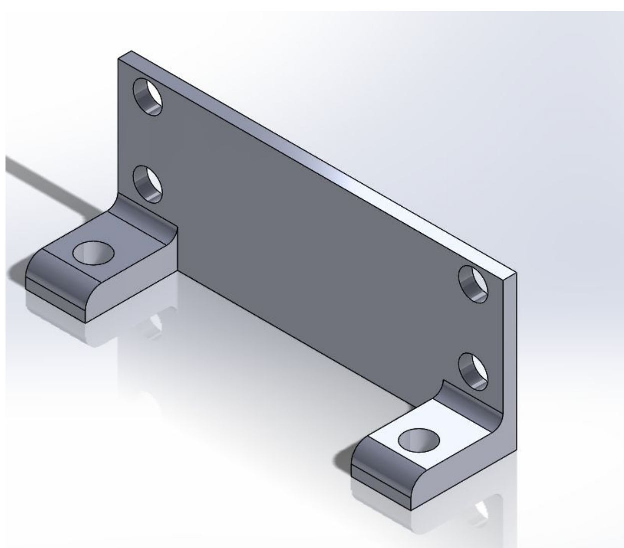

Figure 50: Extruder Shaft Fixture L Bracket 3D Model

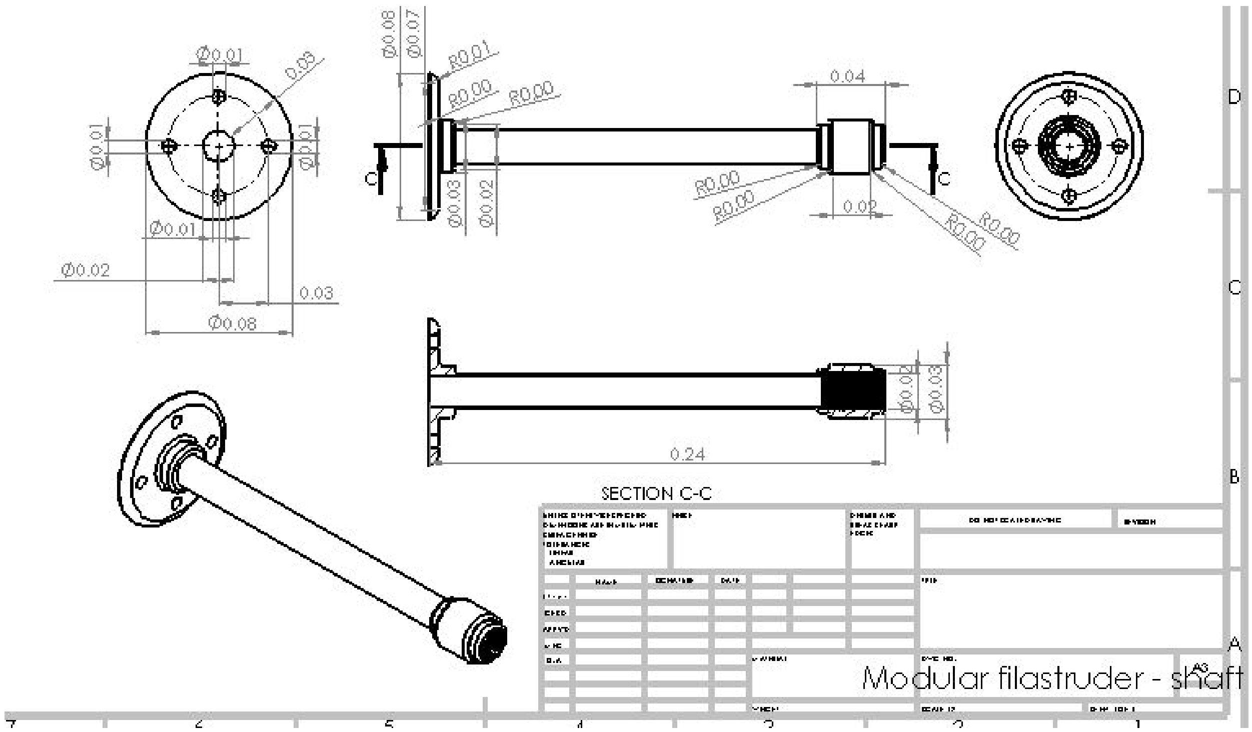

Figure 51: Extruder Shaft Drawing

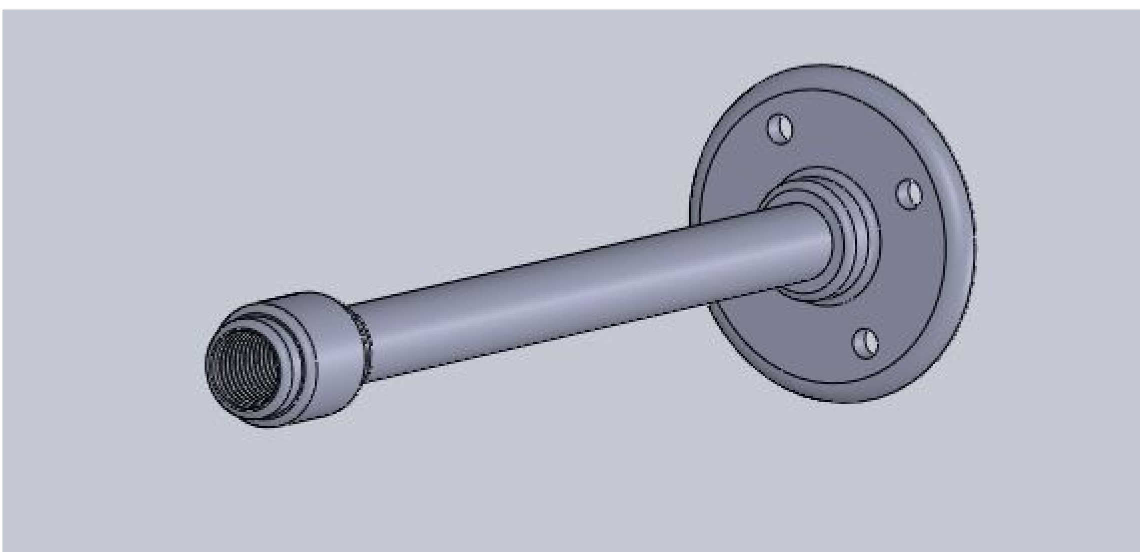

Figure 52: Extruder Shaft 3D Model

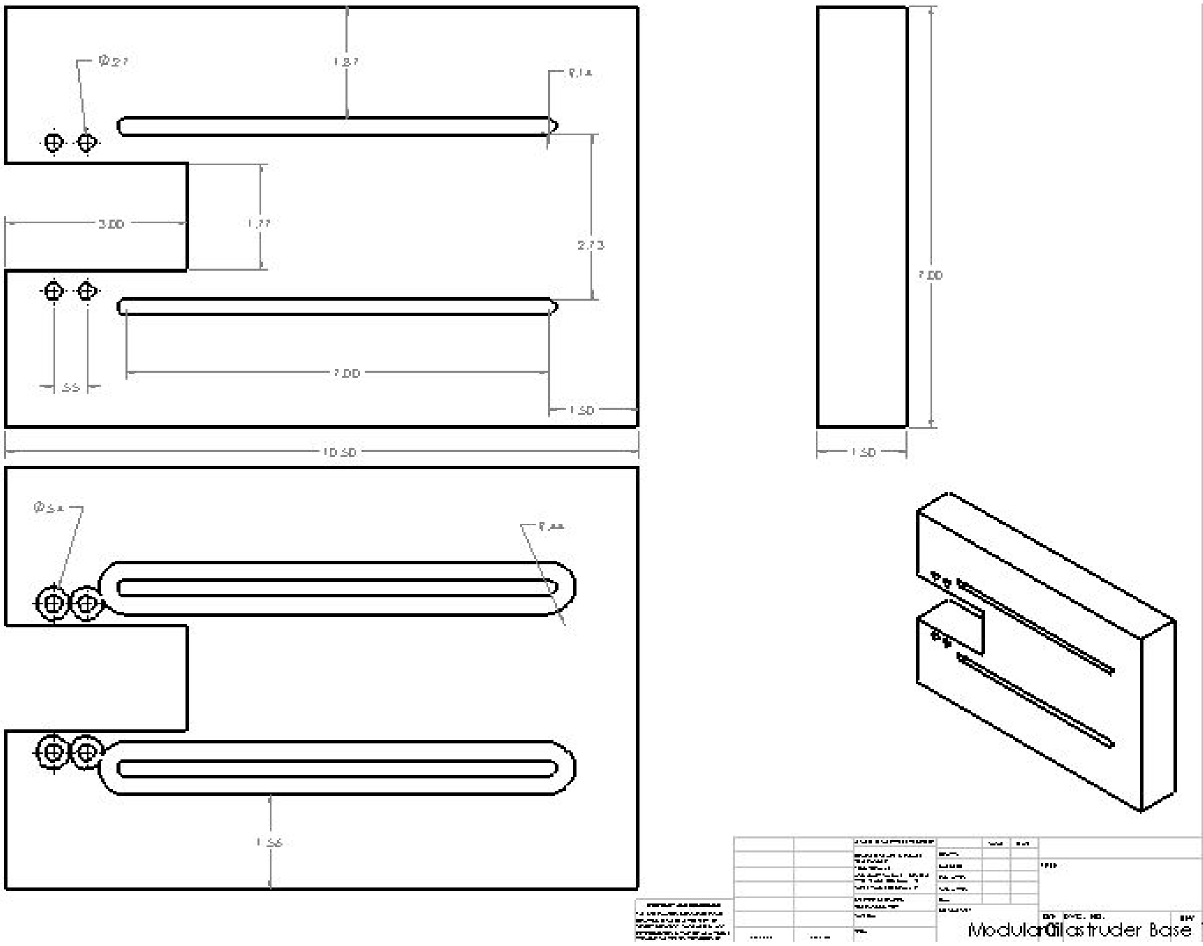

Figure 53: Extruder Base Drawing

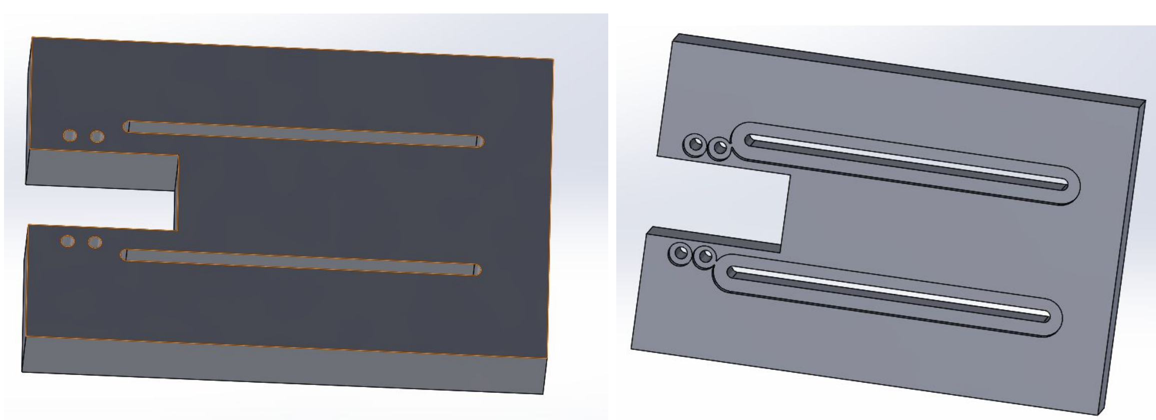

Figure 54: Extruder Base 3D Model

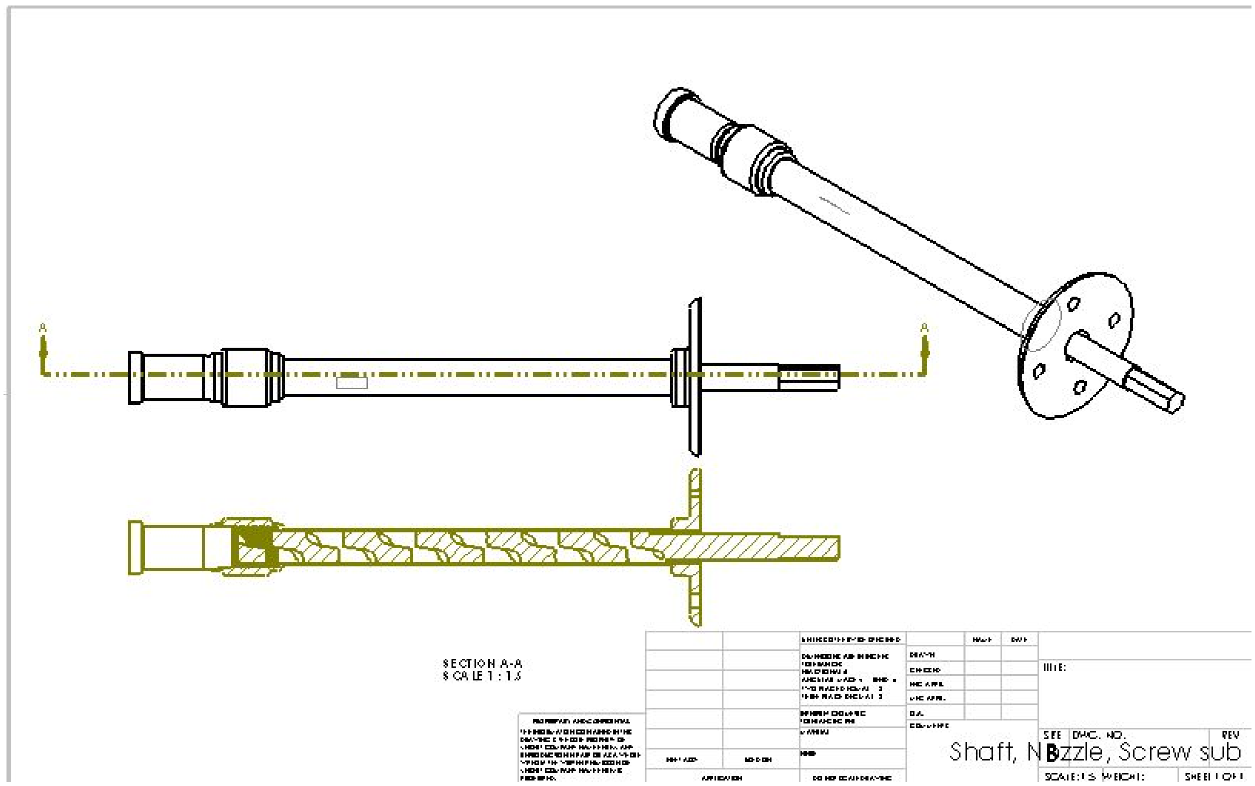

Figure 55: Extruder Screw Subassembly Drawing

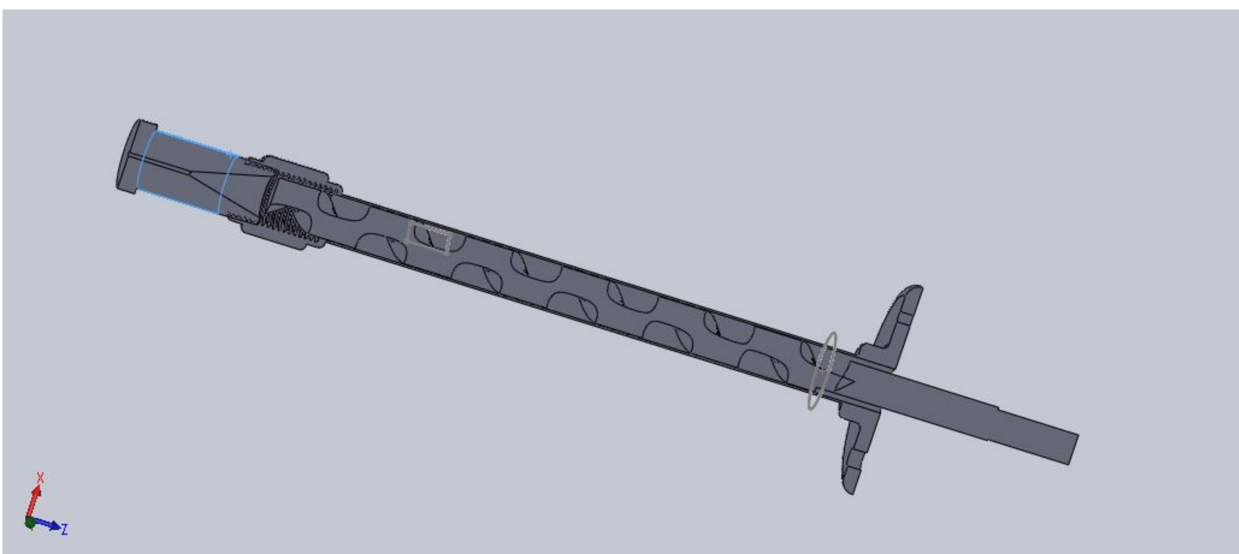

Figure 56: Extruder Screw Subassembly 3D Model (Section View)

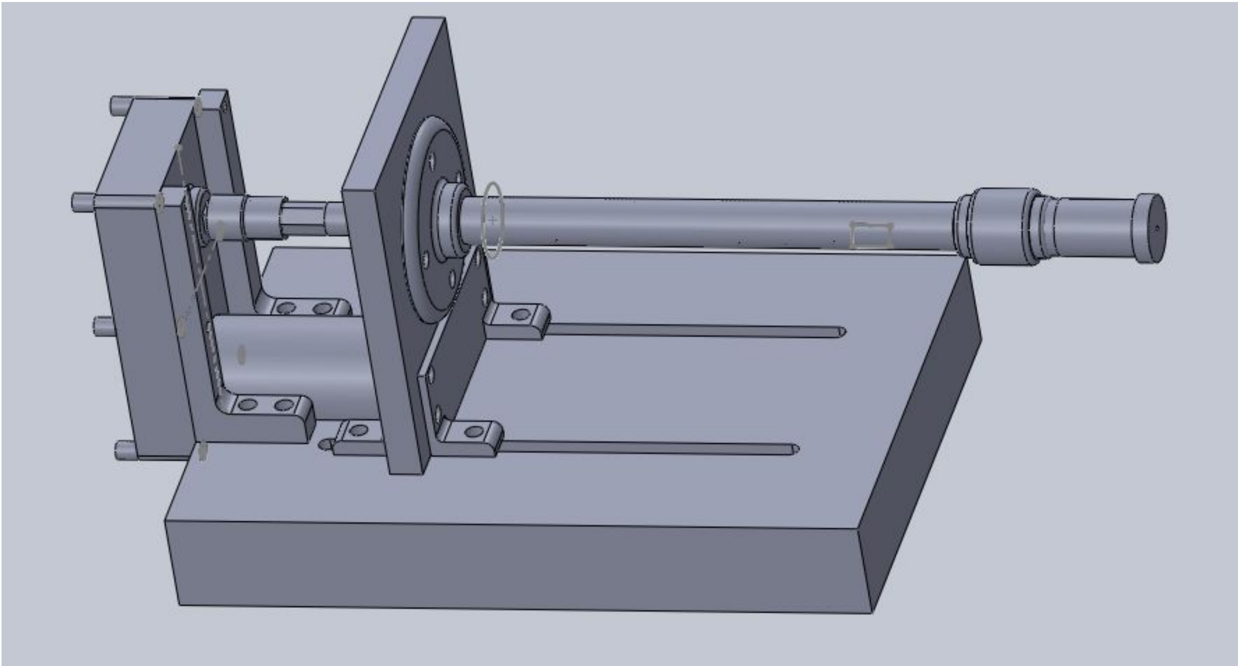

Figure 57: Modular Filament Extruder Assembly Drawing

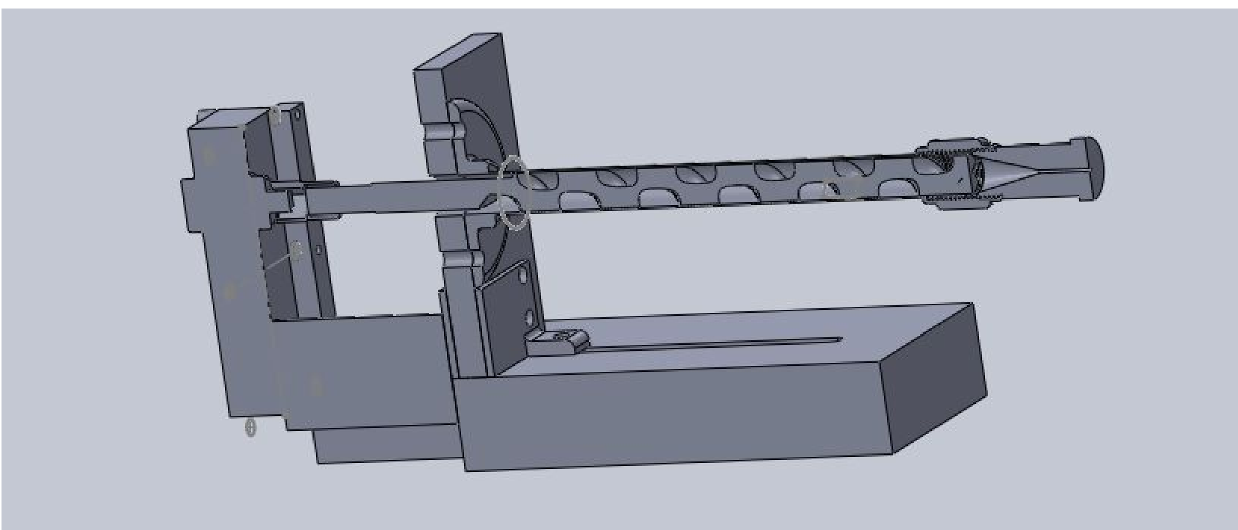

Figure 58: Modular Filament Extruder Assembly Section View

Appendix B: Nozzle EDM & CAM Profile

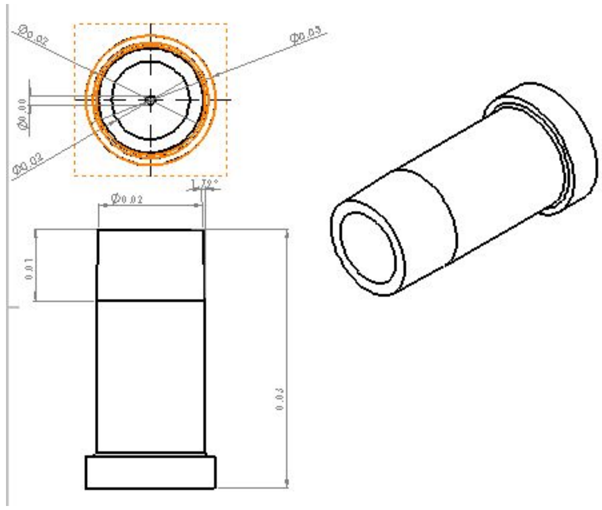

Figure 59: Tapered Nozzle Drawing

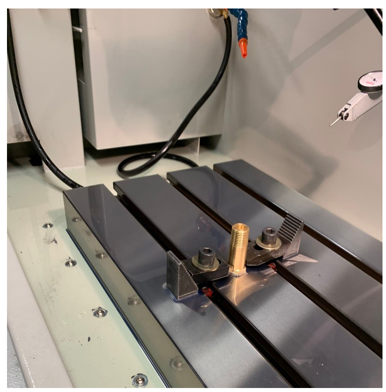

Figure 60: Tapered Nozzle Operation in EDM Machine

Figure 61: Machined Tapered Nozzle - Right:View of Internal Taper

Appendix D: DOE Experiment Data Collection Form (Link)

A link to view the data collection form is below:
https://docs.google.com/spreadsheets/d/16X-3fdeuQPJEFHhKzr2ppNEdQmEMGpjz_Tt2Gg6EP98/edit?usp=sharing

Appendix E: Safety Data Sheet- Protopasta

A link to view the safety data sheet for Protopasta is below:
https://cdn.shopify.com/s/files/1/0717/9095/files/FEP1xxxx_SDS.pdf?1992606272897634343

Appendix F: Somaloy Information Sheet

A link to view the Somaloy information sheet is below:
https://docs.wixstatic.com/ugd/57a430_f04b6c55ec65496487d85762af87294d.pdf

Appendix G: Vertical Extruding Process Document

1. Fixing the Filastruder in a vertical position with a fan at the nozzle to cool the filament as shown in figure ____. This process was begun by a previous group.

Figure 62: Vertical Extrusion Setup

2. Turning on the heating element and letting the Filastruder reach around 140 degrees Celsius,
3. Turning the motor on
4. Load the hopper with the desired material(s).
5. Let the filament extrude out of the nozzle and into the pan

Appendix H: Horizontal Extruding Process Document

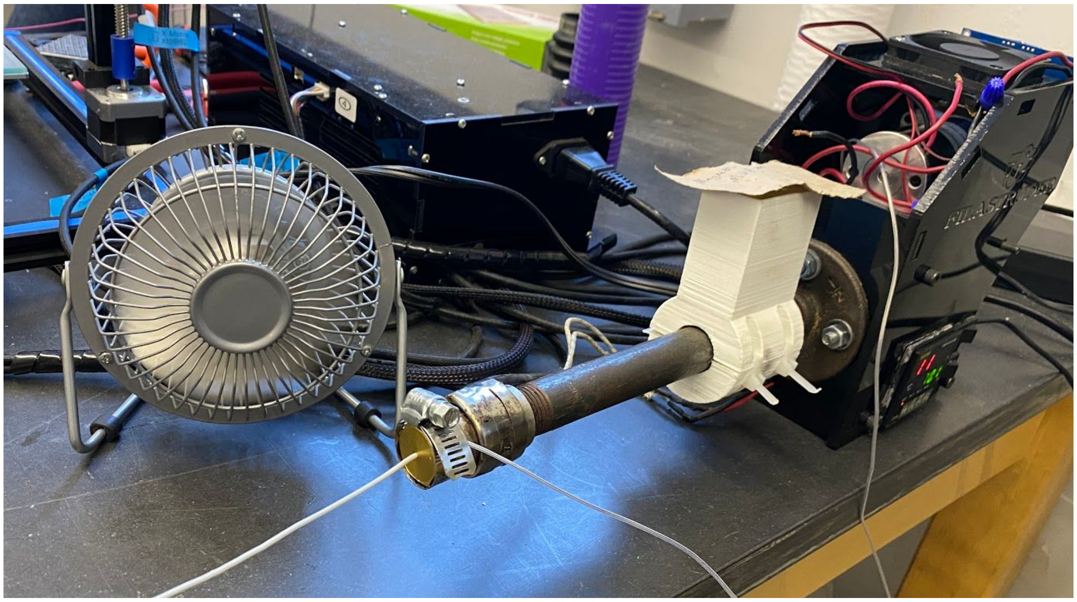

Figure 63: Horizontal Extrusion Setup

The full process is the following:

1. Begin by Placing the Filastruder horizontally pointing off of the elevated surface
2. Turing on the heating element and letting the Filastruder reach around 140 degrees Celsius,
3. Turning the motor on
4. Place fan at the end of the Nozzle and turn on
5. Use blender to grind up material(s) as needed to fit into hopper
6. Load the hopper with desired material(s).
7. Let the filament extrude out of the nozzle and onto the floor
8. Once the filament reaches the floor, with some slack, tape the end of the filament to a spool on the ground
9. Rotate the spool as needed, the filament should fall in a circular fashion

Appendix I: 2nd Press Mold Creation

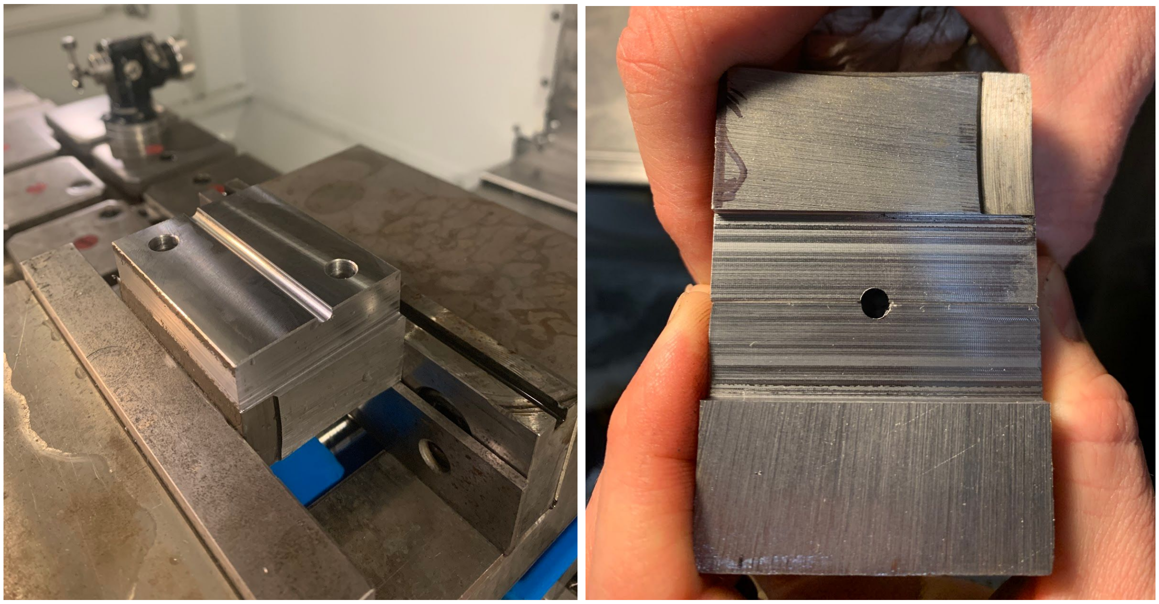

Figure 64: Machining Second Iteration Press Molds in Washburn Shops

Figure 65: Machined Second Iteration Press Mold

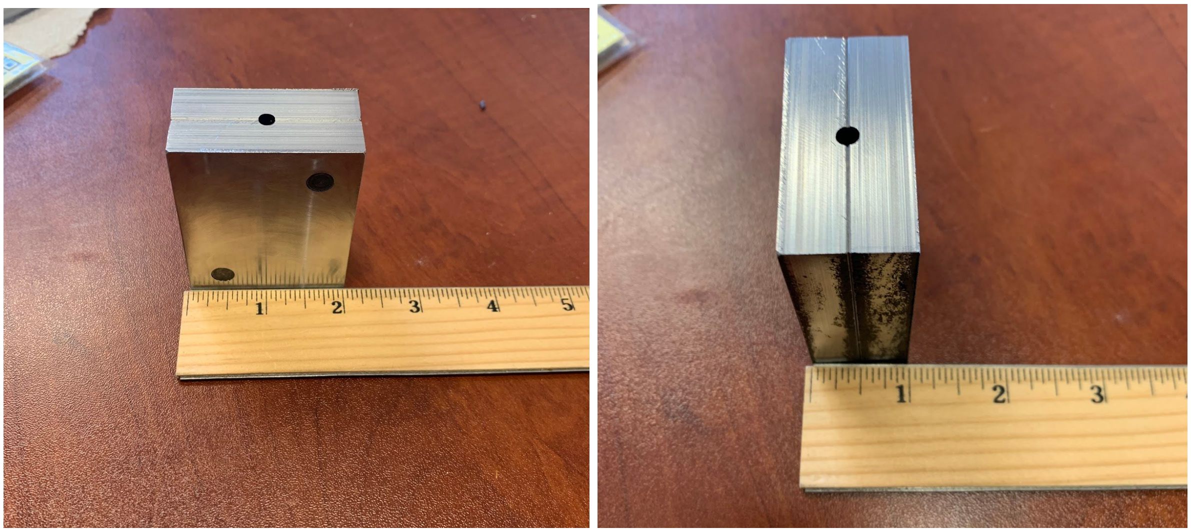

Figure 66: Second Iteration Press Mold Dimensions #1

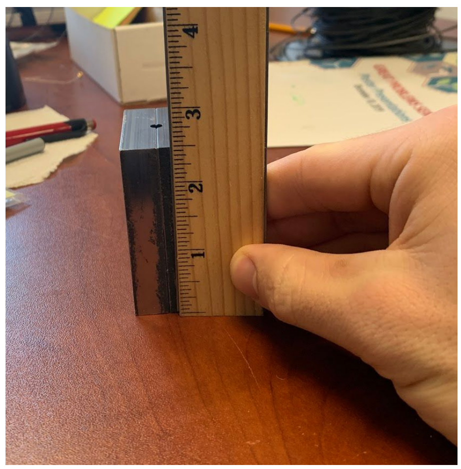

Figure 67: Second Iteration Press Mold Dimensions #2

Appendix J: Prusa Tolerancing Settings

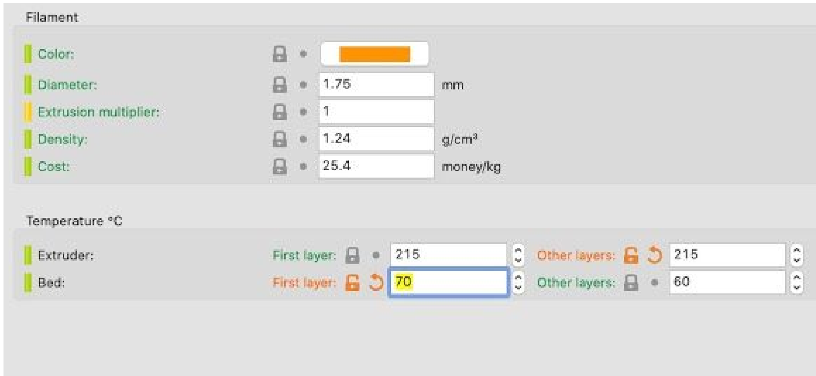

Figure 68: Prusa Stator Print Tolerancing Settings #1

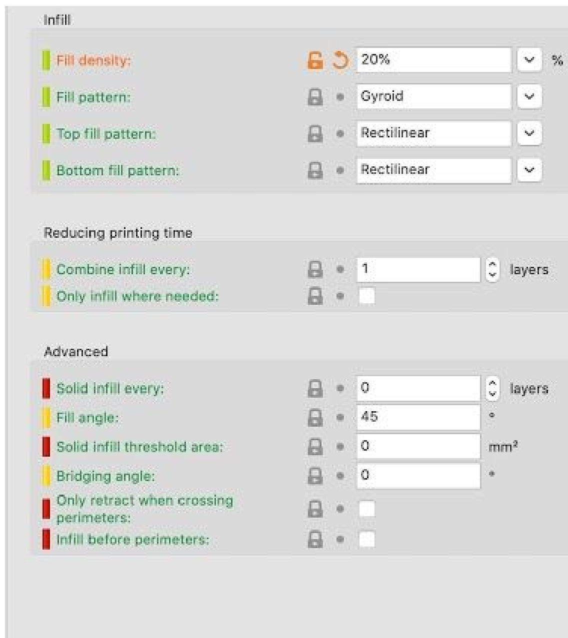

Figure 69: Prusa Stator Print Tolerancing Settings #2

Appendix K: Teardown Analysis Pictures

https://drive.google.com/drive/folders/1AyYb7ebj1Y0yAk_B0RZrAMWII4C_FXgc?usp=sharing

Appendix L: 1st Press Mold Attempt Pictures

https://drive.google.com/drive/folders/1D55Z1BNgULZFR9mKn6faZcECzSXVSP6y?usp=sharing

Appendix M: Eddy Currents Test Arduino Code

```
const int thermocouple_input = A1;  /* AD595 O/P pin */

#include <DueTimer.h>
#include <SineWaveDue.h> //Created by C. Masenas
#include <Wire.h>
#include <LiquidCrystal_I2C.h>

   LiquidCrystal_I2C lcd(0x27,20,4);
   float temperature, max_temp, temp_prev, total, avg_temp, faren1, faren2, last_temp;
   long lastDebounceTime = 0;
   long debounceDelay = 5000; //5 seconds
   int n;
void setup()  {
  analogReadResolution(10);
  analogWriteResolution(10);
  pinMode(9, OUTPUT);
  pinMode(2, OUTPUT);
  digitalWrite(2, LOW);
  Serial.begin(9600); /* Define baud rate for serial communication */

  LiquidCrystal_I2C lcd(0x27,20,4);  // set the LCD address to 0x27 for a 16 chars and 2 line
display

   lcd.init();
   lcd.init();
   lcd.backlight();
```

```
 // Print a message to the LCD.
  Serial.println("Eddy Current Test Bench");

}

void loop()   {
  int adc_val;
  lcd.setBacklight(HIGH);
 for (int i=0; i<11; i++)
 {
  Serial.print("Test Number");
  Serial.println(i);
  Serial.print("Test Number");
  lastDebounceTime = millis();
  adc_val = analogRead(thermocouple_input);
  temperature = ( ((adc_val * 3.22000) - 0.0027000 ) / 10.000000 );
  Serial.print("Starting Temp is:");
  Serial.println(temperature);
  Serial.println("Test will begin in 10 seconds");
  delay(100);
  Serial.println("9");
  delay(100);
  Serial.println("8");
  delay(100);
  Serial.println("7");
  delay(100);
  Serial.println("6");
  delay(100);
  Serial.println("5");
  delay(100);
  Serial.println("4");
  delay(100);
  Serial.println("3");
  delay(100);
  Serial.println("2");
  delay(100);
  Serial.println("1");
  dellay(100);
   digitalWrite(2, HIGH);
```

```
  sw.playTone(200*i);

  if((millis() - lastDebounceTime) > debounceDelay)
  {
    adc_val = analogRead(thermocouple_input);
    temperature = ( ((adc_val * 4.88000) - 0.0027000 ) / 10.000000 );
    Serial.print("Temperature 1 = ");
   Serial.println(temperature);
  }
  else
  {
    sw.stopTone();
    digitalWrite(2, LOW);

  }
  adc_val = analogRead(thermocouple_input);
  temperature = ( ((adc_val * 4.88000) - 0.0027000 ) / 10.000000 );
  last_temp = temperature;


  while ((temperature > 27.0000) && (last_temp > 27.0000)) {
  adc_val = analogRead(thermocouple_input);
  temperature = ( ((adc_val * 4.88000) - 0.0027000 ) / 10.000000 );
  last_temp = temperature;
 Serial.print("Temperature 2 = ");
 Serial.println(temperature);
 lcd.setCursor (0,1);        // go to start of 2nd line
 lcd.print("Temp = ");
 lcd.print(temperature);
  }

 }
}
```

Authorship

Chapter/Section	Author(s)	Editor(s)
Abstract	All	All
Acknowledgments	Tyler Marsh	All
Executive Summary	All	All
Introduction	All	All
Background		
Eddy Currents	Tahvorn George	All
Transducers	Jake Tomkinson	All
Moving Magnet Transducers	Tyler Marsh	All
3D Printing	Brian Liwo, Jake Tomkinson	Tyler Marsh
External Filament Extruding	Tyler Marsh	Jake Tomkinson
Filastruder	Jake Tomkinson	All
Electrical Discharge Machine	Brian Liwo	Tyler Marsh, Jake Tomkinson
Design of Experiments	Tyler Marsh	Brian Liwo
Methodology		
Initial Goals	Brian Liwo	All
Extruding Magnetic Filament	Brian Liwo, Jake Tomkinson	Tyler Marsh
Changing Goals	Brian Liwo	All
Commercial Products	Tyler Marsh	All
Somaloy and Press Molds	Brian Liwo	All
Modular Filament Extruder	Jake Tomkinson	Tyler Marsh
Design of Experimentation	Tyler Marsh	All
Eddy Currents Testing	Tahvorn George	All
Results		
Original Filastruder	Brian Liwo	Jake Tomkinson

Commercial Products	Brian Liwo	Jake Tomkinson
Modular Filament Extruder	Tyler Marsh	All
Eddy Current Testing	Tahvorn George	All
Recommendations	All	All
Conclusion	Brian Liwo	Tahvorn George, Tyler Marsh