The Phoenix MQP: Repurposing PLA into 3D Printing Filament

A Major Qualifying Project
submitted to the Faculty of

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Abstract

Rapid prototyping poses an increasing challenge to the recycling industry. 3D prints are commonly disposed of as projects evolve or prints fail. Many times, when printed parts arrive at recycling centers, they are marked as trash and discarded. With the negative environmental impacts of single use plastic increasing, the need to develop a more sustainable way to repurpose discarded material is necessary. The goal of this project was to develop a compact and low-cost system that would be able to recycle 3D prints into filament without the need for grinding and drying. This goal was achieved and the feasibility of directly heating plastic parts suitable for extrusion at a constant diameter was demonstrated, however the best extruded filament in our prototype had a maximum 1.0mm diameter. The team developed a list of recommendations for the next steps in refining this process.

Acknowledgments

Our team would like to personally thank everyone who helped contribute to this project.

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1.0 Introduction to Plastic Waste

Every year roughly 300 million tons of plastic is produced and over 80% of plastic waste ends up in landfills or in the ocean (*UNEP Beat Plastic Pollution*, 2018). Plastic waste all over the world has altered the planet and our environment; and the impacts are becoming more evident by the day. Humanity is working to decrease the personal use of plastic and strive to live in an environmentally sustainable way. States are passing legislation to limit the use of single-use plastic bags from grocery stores, single-use water bottles, and other main contributors.

Figure 1: Examples of single-use plastics

Across the oceans microparticles of plastics remain suspended in the water since disposable plastics are not biodegradable in realistic timeframes. These components not only pollute the ocean, negatively affecting wildlife, but also find their way into the water mantle. Traces of microplastic particles can even be found in food (*Everything You Should Know about Single-Use Plastic*, 2021).

Figure 2: Waste pickers sorting through landfill

In Figure 2, waste pickers from a landfill in South Africa are sorting through waste to find recyclable plastics. Sorting through landfills and waste sites is hazardous work, and various safety risks and health concerns arise in this field. A study from 2017 documented health risks associated with being a waste picker, and recommended that there be change at not only a government level but also an industry level (Gutberlet & Uddin, 2017). Most industries prioritize cost and efficiency, but also try to minimize societal and environmental impacts.

Additive manufacturing, or 3D printing, has gained traction in a consumer and hobbyist setting. 3D printing allows anyone to quickly manufacture plastic parts in a creative and innovative way. An increasing number of hobbyists have access to 3D printing, however this can lead to excess waste in landfills (Lomas, 2014). Since the associated financial cost to manufacture is low, the environmental expense is high, as these small parts are rarely recycled.

Across the globe there has been great support for reducing plastic waste and in this report, we will explore reducing the amount of plastic filament waste from 3D printers. An example of both the problem and prevalence of 3D printed waste can be found at Worcester Polytechnic Institute, (WPI). At WPI, water bottle filling stations are found in every building, recycling bins exist in every classroom and office, and collaboration spaces encourage users to offer their leftover scrapped pieces for peer reuse. One area where environmental sustainability can be improved is the Makerspace in the Innovation Studio. This area houses over thirty 3D printers that are open to the campus community, and have printed over 1,000 kg of PLA in its three-year lifetime. Prior to the Covid-19 Pandemic, failed prints were recycled by a professional plastic recycling company or kept for teaching purposes. Sadly, since the recycling company is no longer functioning post-pandemic, the Makerspace has been disposing of the waste in the standard trash stream or storing it for future use. Our team met with Mitra Anand, head of the Makerspace, to discuss this issue and of repurposing the discarded prints as well as future collaboration with our team. Through these conversations, our team was provided with the Makerspace's discarded prints.

2.0 Background

Plastic waste is a global crisis that members of all industries are collectively working to combat. Within the additive manufacturing industry, sustainability can be improved upon by recycling the filament from previous projects or prototypes. Currently, companies that manufacture and distribute 3D printer filament prioritize the distribution of new filament over reducing their plastic footprint. When printer filament is placed into landfills it is commonly marked as “trash”, rather than recyclable material. The 3D printing industry can benefit from the push to reduce the amount of filament entering landfills.

3D printer filaments are thermoplastics, polymers that melt rather than burn when they are exposed to high heat. Originally, 3D printer filament was thought of as a single-use plastic. The launch of the first 3D printers in 1981 used polymers that irreversibly hardened after the piece was printed, known as thermosets. This generated some industrial waste but it was minimal due to the low quantity of 3D printers in existence. In 1988, Fused Deposition Modeling was invented and this revolutionized filament for 3D printers (“History of 3D Printing,” 2021). Fused Deposition Modeling is the modern model of printing; the process uses a thermoplastic continuous filament that is melted and applied in layers. Fused Deposition Modeling allows filaments to be applied accurately for quick prototyping custom parts and a variety of other applications for personal use. Consumer filament is sold by spools with their weight ranging from 0.5 kg to 2 kg and the filament mostly comes in two thicknesses: 1.75mm and 3mm. These data points are extremely important when trying to replicate filament because 3D printers are designed for these exact specifications.

There are many different types of thermoplastics such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polyethylene terephthalate glycol (PETG), polyethylene terephthalate (PET), high-impact polystyrene (HIPS), thermoplastic polyurethane (TPU) and aliphatic polyamides (nylon). PLA and PETG are the more common FDM plastics used in 3D printing. This work restricted the tests to PLA, the most common FDM plastic used currently.

In 3D printing, there are many different ways that waste accumulates and the filament is considered obsolete and generally discarded. Unwanted prototypes, support structures, failed prints, and other miscellaneous mistakes are the primary ways. All together, 3D printer waste generates over 8 million kg each year which is being distributed into landfills. It is estimated that in 2015, 79% of plastic produced was either littered or sent to a landfill (Geyer et al., 2017). Despite PLA's label as "biodegradable", it is estimated to take 80 years to fully degrade in a landfill (*Is PLA Filament Actually Biodegradable?*, 2019). To reduce the amount of waste that is generated there are a variety of steps that can be taken.

2.1 Properties of Plastic

The mechanical and thermal properties of all plastics are dictated by their interior structures. The interior structure of a plastic is composed of various long strands of molecules. These strands are known as polymers, deriving from the Greek "polu" (many) and "merus" (a part). Polymer strands consist of a repeating unit of atoms that repeats for an average number of occurrences (Polymers, 2021). The numerical average of the lengths of polymers in a sample is known as the "degree of polymerization". A high degree of polymerization coincides with higher strength since the longer strands tend to get more tangled around each other and produce more secondary bonds between strands ("Degree of Polymerization of Polymers," 2021).

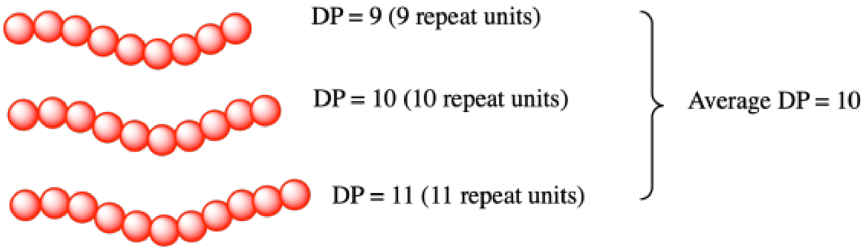


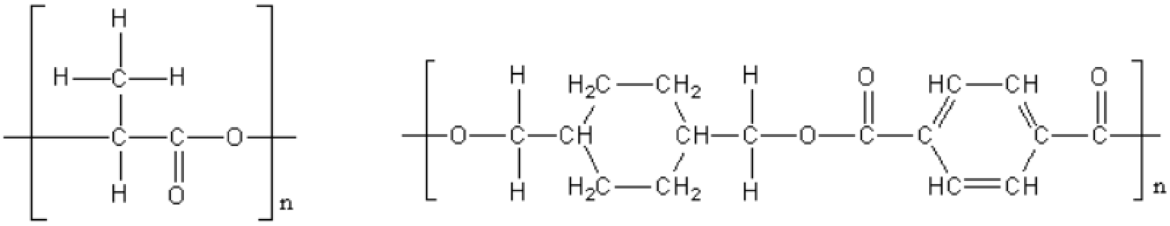
*Figure 3: An illustration of a polymer's degree of polymerization. Often within a plastic there is a range of lengths since the polymer chains are all slightly different, and the DP is a numerical average (Schaller, n.d.)***.**

Polymer strands are often held together by two types of bonds. The atoms within each strand are held together with strong covalent bonds. There are secondary bonds between strands that hold the plastic together (typically through hydrogen covalent bonding). When melted, only the secondary bonds are broken between the molecules, allowing the strands to flow freely past each other. Much higher melting temperatures and/or the addition of pressure during melting can degrade the covalent bonds within polymers and separate atoms from their chains, destroying the strands.

Strand alignment is another important quality of a polymer through the property of "crystallinity". This refers to how highly or loosely packed the polymer strands are inside of the plastic. Each type of plastic has its own likelihood of crystallization. Closely-packed plastics are referred to as highly-crystalline, comparatively those that are not closely-packed are known as amorphous. Since 3D printing is highly dependent on print direction, it is important that 3D printer filament's crystallinity is controlled. PLA is a semi-crystalline plastic, so it will crystallize under the correct thermal conditions, including slow cooling from the melting temperature (Liao et al., 2019). In order to ensure good mechanical properties of 3D printer filament, it is important to encourage crystallization in the polymer.

PLA is the predominant filament for basic 3D printing because it has a low melting point, a good strength, adheres easily to itself, and is affordable to manufacture. These qualities come from its relatively simple structure, which is a polyester with formula $[-CHCO-]_n$ ("Polylactic Acid," 2021). PLA's strength generally comes from its strong hydrogen bonding between chains. This occurs between the double bonded oxygen on one strand and the hydrogen from the methyl group on another strand. PLA is typically semi-crystalline, which means that the molecules are ordered in specific shapes and crystal structures. It can also be found in an amorphous variant, which is more warp-resistant and generally stronger (Essentra Components, 2018).

PETG is a copolymer variant of PET (Polyethylene Terephthalate). The main difference between PET and PETG is that the latter has the addition of glycol (Polyethylene Terephthalate glycol-modified) which changes the chemical properties enough to make it semi-flexible and amorphous. When compared, PETG is more sensitive to degradation by hydrolysis while PLA can crystallize more easily (*PETG vs PLA - Matmatch*, n.d.).



PLA
Polylactic Acid

PETG
Polyethylene Terephthalate Glycol-modified

Figure 4: A comparison of the mer structures of PLA and PETG.

The following polymer properties have been tabulated for comparison and use in this project:

Property	PLA	PETG
3D Printing Temperatures	200 to 220 °C	230 to 250 °C
Melting Temperature	130 to 180 °C	230 to 260 °C
Glass Transition Temperature	55 to 60 °C (amorphous) 60 to 80 °C (semi-crystalline)	67 to 81 °C
Crystallization Temperatures	90–110 °C 25%-30% crystallinity.	N/A
Density	1.210 to 1.430 g/cm^3	1.38 g/cm^3
Modulus of Elasticity	2.7 to 16 GPa	2.8 to 3.1 GPa
Yield Strength	50-55 MPa	55 to 75 MPa

Table 1: PLA properties vs PETG properties.
PLA values from (Poly (Lactic Acid) | ScienceDirect, n.d.; "Polylactic Acid," 2021).
PETG values from ("Polyethylene Terephthalate," 2021)

2.2 Melting

2.2.1 Melting Filament

To extrude plastic into a spool of filament, it must first be in a melted form. Melting temperatures are sometimes given as a range, as polymers tend to get pliant and soft right before melting. As the temperature is increased, the plastic's viscosity decreases until it enters its molten phase (Speranza et al., 2014). This melt can then be directed into the extruder to be shaped before being cooled. In many large-scale manufacturing systems, melting happens in several stages in an enclosed environment such as an extrusion screw. An alternative to this is the plastic will enter an oven and become molten. This method will remove unnecessary stresses in the material. Regardless of the melting method, it is critical to maintain constant temperature to prevent the plastic from burning or degrading.

When generating filament, it is important to remove as much moisture as possible before extrusion. Water can degrade the polymer strains through a process called hydrolysis. In the hydrolysis process, long polymer chains are cut prematurely by water molecules. One half of each strand terminates with a hydroxyl group (OH-) and the other half terminates with a hydrogen atom (H-). Not only does the addition of the hydroxyl group change the individual properties of the strand but shortening polymer strands reduces the plastic's degree of polymerization (*Hydrolysis - Biology LibreTexts*, n.d.).

Many plastic manufacturers opt to dehumidify plastic pellets through a dry heating process. Alternatively, a method of dehumidification is to melt the plastic through a semi-open chamber so that evaporated water can escape. Then the melt can be separated using the difference in boiling points between water and plastic. Heating can be performed through many processes; the most common in small-scale machines is to use a resistive wire.

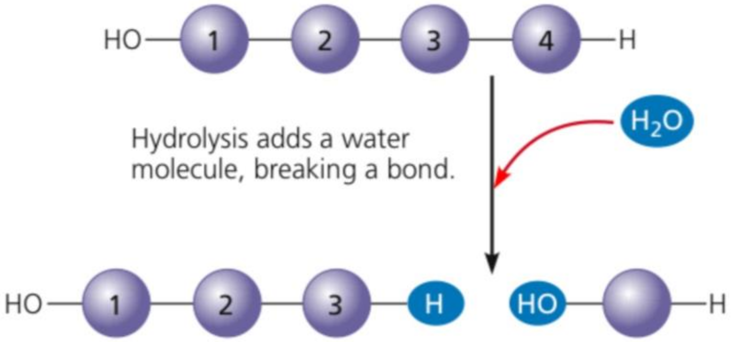


Figure 5: A depiction of a water molecule breaking up a polymer chain (Urry, 2007).

2.2.2 Consumer Melting Solutions

Consumer cooking and melting solutions in cookware such as crockpots, air fryers, and coffee makers are great applications of electric heating methods. Initially, the crockpot seemed like the most comparable to what our project wanted to achieve, melting the plastic at a constant rate for an extended period of time. Crock Pots are made with two castings, the outercasting being a metal and the inner being a ceramic composite (*How Slow Cookers Work*, 2009). The two castings encapsulate electrical coils, in which the heat is transferred through the ceramic to heat the inner chamber of the crockpot. Electrical coils, or electromagnetic coils, is an electrical wire that causes inductance in a circuit by opposing the flow of current to generate heat (*Electric Coil: What Is It?*, 2021). This method of heating is great for low temperatures of 82 to 150 ℃, but it is well below the melting point of PLA.

Dissimilar to the crockpot, air fryers have the capability to achieve much higher temperatures. Air fryers are compacted cylindrical convection ovens that distribute hot air in a small space ("What Is an Air Fryer?," 2021). Convection ovens circulate the air around the oven rapidly to create a faster and evenly distributed heating source. There are fans on the top portion of the chamber of the air fryer that continuously push the hot air down as it rises. The air fryer can heat up to 205 ℃ in only a matter of minutes. In general, convective heating quickly brings up the surface temperature and then conduction will transfer the energy to the interior.

Another, comparable technology is the coffee maker. Coffee makers must quickly heat the water within a chamber and then have it exit through a small hole at the bottom of a funnel shape. Coffee makers have three distinctive components, the heating element for the water, the chamber for the water and coffee grounds to mix, and the heating element on the bottom to keep the coffee warm. Coffee makers use resistive wire that is pressed up against metal components to conductively transfer the heat through the metal. This is the optimal option for modeling our system after due to the parallels between the systems (*How Coffee Makers Work*, 2006).

2.2.3 Resistive Wire

Resistive wire is an important and cost-effective method for heating. When an electric current is applied to the wire, the high resistance value converts some of the passing current into heat energy. The heat energy transfers out of the wire through convection into the air or conduction into an adjacent solid material. Resistive wire is typically rated and priced for its resistance per unit length in Ohms/meter (“Resistance Wire | MWS Wire,” n.d.).

Resistive wires come in a variety of compositions and sizes, with the most popular material being Nichrome, a mix of 80% nickel and 20% chromium. Nichrome is popular because of its oxidation properties; when heated it develops an exterior chromium-oxide layer. This layer of Cr_2O_3 is an optimal medium for conducting the heat from the wire to the air and prevents other types of insulating oxidation from forming that other metals generate. Nichrome has a melting point of 1400 °C and a typical resistivity of 675 Ohms/ft (“Nichrome,” 2021).

Selecting the correct resistive wire for the application at hand is important. A resistance too high will instead act as an insulator and will prevent any current from running through the full length of the wire. A resistance too low will not transfer enough heat into the medium.

2.2.4 Insulation

To maintain a constant temperature and preserve energy, sufficient insulation must be used to satisfy thermal design requirements. Ovens see temperatures ranging from 120-250℃. Typically, fiberglass insulation or ceramic fiber blankets are used as they can withstand and insulate temperatures up to 1600 ℃ (“Ceramic Fiber Blankets for Industrial Furnaces,” 2020). Fiberglass has ideal material properties for high temperature insulation such as low thermal expansion, high thermal endurance, and insulation (*Properties of Fiberglass Fabrics*, n.d.).

2.3 Shredding

The first step in many recycling systems is to turn the varying sizes of input plastic into a similar shape and size for processing. For plastics, this process is typically done by shredding. There are advantages of a shredder within a refurbishing system for plastic filaments. Shredding plastic to similarly sized pellets can facilitate heat distribution in an oven. An additional benefit of melting equally sized pellets is that they would generate a consistent output flow of melted plastic. Inversely, with varying shapes, sizes, and thickness of input material without a shredder, the flow of melted material to the extruder might be inconsistent. A final but important reason for shredding plastic is that it allows for a smaller oven size. Since the oven may be limited in size, deciding to not shred plastic parts before melting would limit the input size of parts. A shredder can be much larger since thermal distribution is not a consideration.

However, shredding plastic parts before melting also introduces many consequences. For one, an entire separate subsystem must be constructed. This system requires considerable force to break apart (shred) plastic and will take up a larger volume. A shredder that produces a consistent size of resin pellets regardless of the input material will be difficult to perfect. Furthermore, the system will require high power and might require some human input to operate and ensure no clogs occur. Finally, a machine which shreds strong plastics to a resin is dangerous and creates safety concerns surrounding its operation. For these reasons and albeit with advantages, the drawbacks of a shredding step were deemed unfavorable, and a thermal solution strategy was adopted.

2.4 Other Companies

Recycling plastics for additive manufacturing use is an emerging industry. For 3D printing specifically, the process of recycling is divided up into two steps: the first being grinding down the material, and the second being the act of extrusion. The process of recycling filament is of interest to many companies, but there is a great need for an affordable hobbyist machine. There also is an integration gap in the industries between waste collection and the act of processing the waste to reuse it. Few 3D printing companies have been successful in bridging this gap and many instead address the two steps independently.

2.4.1 Filabot

Filabot is a Vermont based company that is committed to shifting a “throwaway society” into one that “reclaims and creates”. They have the same goal as our team: to recycle plastic waste and re-extrude it into filament. Filabot is partnered with TerraCycle, who offers 3D Print Zero Waste Boxes for $84.95. Customers fill their box with failed prints and left over filament, and ship the box back with a prepaid label to TerraCycle for recycling. TerraCycle then handles sorting and breaking down the plastics into a state where they can be reused in large scale facilities throughout the United States (*About TerraCycle®*, n.d.).

Aside from recycling, Filabot’s main revenue comes from materials testing. Clients will send raw material pellets and the corresponding datasheets to Filabot, then engineers will use either the Filabot EX2 or EX6 to create filament for strength testing. Pellet extruding tests cost $375 and the solid grinding extruding tests cost $425. Although Filabot has not closed the gap between the recycling process and the extrusion process, they are a great resource for small businesses and enthusiasts to ensure they are maintaining quality in their plastic production (*Filabot Services*, n.d.).

2.4.2 3DEVO

A company that offers both plastic grinding and extrusion is 3DEVO. Based in the Netherlands, 3DEVO engineers have designed the GP20 machine to take 3D prints, shred them down in a hopper, and press them into pellets. These pellets can be used in one of their four filament extruding machines. Though the GP20 is not priced yet, it will most likely be priced comparable to their extruders. These extruders range in cost from $7,400 to $9,600. If a customer wanted to be able to both grind and extrude material using the two separate systems, they would be spending around $20,000. This price point exceeds the budget of hobbyists and some small businesses and makes recycling plastic into filament using the 3DEVO products impractical (*GP20 Plastic Shredder Hybrid | 3devo*, n.d.).

Another caveat of the 3DEVO is that for problem free extrusion, the user can only extrude plastic from pellet form. 3DEVO has no customer reviews displayed on their website, however many hobbyists have shared their concerns via youtube or online forums. Customers and experists have tried to modify the machine to allow shaved plastic to enter the hopper, and many issues have been reported. The sharp corners on the pieces of resin restrict flow from the funnel into the extrusion screw. When working with materials with these physical parameters, an additional material vibrator is sometimes necessary to shake material to stop blockages. However, the vibrator must pulse in delayed intervals since a continuous vibration may result in air pockets entering the screw. Before filament is extruded, it is recommended to add a filter on the front of the nozzle to keep out the bigger particles from the filament (CNC Kitchen, 2021).

Figure 6: 3DEVO Composer and Precision Series Model Extruders

3DEVO extruders operate using feedback loops. Once the filament is extruded, it passes through two half cylindrical rollers and finally a diameter sensor. This sensor will increase the pulling speed of the plastic if the diameter is found to be too large, or slow it down if the diameter begins to be too small.

2.4.3 Filastruder

An extruder brand that is priced for hobbyists is the Filastruder. This creates filament from small plastic pellets. A customer can select to purchase a Filastruder Kit for $300. This is a self-assembled extruder kit with an optional $170 additional filament winder. The kit is advertised to have an easy user interface where speed and torque can be adjusted and multiple nozzles to vary filament diameter. Moreover, there are a variety of miscellaneous parts hobbyists can purchase if they are making extruders of their own. Filastruder claims that their kit can extrude 1kg of filament in 5-8 hours, however some customer reviews say this process can take up to 12 hours (Makezine.com, 2013).

2.4.4 Injection Molding

Another additive manufacturing process that parallels filament extrusion is injection molding. Small plastic pellets enter the extrusion screw chamber and are heated into molten plastic in between the flights of the extrusion screw. As the plastic travels down the screw the tolerance between the barrel edge and the screw becomes tighter, increasing the mixing of plastic and yielding a more thorough heating process. Additionally, the inside diameter of the screw increases with length, forcing air out of the plastic between the flights. Plastic escapes the barrel through flutes on the end of the screw and the molten plastic is pushed into the mold. To speed up the cooling of the injected plastic, coolant or water will flow through tubes adjacent to the mold. This cooling differs from that of the 3DEVO since the primary cooling for the extruder is done by two fans. (engineerguy, 2015).

3.0 Design Process and Fabrication

The design process involved separating the main components of our assembly into seven subassemblies: Frame, Oven, Temperature Control, Motors, Diameter Measurer “Diamatron”, Cooling and Spooler. In weekly meetings, design iterations were discussed, 3D-modeled, and analyzed for all aspects of the system. A major obstacle that dictated some of the design constraints was the limited budget, so many designs were modified as new or lower cost stock parts and material were found on campus. To begin the brain storing process, our team took inspiration from traditional filament extrusion practices and hobbyist prototypes.

3.1 Initial Frame Design

The driving design requirement for our machine’s size came from hobbyists, as they are the primary target consumer of this type of product. A small system is ideal for at home workspaces and many consumer 3D printers have a bed size of around 8.5 square inches (220mm), so a constraint became to design a compact footprint. The frame stands 4-feet tall, with a 1-foot by 1-foot square base. It provides structural support for all subassemblies of the system. Due to the temperature requirements of our design and the nature of this prototype, it is constructed out of 1010 and 1020 T-slotted aluminum bars. Metal brackets secure the connections of the frame along with the appropriate M5 hardware. In the middle of the frame, there are two horizontal bars that hold the base of the oven. The oven is the heaviest part of this assembly and needs to be fastened safely as it holds molten plastic.

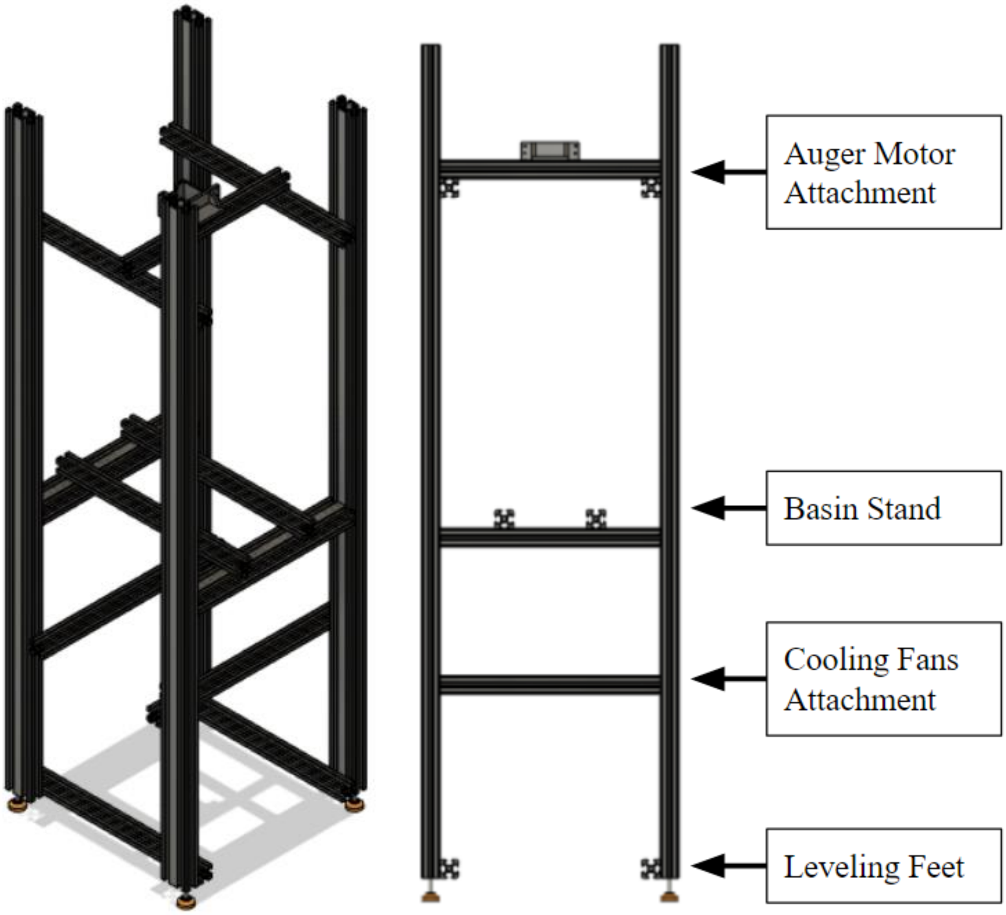


Figure 7: Frame without any parts attached.

3.2 Oven Design and Extrusion Design

3.2.1 Pressure Extrusion Test

Two options that were explored for the oven were a pressurized chamber and an auger-based extruder method. In the first option, a sealed heated pressure vessel would melt the plastic, and as plastic becomes molten, it would escape through an extrusion hole at the oven's base. Since this type of extrusion method is uncommon, initial testing was required as a proof-of-concept. The goal of this test was to see if plastic (heated to 225 °C) would flow through a 2mm hole at the bottom of a cylindrical funnel if an external force was applied. Our team was interested in observing the viscous behavior of plastic at this temperature, as well as temperature leading up to 225 °C. Moreover, our team was concerned about the possibility of achieving a constant filament diameter under these conditions. A prototype was made from a 2-inch by 2-inch aluminum stock, with a 2mm hole in the center, as shown in Figure 8. We used a 2mm extrusion hole over a 1.75mm, since the plastic will shrink as it cools leaving the test rig. The “funnel” piece had a ramping angle of 15°.

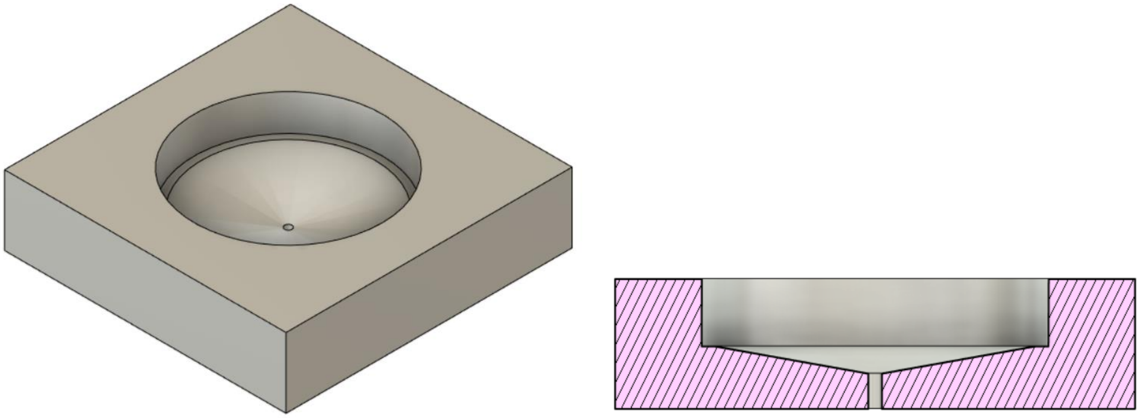


Figure 8: CAD Model of the base of Prototype 1.

A small hollow cylinder was placed on top of the prototype's base, as shown in Figure 9. Inside of this cylinder, five plastic disks were loaded. These disks were waste from WPI’s Maker Space, these disks can be seen in Figure 10. A small cylindrical “plunger” was placed on top of the plastic and loaded during testing.

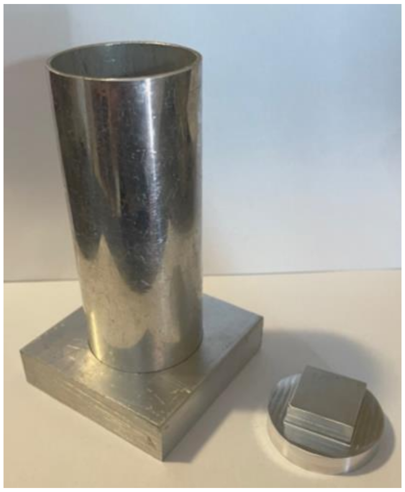


Figure 9: Image of Prototype 1

Figure 10: Plastic used in Prototype 1

With the preliminary results that were extracted from this test it was evident that the system needed a constant pressure that would regulate the amount of force driving the plastic through the 2mm hole. This option would require extreme pressure, which would have had to be externally added. With this external pressure, it was unclear the numerical amount we would have needed to apply to get a constant diameter from the oven. This preliminary prototype proved that the plastic would achieve the required viscosity but the high pressure requirements encourage our team to pursue our other option.

3.2.2 Auger Extrusion Design and Implementation

The traditionally used auger screw method controls the flow of material down a heated tunnel. In this design, an auger screw pushes molten plastic down its flights to an extrusion point at the bottom of a shaft. One disadvantage of this method over the pressure vessel is the screw shaft limits the size of the plastic parts that can fill the oven, since it sits in the center of the oven. Similarly, the shaft extends thru the access lid introducing potentially more oven heat loss. However, on balance the auger strategy had far fewer unknowns and significantly reduced expenses, both immediate and annually. We designed the sub-assembly in Figure 11.

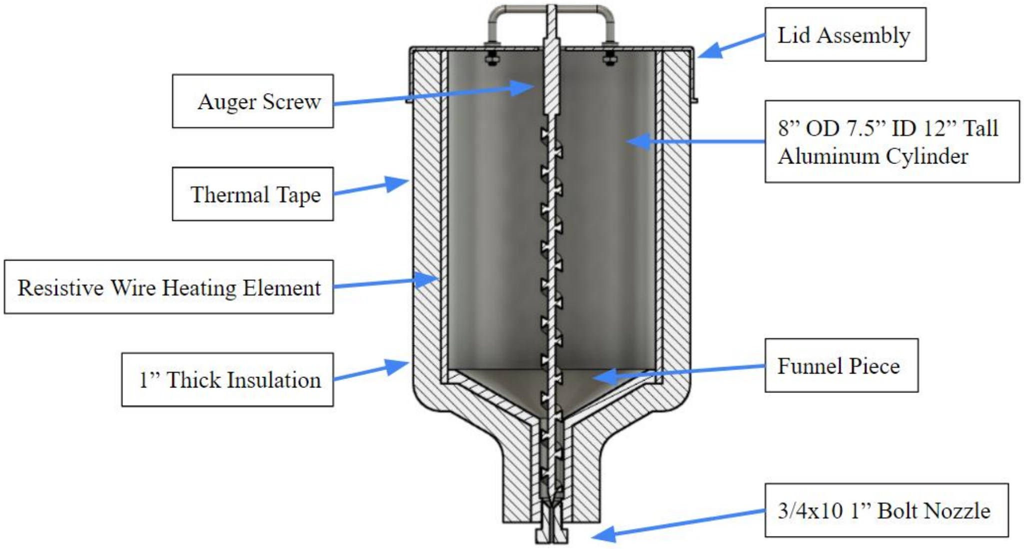


Figure 11: Oven Section View

The oven is made of two large aluminum pieces: a large pipe and a ramped funnel. These two pieces are permanently attached by set screws and aluminum-grade JB-weld. Pushing plastic down the funnel and into the nozzle is the 3/4" OD auger screw. This 18" long auger screw is held in place by the narrow shaft at the bottom of the funnel and held up by a stepper motor attached to the frame above the oven. At the bottom of the narrow shaft is the nozzle, through which plastic is extruded. The base of the funnel's narrow shaft is threaded, which allows the nozzle size to be changed to test different extrusion diameters. The large pipe, ramped funnel, and nozzle are all heated by resistive wire, which is wrapped along the whole assembly. Resting tightly against the resistive wire is an insulation blanket to thermally insulate the oven from its environment.

The top of the oven is covered by an oversized lid, which can fit around the insulation. To accommodate our limited budget, an aluminum 9-inch cake pan was purchased to use as a lid. To accommodate the auger screw, a 1” hole was drilled in the center of the lid. Next, two smaller through holes were drilled close to the edge for the handle attachment. The handle is joined to the lid with two bolts and nuts. The lid assembly can be seen in Figure 12.

Figure 12: Lid Assembly

The oven’s size was dictated by the cost of hollow metal stock and the limitations of the machines in WPI’s manufacturing facility Washburn Shops. Given that the largest lathe (HAAS ST-30SSY) in the shop can only turn a maximum outer diameter of 9-inches, our team chose to center our design around an 8-inch outer diameter pipe. Steel was quickly ruled out because of its high price point and increased difficulty to machine, which made aluminum the optimal material. The aluminum pipe is 0.25” thick, which allows enough material to be threaded for fastening small set screws and is thin enough for easy conduction of heat.

3.2.3 Funnel Design and Manufacturing

Once plastic in the oven melts, it needs to be directed down and extruded out of the nozzle. This process relies on the funnel, a large custom-machined piece of aluminum that connects the oven to the nozzle.

This funnel is fixed inside of the aluminum pipe by a high-temperature epoxy, JB-Weld. Eight set screws were installed to keep the parts in place while the epoxy was dried. The epoxy was vital in sealing the air gap between the two pieces to ensure no plastic leakage during use. Figure 12 has a sectional view of the attachment method.

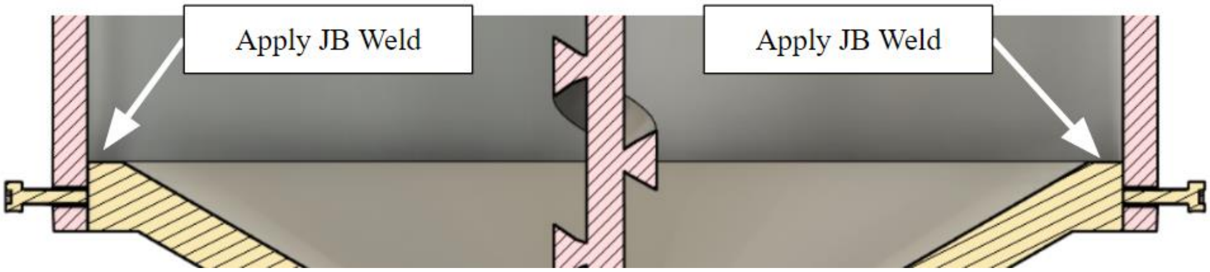


Figure 13: Section View of Ramp and Pipe Attachment

This design choice of fixing the ramped funnel inside of the pipe was made because a 7.5” OD aluminum cylinder was freely available for use in Washburn. Ideally, our team wanted to have a funnel that would be fixed to the outside of the pipe to prevent any plastic from seeping out creases, but this would not be possible due to our budget. Instead, with the current design the JB-Weld helped prevent plastic from seeping out. Another option our team exploded was having an adaptive “donut” to secure the ramp to the pipe. However, this was ruled out because of increased manufacturing time and additional cost of stock material. In Figure 14 are section views of these two possibilities.

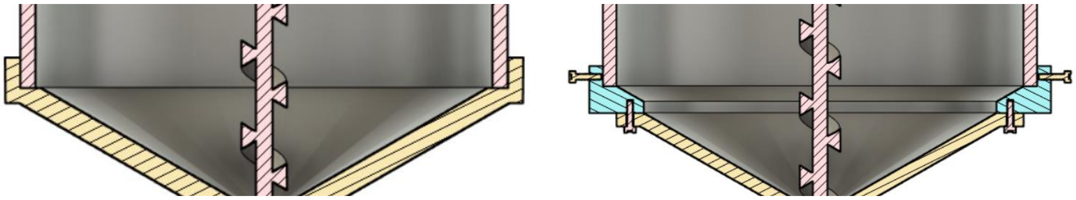
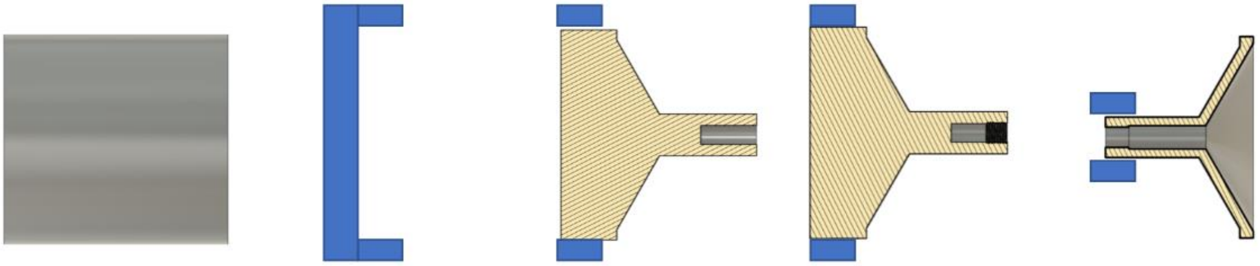


Figure 14: CAD model Section views of two alternative attachment methods.

Manufacturing the ramped funnel presented many challenges. The walls of the ramp needed to be thin enough to allow heat to conduct easily but also thick enough to be able to be machined. Not only this, but the challenge of securing a 7.5-inch aluminum cylinder safely in the lathe had to be overcome. After many meetings with the Washburn staff, especially with James Loiselle, it was determined that all machining could be done on a lathe. In Figure 15 are the operations used to create the funnel.



STOCK
7.5" OD x 8" Long

OP#1
Lathe
Machine Jaws to
7.5" OD

OP#2
Lathe
Grip outside
Cut funnel exterior

OP#3
Lathe
Grip outside
Thread Interior

OP#4
Lathe
Grip Funnel Tube
Cut funnel interior

Figure 15: Oven Manufacturing Operations

The first operation in this process was to machine new jaws that could accommodate the 7.5-inch diameter, since those were not readily available. These jaws had a small inner radius on their interior post-machining, so the edge of the fixed face of the cylinder had to be filed for maximum surface area contact. Once the stock was in place, it was quickly faced to smooth the rough bandsaw marks. Since the stock was so large and heavy, Washburn staff encouraged our team to use the tailstock to secure the piece from both directions before performing the intense roughing operation. This required a small #7 hole to be drilled 0.25-inch deep at the end of the stock. With the tailstock securing the stock along with the custom jaws, Operation 2 from Figure 15 was completed. This operation roughed the outside of the funnel, a very slow and careful operation that took 38 minutes to complete. Figure 16 is the exterior of the funnel being machined by small roughing passes.

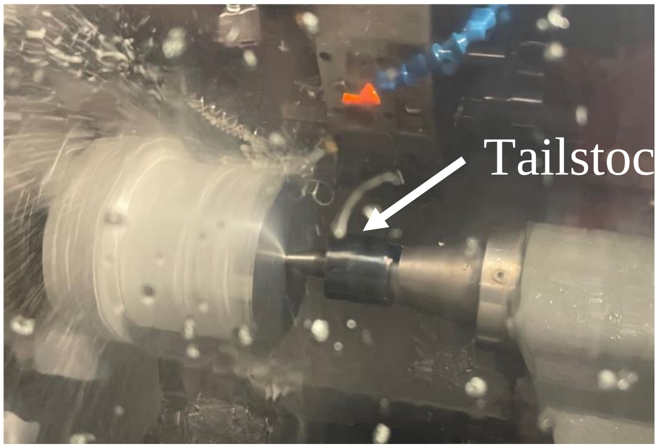


Figure 16: Operation 2: Exterior of Funnel Roughing

Once the exterior was formed, the tailstock was removed so the bottom nozzle connection part of the narrow shaft could be drilled with an 11/16” tap drill. The results from this step and the drill bit used can be seen in Figure 17.

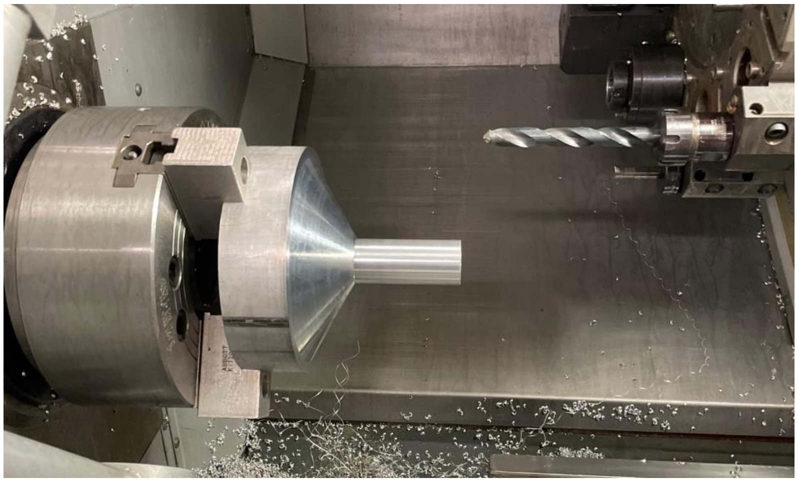


Figure 17: Operation 2: Final Funnel Exterior

Following this, the drilled shaft was threaded with 1-inch of 3/4”x16 threads for the nozzle attachment. A picture of nozzle fixed in the funnel can be seen in Figure 18.

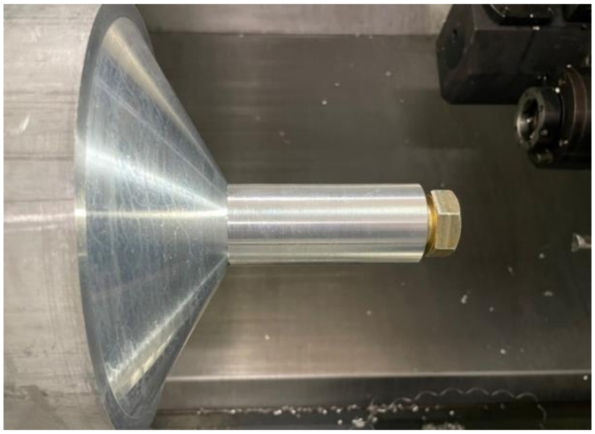


Figure 18: Nozzle Test Fit after Operation #2

The piece was then flipped, and the exterior of the small shaft was clamped into the lathe. A 0.5-inch boring bar was used to make small passes to the interior ramp. Since the majority of the material from the interior was going to be machined out, the radial speed had to be decreased on the lathe. This dramatically increased machining time. As the walls of the funnel were getting more and more thin, an alarming sound began to occur during every pass. In this operation especially, the chip formation was difficult to manage, as chips were shaped as long continuous strands. Ultimately, we stopped machining before the wall thickness could reach the designed 0.5” since lab monitors were worried about the part fracturing. Figure 19 is a progress picture of machining.

Figure 19: Interior Funnel Machining Progress Picture

Regardless of these inconveniences, the funnel had a smooth interior finish. This allows for molten plastic to easily travel towards the auger screw. Figure 20 shows the completed funnel.

Figure 20: Final Funnel

3.2.4 Oven and Frame Fabrication

To begin assembling the oven, a press fit was used to position the funnel in place in the 7.5-inch cylinder. Set screws on the exterior of the cylinder were fastened to hold this positioning. JB weld was applied to the interior and exterior seam of connection between the two parts. This was allowed to dry for 24 hours, and another coat was applied to ensure no plastic leakage during testing. After this was completed, an independent nozzle was screwed into the threaded shaft as shown in Figure 21.

The next step was to add the resistive wire to the exterior of the oven. Leaving a 2-inch gap at the top of the oven for the lid, the resistive wire was wrapped with 0.5-inch gaps as shown in Figure 22. The wire was fixed to the oven using high temperature tape.

Figures 21 and 22: Beginning of Oven Assembly (left) and applied resistive wire (right)

Once the resistive wire was attached to our liking, a thermocouple was tapped onto both the middle of the oven and the lower shaft. These will be used to monitor the temperature during extrusion. Following this, ceramic insulation was cut and tapped using leftover high temperature tape on the entire exterior of the oven. The completed oven assembly can be seen in Figure 23.

Figures 23 and 24: Completed Oven Assembly

Prior to Frame assembly, 1010 and 1020 aluminum framing bars were measured, marked, and cut to length. Corner fixtures with T-nuts were used for fastening bars together. To ensure that the system is stable during use, leveling feet were added to the base of the frame. In Figure 24, the completed frame assembly can be seen.

The oven sits on two horizontal bars, while the auger screw and motor are centered using the topmost horizontal bar. To further hold the oven in place, metal wire was wrapped around it and tied to opposite corners of the frame. A laser cut panel holds the temperature control system just below the oven. A 3D printed mount holds the temperature power supply and the temperature control motor. The auger screw is joined to the frame with a 3D printed mount. This mount slides in the rails of the topmost 1020 bar. To attach the auger screw to the motor, a metal coupler was used. In Figure 25, the motor holder (in red) is pictured.

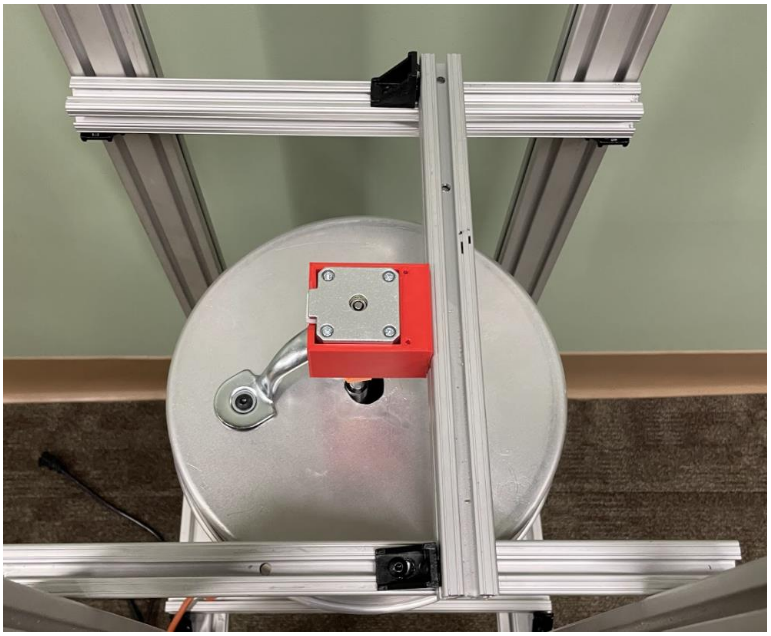


Figure 25: Motor Attachment to Frame

3.2.5 Nozzles Design and Fabrication

Once the oven sub-assembly was created, interchangeable nozzles were designed to screw into the lower shaft of the bottom of the funnel. The nozzles were built from 3/4”x16 x 1” threaded bolts since they could easily be bought for $15 in sets of five. This allowed various extrusion hole sizes and geometries to be tested. The starting nozzle size that was used was 2mm. This decision was influenced by the results of the first prototype testing that was done in the early stages of A-Term. The diameter of the extruder had to be over 1.75mm because the plastic elongated and cooled once extruded. After each extrusion test another nozzle would be made with a larger or smaller diameter based on its predecessor’s performance.

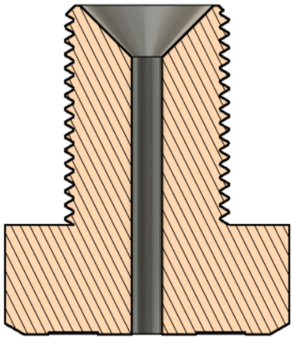


Figure 26: The CAD model section view of a nozzle and the first nozzle to be manufactured

Each time a new nozzle was created, the same procedure was followed. The through-hole with the desired diameter was drilled first in the center of the bolt. Next, a chamfer bit was used to create a ramp on the top of the nozzle to allow plastic to flow into the extrusion point more easily. In Figure 27 is an image from the fabrication of the 4mm nozzle.

Figure 27: Nozzle Fabrication

3.4 Temperature Systems and Thermal Requirements

Resistive ribbon pipe heaters, McMaster-3631K901, were used to heat the oven. They provided constant power of 1.296 KW across its 18-foot length and 1-inch width. The resistive wire is taped onto the oven with high temperature tissue paper tape that is used on PCB boards. A roll of 2-inch by 108-feet of high temperature tissue tape that could withstand up to 260℃ was purchased from Amazon. This width ensured that tape would fully cover the 1-inch wide resistive wire. Placed over the tape there is a 1" ceramic insulation blanket, which insulates up to temperatures far above our operating range (+1600 °F).

To monitor the temperature inside of the oven, various options were explored. One option was to use a high temperature silicon band gap sensor. These sensors can be plugged into a microcontroller and quickly programmed to display current temperature readings. A major downside of using silicon band gap sensors is at higher temperatures, the accuracy is compromised. Instead, our group turned to the second option: high temperature thermocouples. Type J thermocouples operate in the 0-750℃ range, while Type K ranges from -200-1250℃. At first, Type K thermocouples were available to use in Higgins Lab. These provided results for preliminary temperature readings, as they were calibrated with a thermistor. Our team originally used Type K thermocouples, which needed to be calibrated with a thermistor, we ultimately used Type J thermocouples with breakout boards that had a downloadable library. These were used because they required no manual calibration or ice bath reference. The code to run a Type J thermocouple can be found in Appendix C: Type J Code.

To control the temperature, the resistive wire has a knob that modifies an analog time-percentage controller through a potentiometer. To modify this value in our feedback loop, we utilized a stepper motor to turn the knob based on the temperature output from the thermocouple on the outside of the oven. Initial stages of our code allowed the loop to keep the oven's temperature between two values. Further iteration on the code allowed this feedback loop to approach one desired temperature instead of bouncing between two limits. This code can be found in Appendix A: Extrusion Test Code. To facilitate movement of steppers, a custom library was created to modify many aspects of the well-known AccelStepper Arduino library. This custom library, found in Appendix B: PhoenixStepper Code, allowed the team to control many steppers with ease and monitor their position. The temperature control motor must be placed at 0% power on the resistive wire power supply to begin this process to "home" the stepper motor. The code reads the oven temperature from the thermocouples and adjusts the knob in 20% increments until the temperature gets close to the desired value. As it gets closer, the adjusting increment decreases to 5%. There is a Boolean variable in the code, `augerEnable`, which controls if the auger screw stepper spins or not.

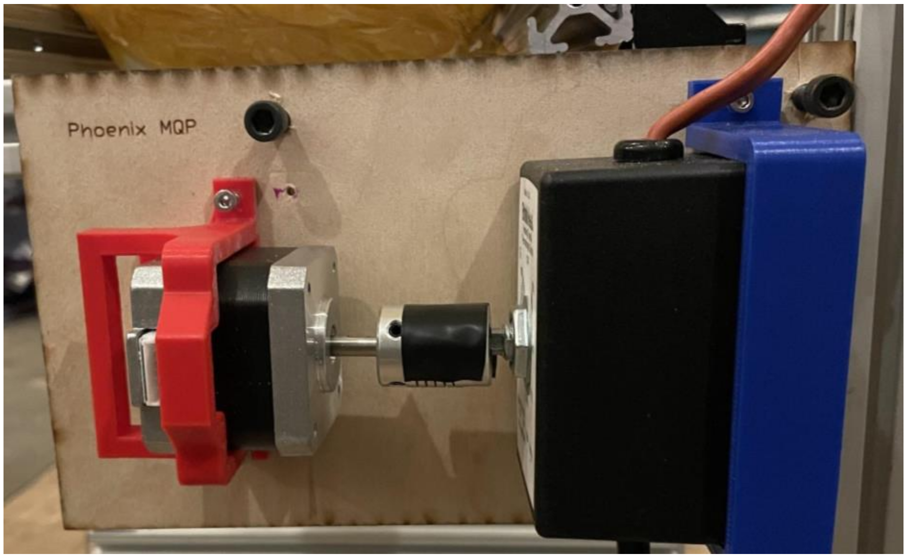


Figure 28: Temperature Control System

3.5 Stepper Motors and Electrical Systems

Stepper motors are used in a few areas in this machine. These motors are used to drive the auger screw and in the temperature control system and spooler. Steppers were chosen over servos because of the need for precise and consistent movement in both the temperature control and spooler subsystems.

The stepper motors that are being used are Nema 17 17HS hybrid stepper motors. These steppers were driven with A4988 drivers (since the DRV8825s that were originally used proved to be too unreliable) each at 1/16th micro-stepping. Two Arduinos were used to drive them, one for the temperature and auger, and another for the spooler. Due to the nature of the A4988 driver, a 47 μF capacitor is used to protect both the motor and driver from intense voltage spikes.

The power requirements of this circuit made fitting an existing power supply easy. Each motor and driver combo worked best when given 12v and 1.5A when the A4988 current limits were set correctly. The circuit also supplied power to the cooling fans, which drew around 0.8 A during operation. This adds up to a requirement of 12v, 5.3A in maximum use, although the amperage required was only 3.8A since the auger stepper stopped moving whenever the temperature stepper was powered. This allowed a simple 12v 5A power supply to power the circuit. Throughout testing and construction of the circuit, the team used a variable DC power supply available from our engineering experimentation laboratory.

A complete circuit diagram is shown in Fig. 29. All of the connections were soldered onto a prototyping board to prevent accidental disconnections.

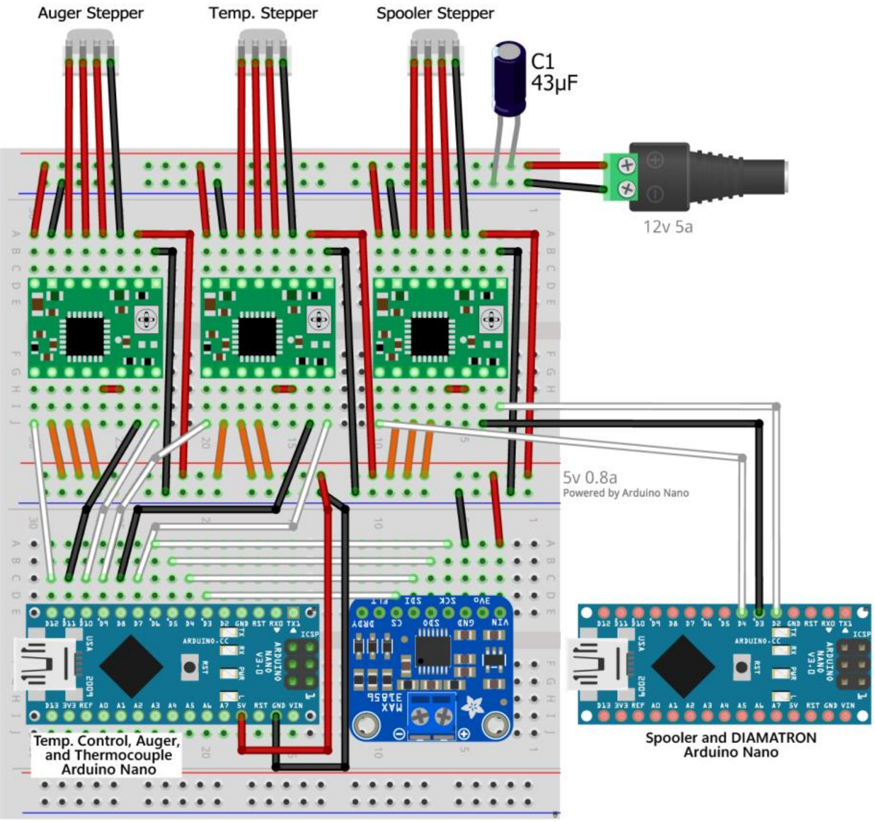


Figure 29A: Circuit Diagram of Prototyping Board

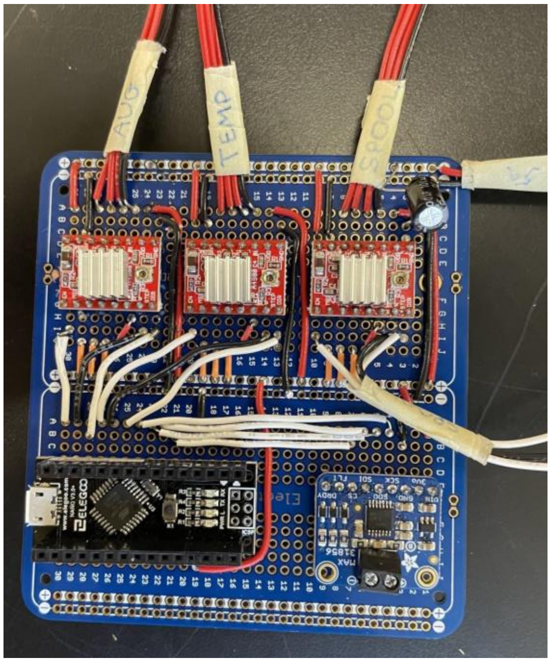
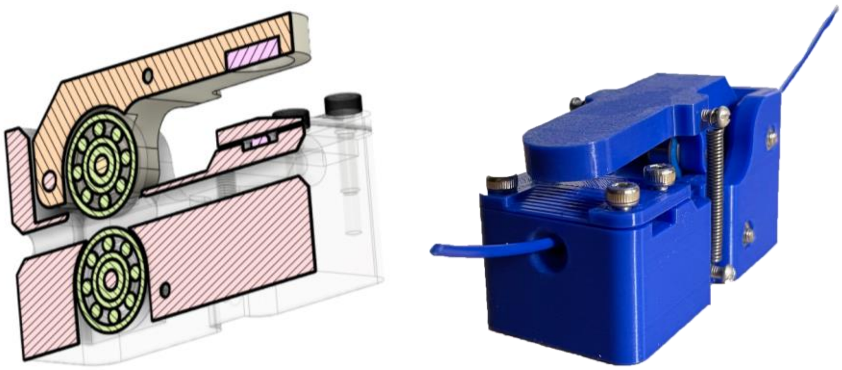


Figure 29B: Picture of Soldered Prototyping Board

3.6 Diameter Measurement: the “Diamatron”

After filament leaves the extruder, several subsystems work to lower its temperature, measure its diameter, and spool it onto a pre-existing filament spool. This produces accurately measured filament after spooled samples are collected.

Our diameter measurement sensor, dubbed the “Diamatron”, is a simple assembly that uses mechanical advantage to produce a continuous reading of filament diameter. This assembly was designed to be affordable, easily constructed, and extremely precise for the range of filament extrusion that might be expected in this project. There are many different methods of measuring the diameter of the filament, including laser distance sensors, displacement sensors, and off-the-shelf measurement devices, however the team elected to use magnetic displacement sensors. This method was popularized by Thomas Sanladerer in his YouTube video “Make your own inline filament diameter sensor (under $5)!” (Thomas Sanladerer, 2021). The design used a lever arm with a bearing that follows the filament path, this moves a magnet closer or further from a magnetic hall-effect sensor as the filament diameter decreases and increases. The sensor can then accurately report the magnetic field strength as a voltage which is directly correlated to the distance from the sensor to the magnet.



Figures 30 and 31: An image and section view of the Diamatron

The Diamatron in Figures 30 and 31 reflects Sanaderer's design by function, although it has many optimizations for this specific project. Initial sensor testing revealed that the SS495 hall-effect sensor provided meaningful data when the magnet was 7mm-26mm away (as shown in Figure 32), following a polynomial curve as the magnet was moved further away concurrent with the magnetic Inverse-Square Law. The sensor itself outputs a range of voltages including 1000 mV (strong positive field), 500 mV (no field), and 0 mV (strong negative field).

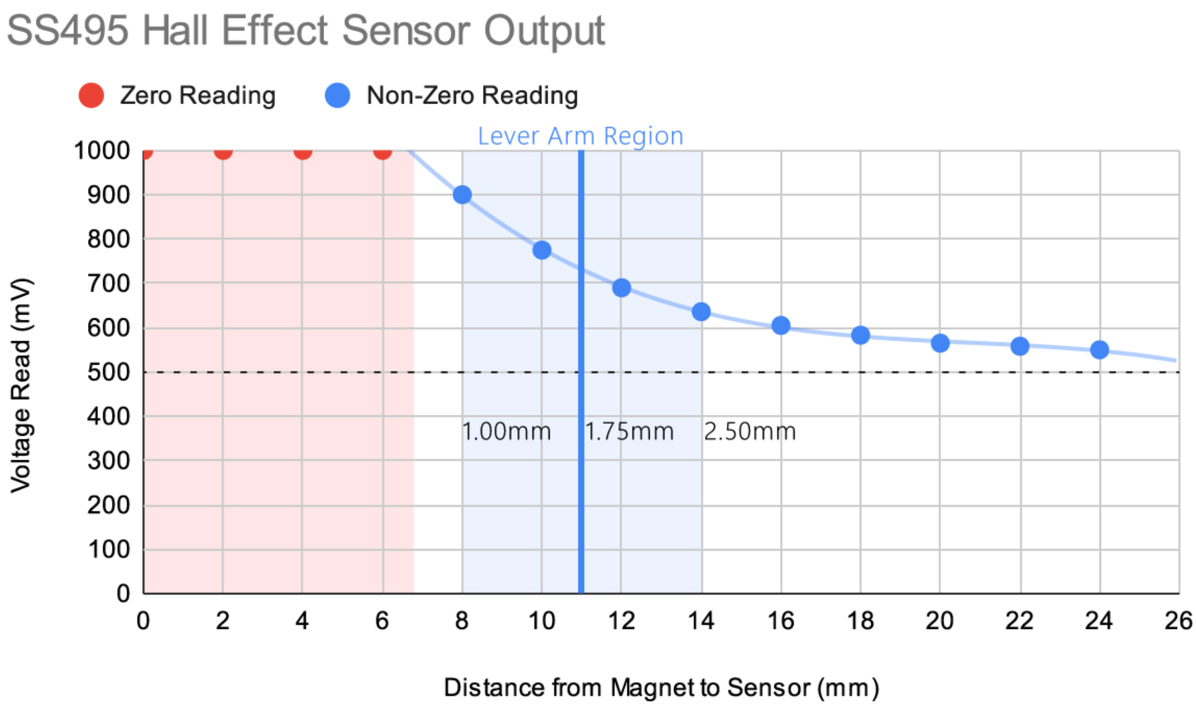


Figure 32: SS495 reading with increasing distance from 12mm diameter neodymium magnet.

The Diamatron is designed such that diameters from 1.00mm - 2.50mm correlate with magnet displacements from 8-14mm, since that region (shown in Figure 32 in blue) is within the bounds of the sensor and has a high enough slope to produce more distinct changes in voltage for small changes in filament size. Our lever arm gives us a 1:4 mechanical advantage, so a 0.1mm change in filament diameter will equate to a 0.4mm change in lever arm, which might correlate to as much as a 50mV difference.

The hall-effect sensor was wired through an Analog to Digital Converter (ADC) to help preprocess the signal. This, combined with a simple linear regression code, which sampled three different known diameters to produce an accurate mapping of voltage-to-diameter, produced results that were within ±0.002mm accuracy. This is an order of magnitude smaller than most commercial filaments which are rated at ±0.03mm dimensional accuracy.

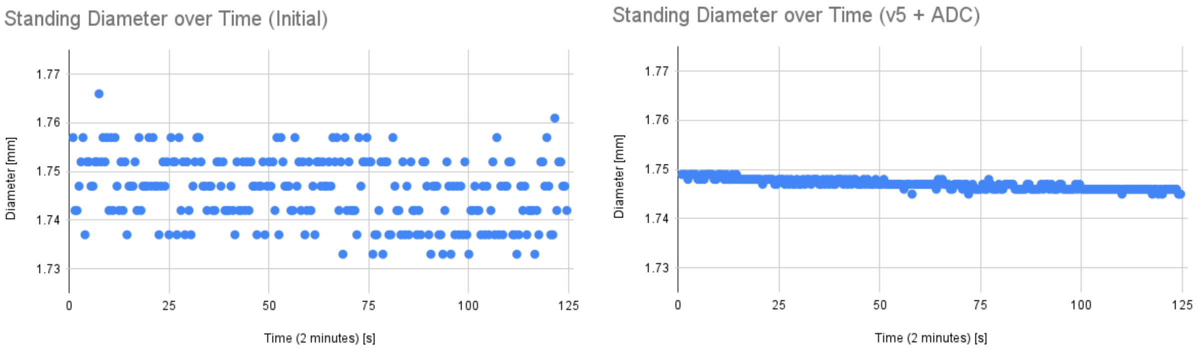


Figure 33: Diameter readings before and after use of ADC in the circuit.

In the machine’s final implementation, the Diamatron was never attached directly to the filament path. Instead, after extrusion, the spool was unspooled and fed through the Diamatron to get diameter results. Given more time, the Diamatron would have been added to the filament path before spooling to create an active feedback loop based on the diameter value.

3.7 Cooling

The cooling system was implemented with the use of four 5v DC squirrel fans. These fans were used to rapidly cool the filament to make it pliable enough to engage in the spooling mechanism. The fans are each mounted in a cooling box, which cools the filament directly at the exit of the nozzle from all 4 sides. This box sits on the frame, positioned just below the nozzle. It is made from 0.25-inch laser-cut birch wood, with slots to mount the fans with M3 machine screws and nuts. The fan mount design can be seen in Figure 34 and the overall cooling system assembly can be seen in Figure 35.

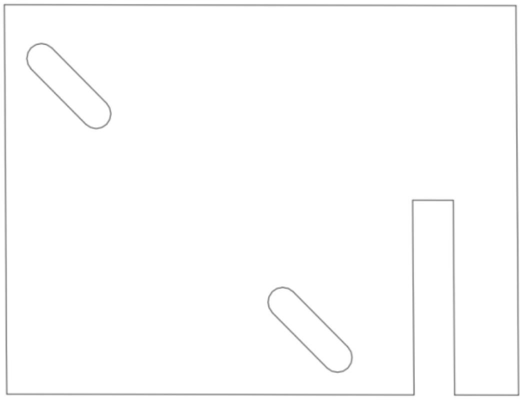


Figure 34: Fan Mount Design

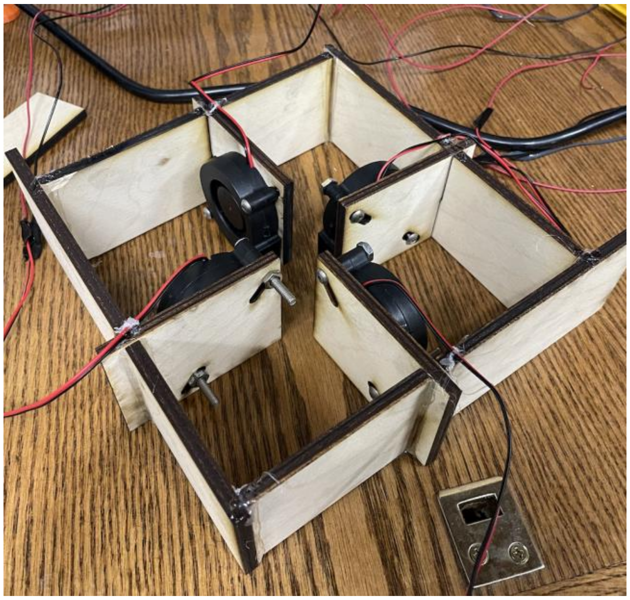


Figure 35: Cooling System Assembly

The cooling box containing the fans sits on two pieces of wood that rest on two horizontal 1010 bars. This allowed us to freely reposition the fans as needed to ensure optimal placement for filament cooling, however it was not rigidly attached to the frame due to time constraints. Extension wires were soldered to each fan since the wires were too short to reach the power supply. During assembly, the fans were wired in parallel and connected to the 12-volt power supply, because this orientation yielded the fastest fan speed. Even though the fans were rated for only 5 volts, it appeared that 12v did no harm and improved their function. Figure 36 shows the cooling system attached to the frame.

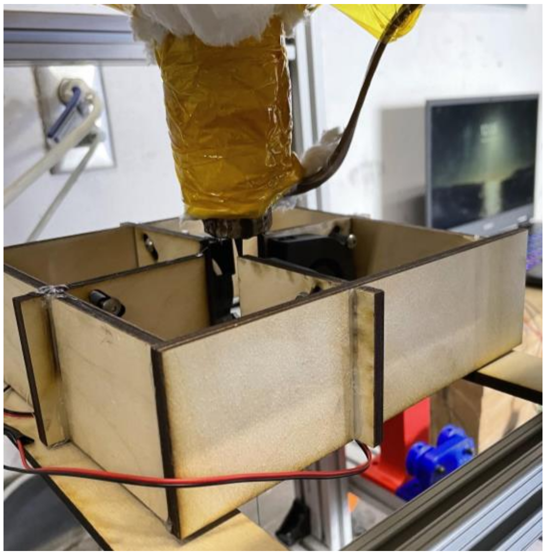


Figure 36: Cooling System Placement on Frame

3.8 Spooling

The need for a system to control the rate of extrusion and to collect extruded filament led to the design of a spooler. This subassembly spins an empty filament spool at a constant, controllable rate. Filament, after being cooled, is immediately pulled into this simple system. Having a constantly rotating "pulling force" exerted on the filament proved to be very important in maintaining a semi-consistent diameter. Filament sagging led to many consistency issues, so the spooling rate was kept high to pull it out before it could begin to sag.

To keep the system as simple as possible, it relies on only a few parts. The spool sits on bearings with 3D printed grooved headers, which help it stay in place and freely rotate. The stepper motor has a claw-like attachment that fits in the ridges of the filament spool, giving the stepper full control over the rotation of the spool. The bearing mounts and the stepper mount are both attached to a 1020 rail which is mounted to the side of the machine.

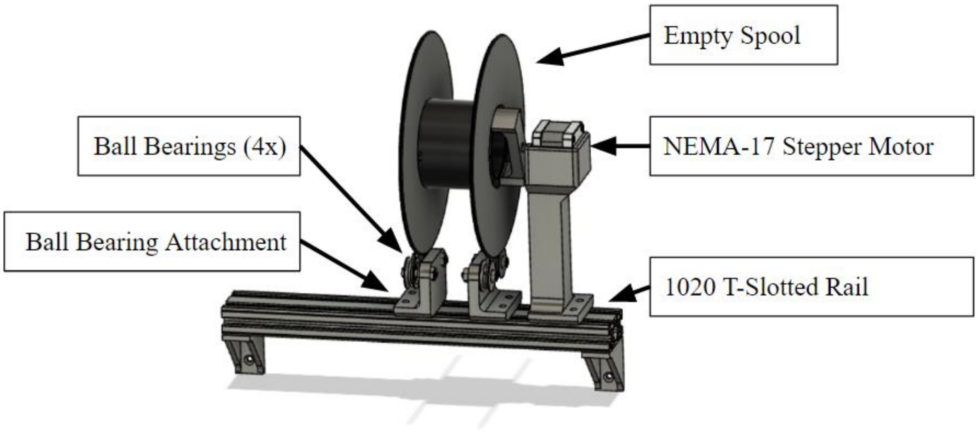


Figure 37: CAD model of the Spooler

The spooling system is mounted to the frame via the 1020 bar holding the 3D printed pieces. Corner brackets and T-nuts were used for attachment. The spooling system sits at the bottom of the frame as shown in Figure 38.

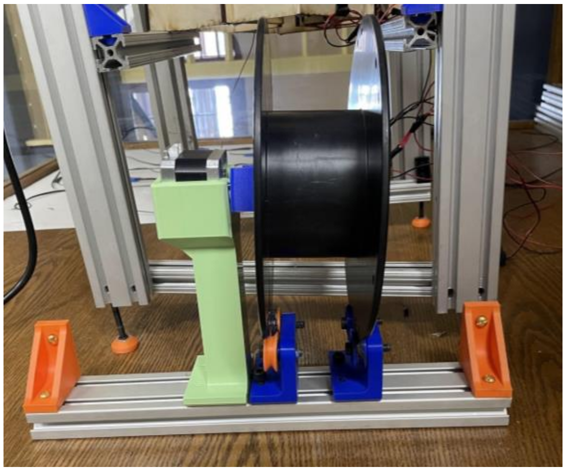


Figure 38: Spooling System Placement, not attached to the Frame

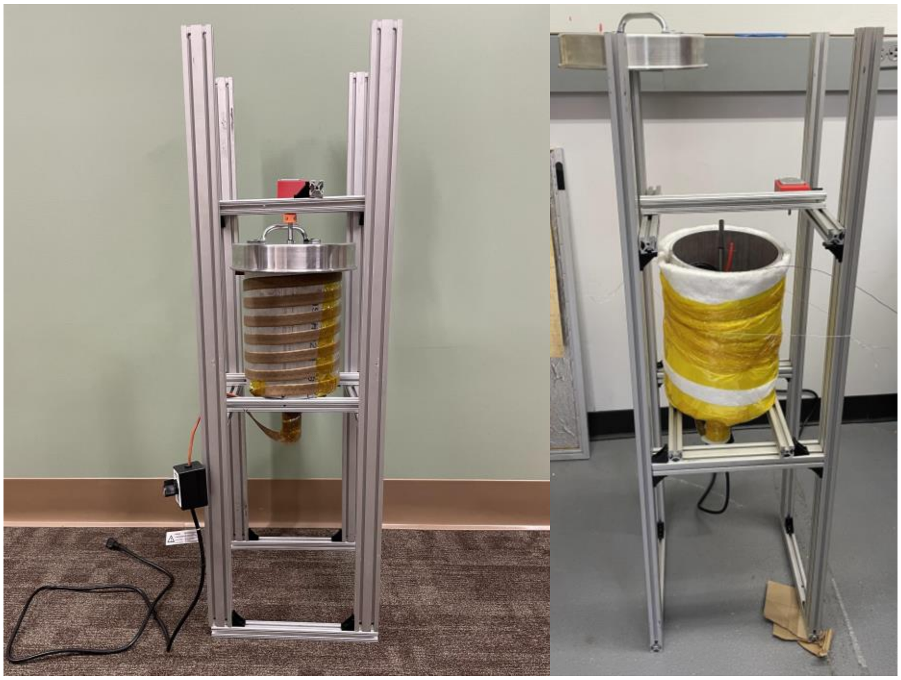
4.0 Results

The following section details each of the filament extrusion tests that were conducted in January and February 2022. Each test saw the addition of new electrical systems, assemblies, and programming to the machine to control the machine as we iterated its design.

4.1 Extrusion Test 1

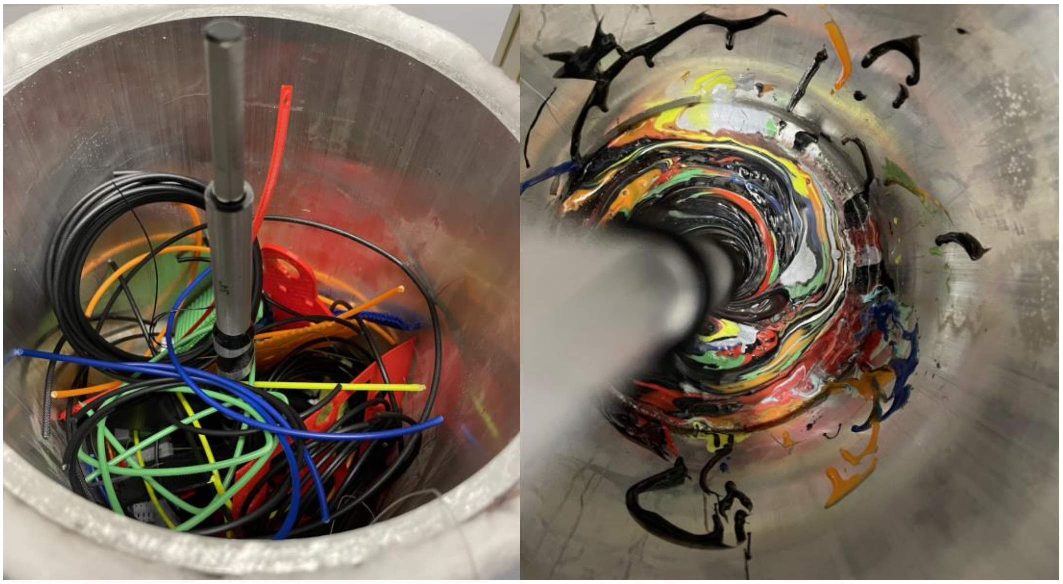
Friday January 21st, 2022

The main purpose of our first extrusion test was to prove the ability of the system to effectively melt and mix plastic. Our barebone system only had the resistive wire, insulation, oven, frame, and auger screw installed. One thermocouple read the temperature value halfway down the basin and we adjusted the temperature by hand. Figure 39 and Figure 40 shows the full system:



Figures 39 and 40: The machine before (left) and during (right) the first extrusion test. Between the two pictures, the insulation was wrapped over the resistive wire.

In Extrusion Test 1, a 2mm nozzle was used. Approximately 75 grams of plastic was added into the oven for this test. A before and an after image of the melt plastic are shown in Figure 41 and Figure 42.



Figures 41 and 42: Before and After of Plastic in the Oven in Extrusion Test 1

For this test, the oven's temperature was hand-controlled and the plastic was occasionally mixed by hand, since there was no functioning auger motor or temperature control system yet. To begin the test, the oven was heated at 75% of the resistive wire's full power. In Figure 43 is the heating chart over the test's duration. At 308 degrees (23 minutes), the power supply was manually cut back to 20% due to smoke building up in the oven from the overheated plastic. The temperature began to drop at a slow rate, so all power was cut at 35 minutes as smoke was still accumulating and there was no proper ventilation in the lab space used.

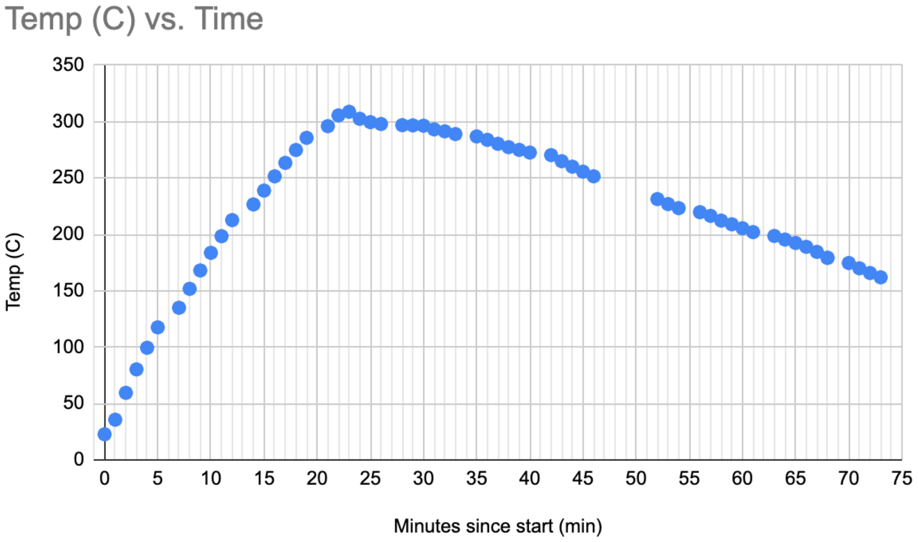


Figure 43: Temperature Plot Extrusion Test 1

Although there was no plastic extruded from this test, it was considered a success in information learned. Our team learned that the plastic needed to be more slowly heated over time. A post-cooling analysis revealed that the viscous plastic was only able to make it halfway through the extrusion nozzle. For the next test our team knew we had to increase the slope on the top of the nozzle as well as the diameter of the nozzle's extrusion hole. In addition to these changes, the small tip on the end of our second auger screw would be cut off, in case it was interfering with plastic flow during the test.

The team also decided to work on creating an active feedback loop for the temperature control before the next test. This would hopefully reduce the smoke and allow the fine adjustment for temperature control. For the next test, the motor controlling both the auger screw and temperature would be fully functional.

4.2 Extrusion Test 2

Wednesday, February 2nd, 2022

The goals of our second extrusion test were to prove the viability of our temperature control feedback loop, reduce smoke output, and to extrude some filament. To start, the 75 grams of plastic from the previous tests was reheated along with about 80 grams of additional material. The old 2mm nozzle was replaced with a 4mm nozzle with a larger chamfer, although the auger screw was not replaced and still had a fine tip at the end. This test was performed in a better ventilated area with a garage door that could be opened if there was excessive smoke build up in the room after the lid was opened.

This test also saw the addition of our active heating feedback loop, in which the thermocouple temperature data directly influenced a stepper motor which could turn the temperature dial. The temperature was maintained between 220℃ - 240℃ for the first 110 minutes, and was increased to 260℃ - 270℃ for the remainder of the test. Figure 44 is the data our team collected while monitoring the temperature conditions of the oven.

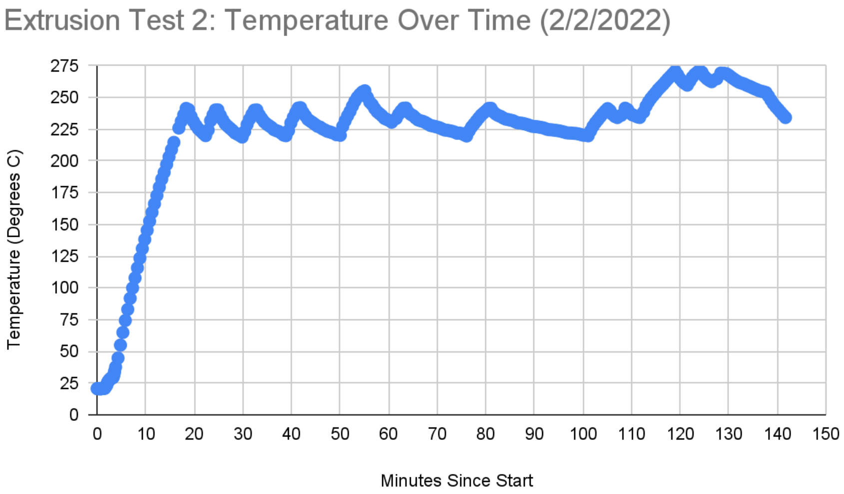


Figure 44: Temperature Plot Extrusion Test 2

Results from this test were promising, as a few little pellets of plastic were extruded at the end. This test signified that the temperature should be maintained at much higher temperature than 220°C before the extrusion begins, and that it will take a significant amount of time to melt the plastic to a state ready for extrusion.

Despite the stepper motors working much better this time, the auger screw was not able to be used for this test. The plastic never was hot enough to allow easy movement of the screw, and the center was still relatively solid at the end of the test. We decided that an even longer amount of time was required to see good results.

4.3 Extrusion Test 3

Thursday, February 3rd, 2022

Extrusion Test 3 used the same set up as Extrusion Test 2 with the 4mm nozzle and auger screw with a pointed tip. An additional 20 grams of plastic were added to the solid chunk of plastic inside the oven. In previous tests, as the plastic that touched the metal oven sides was vaporized; it produced some smoke which exited through the auger screw hole in the lid. To combat this excessive smoke problem, a plug of leftover insulation was put over the hole in the lid where the auger is inserted into the oven.

The graph shows the temperature fluctuation throughout the duration of the test. From 100-133 minutes, a faulty wire on the breadboard resulted in a disconnect between the thermocouple and the Arduino, resulting in a temperature readout of “0.00 C”.

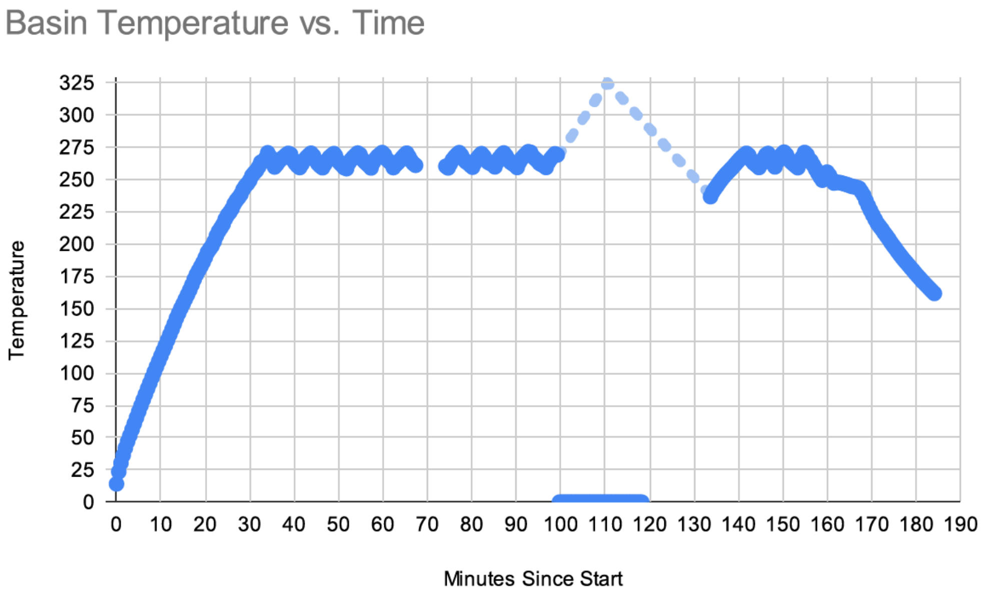


Figure 45: Temperature Plot for Extrusion Test 3. During the time period between 100 - 133 minutes, a "projected temperature range" is shown in the light dotted lines.

After a faulty wire and the cutting of the power, as displayed in Figure 45, the power was restored and plastic began to extrude out of the nozzle in a continuous stream. The increased temperature potentially spiking to 325℃ during the "blackout" might have been enough to kickstart the process, or the readjustment of the auger screw might have unplugged the nozzle hole. Regardless, a consistent stream of quickly moving and very hot filament had begun extruding at around 120 minutes.

It was trial and error to find the correct speed to spin the auger screw once plastic became molten. A full rotation per second ("RPS") at 1/32 microstepping was tested, but the auger screw would occasionally skip steps. Speed was brought back to a half rotation per second. The initial filament was stringy and rapidly came out. At the 143-minute mark, a box fan was bought over to the system to cool the filament being extruded. This technique worked and at the 150-minute mark, thicker material came out and our team was able to hand pull filament. From here the temperature was reduced to 220-240 degrees to see if this would yield a more constant diameter.

Filament extrusion followed a pattern where the initial material would come out and cool, causing it to clump at the edge of the nozzle. This clump would naturally begin to fall and pull a more consistent diameter filament out of the machine until the clump eventually hit the floor. Each time the clump hit the floor, the process would repeat, with a new clump forming at the tip. While different parameters were tested (fan power, auger speed, and oven temperature), samples were cut and collected for documentation. In Figure 46, the filament from this extrusion test is pictured. In light of these results, our team found it necessary to add a cooling and spooling system to the machine. We believe that with a steady cooling and a consistent drawing process, the diameters can be improved to be more constant.

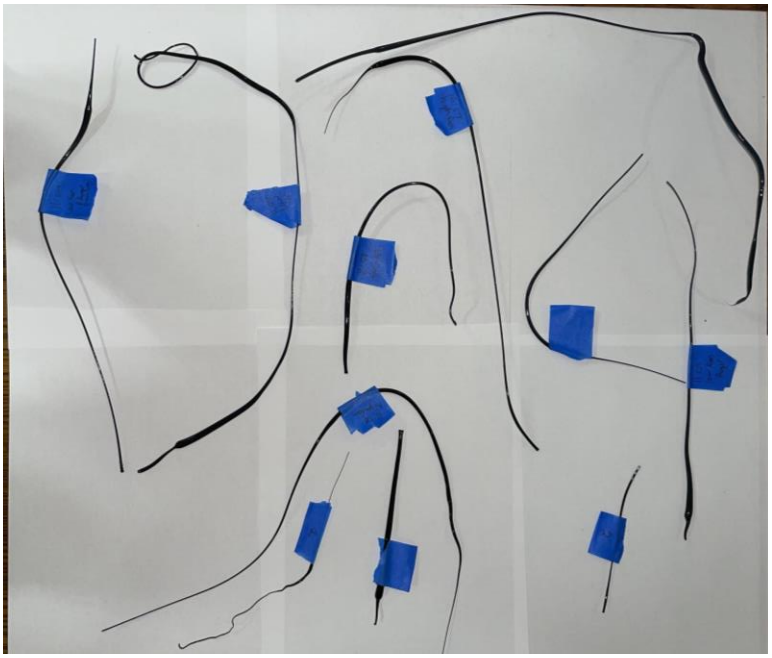
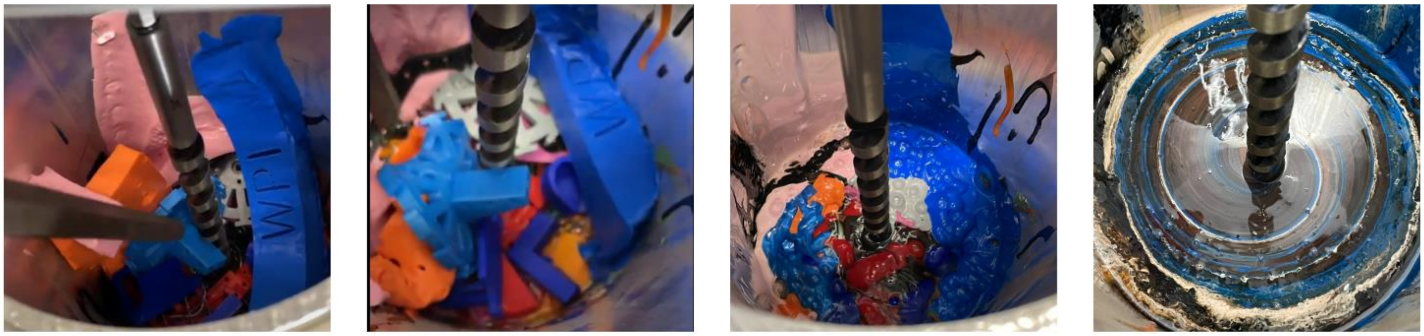


Figure 46: Extrusion Test 3 Filament Samples, each extruded with different parameters.


30 Minutes into Heating

60 Minutes Into Heating

2 Hours Into Heating

After Extrusion. Note the swirl by the auger screw.

Figure 47: Pictures from within the oven during Extrusion Test 2's melting (pictures 1 and 2) and Extrusion Test 3's melting (pictures 3 and 4). The swirl in the final picture indicates that mixing was occurring within the oven.

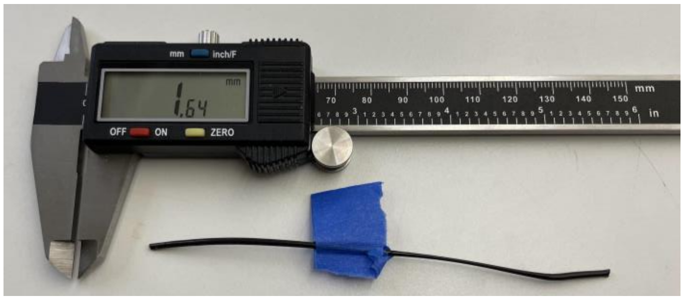


Figure 48: One of the most "promising" strands of filament that was extruded during this test.

4.4 Extrusion Test 4

Friday, February 11th, 2022

For Extrusion Test 4, the goal was to extrude more uniform plastic consistently. For this test, the 4mm nozzle was again used, along with a tipless auger screw, and temperature control system. Fans were added to the system to implement cooling, and a spooler was installed. An insignificant amount of PLA was added to the oven, meaning the test was performed with mostly plastic that had been heated and cooled multiple times.

As done before, the oven was set to heat up at 75% capacity until it reached and then fluctuate between 75% and 15% power once it reached the temperature range of 260°C to 270°C. The temperature over time is shown in Figure 49. This test especially shows the effectiveness of the temperature control system, as the temperature is highly regulated within the given range. After around 2 hours of the oven heating up to temperature, we attached the auger screw to the motor attachment and lifted the motor attachment and coupler up by 1-inch to allow for the tip of the auger screw to not cover the nozzle.

Once we turned on the auger screw's stepper motor, it continuously extruded for the entire remainder of the test at 260°C to 270°C. As we learned from the Extrusion Test 3, we needed to cool the extruded plastic soon after it exited the nozzle. Initially, we held two 5 volt DC squirrel fans by hand to cool the extruded plastic. This process did not cool the extruded filament quick enough to make a significant impact on the quality of filament. With this finding we continued to use the box fan from Extrusion Test 3 on full power. The box fan significantly cooled the filament down enough to begin spooling it.

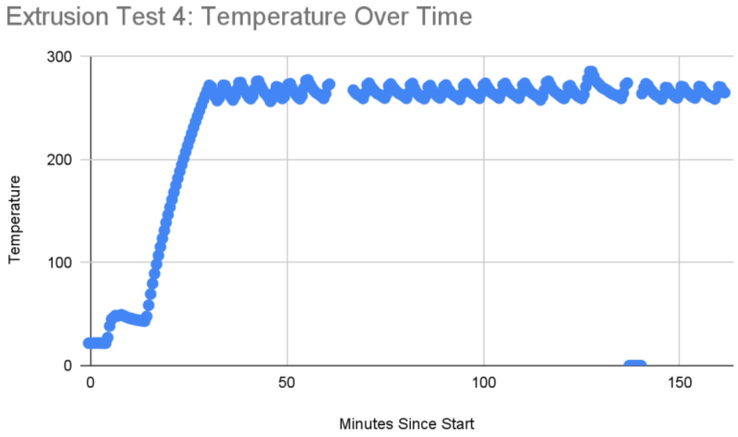


Figure 49: Temperature Vs. Minutes chart from Extrusion Test 4

This test was the first time we implemented the spooling system. Initially, the spooler was spun by hand to engage the end of the plastic in the spool. A stepper motor was added to the spooler to regulate the speed of rotation, and we adjusted this speed many times to find the correct value to have a constant simultaneous spooling and pulling of the filament without any sagging. In the end, this magic rotation speed for the 4mm nozzle was found to be 0.125 RPS, completing one rotation every 8 seconds. Figure 50 shows the final set up of the oven with the spooler beside it.

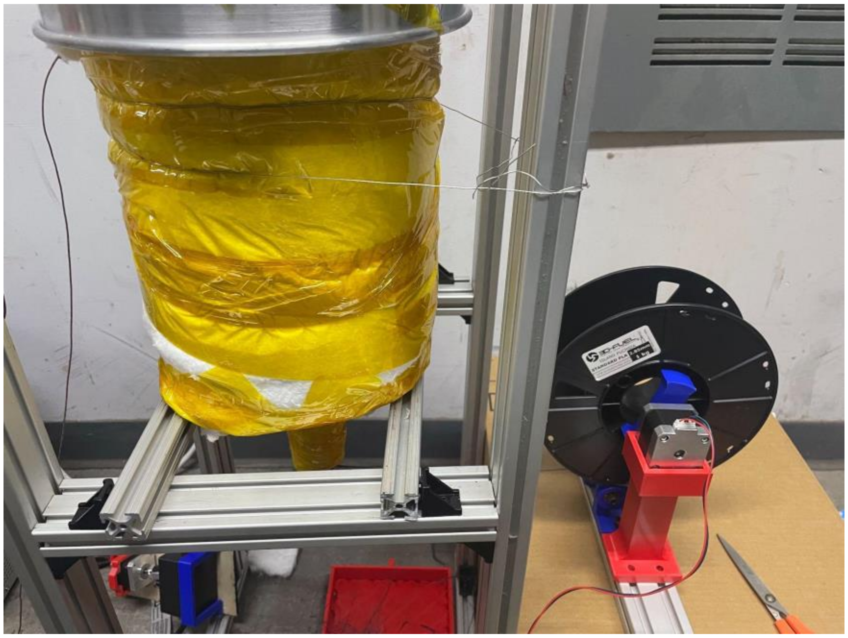


Figure 50: Set up with Spooler and oven, Extrusion Test 4

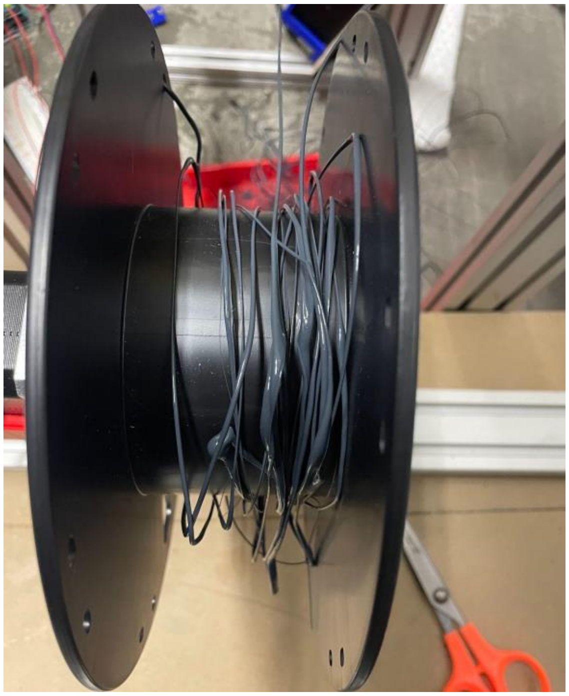


Figure 51: Spooled Filament from Extrusion Test 4

4.5 Extrusion Test 5

Wednesday, February 16th, 2022

In Extrusion Test 5, the main objective was to extrude and spool consistent-diameter filament. For this test we switched out our auger screw to one that no longer had the tip portion, as shown in Figure 52. Everything else on and in the oven was consistent from the previous tests. Before heating the oven, we filled it with PLA to the brim as shown in Figure 52.

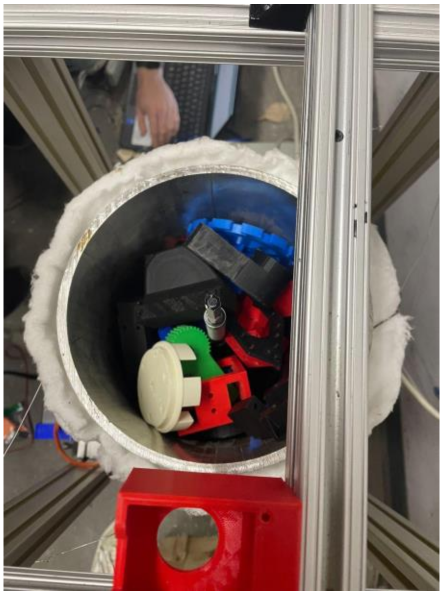


Figure 52: PLA in oven before Extrusion Test 5

The oven heated for 2 hours before extrusion, showing that even with a full oven of PLA the time it took for the plastic to become molten was relatively constant. We encountered stepper voltage issues during the end of the test so for most of the heating up process the dial was manually controlled to stay within the 250 ℃ and 280℃.

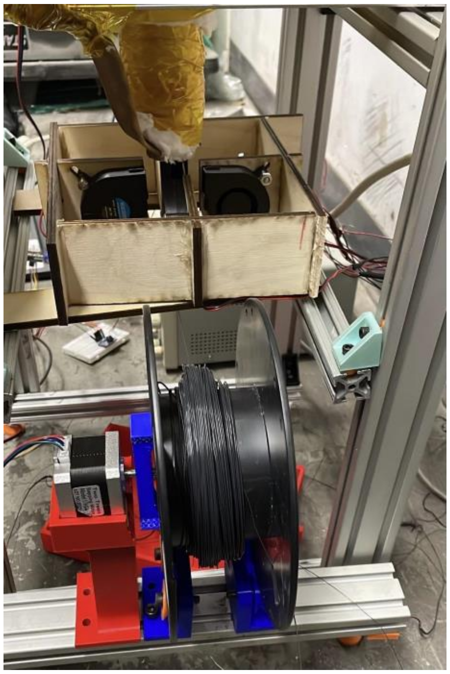


Figure 53: Filament Spool with Constant Diameter

The results of this extrusion test were extremely promising for the future of this machine. Initially the oven was resting between 280°C - 290°C which resulted in the plastic coming out of the nozzle too quickly and with a string-like consistency. After it cooled down to 250°C the extruded filament was pliable and could easily be added to the spooler. The spooler spun at a rate of 0.25 RPS, for 30 minutes. This led to 48 g of relatively consistent-diameter spooled filament. As shown in Figure 54 the diameter of the extruded filament is relatively consistent, although it sloped downwards as time went on. We think that as plastic was extruded, less plastic was in the oven, leading to a lesser pressure on the plastic close to the nozzle. We believe this was why the diameter started around 1mm and ended around 0.8mm. The other major issue with the extruded filament was the actual diameter; This diameter ranged from an average maximum of 1.1mm down to a minimum of 0.75mm, when the target diameter for filament is 1.75mm. This distribution is shown in Figure 54. The next steps for Extrusion Test 6 were to improve cooling and to make an even larger nozzle to facilitate larger diameters.

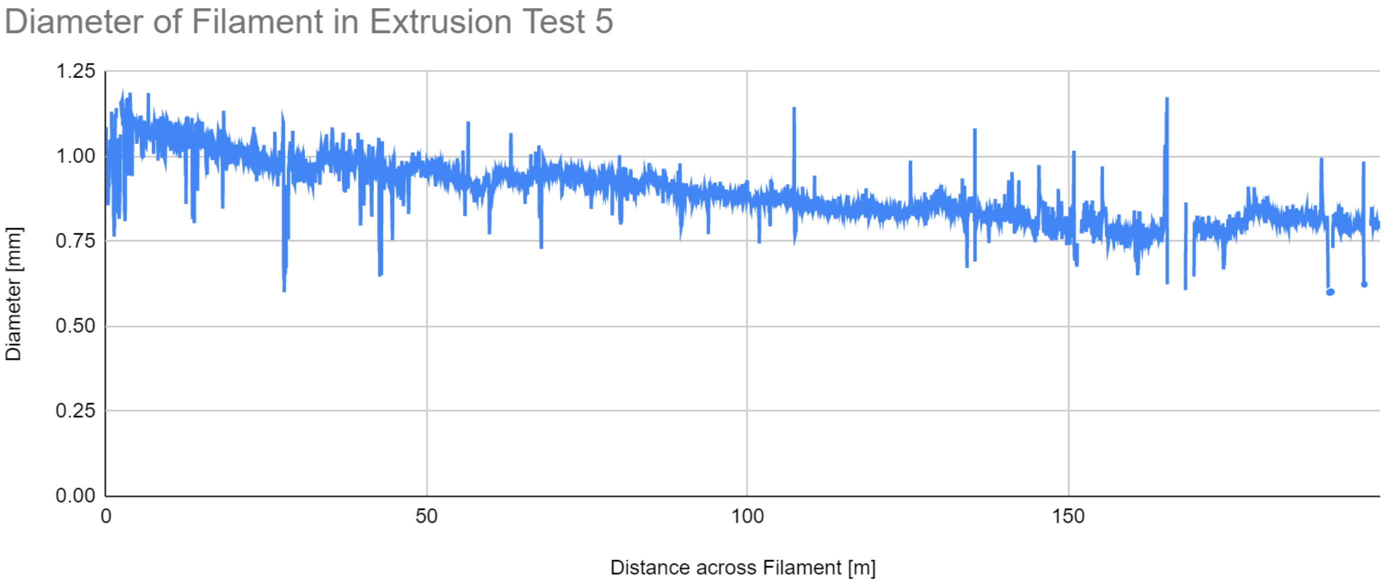


Figure 54: Diameter of Filament in Extrusion Test 5

4.6 Extrusion Test 6

Monday February 21st, 2022

After a successful test the previous week, the goal of this test was to have a larger constant diameter, closer to 1.75mm. To achieve a larger constant diameter we machined a 7.5mm nozzle with a slight chamfer on the top. We filled the oven with PLA to ensure we had a significant amount of plastic to run a successful test, this shown in Figure 55. This test had the most complex setup of our machine, with a mounted spooler, full cooling box, soldered prototyping board, and all 3 motors working with both Arduinos. We also implemented the newest version of our cooling code, in which the temperature feedback loop aimed to reach one temperature instead of bouncing between two bounds.

Figure 55: Plastic Added before Extrusion Test 6

The preliminary heating oven was done as in Extrusion Tests 2, 3 and 4. The distribution of the heating, percentage and time is shown in Figure 56**.** The heating pattern differed once the plastic became molten. The plastic was coming out of the nozzle quickly and in an inconsistent rhythm, it varied to the extent that some extrusions were string-like and others were teardrop shaped and thick. To combat this inconsistency and to maintain a more controllable filament, we lowered the temperature to 220°C, with the hope that this would slow down the extrusion. Once the temperature was lower we changed variables among all sections of the system.

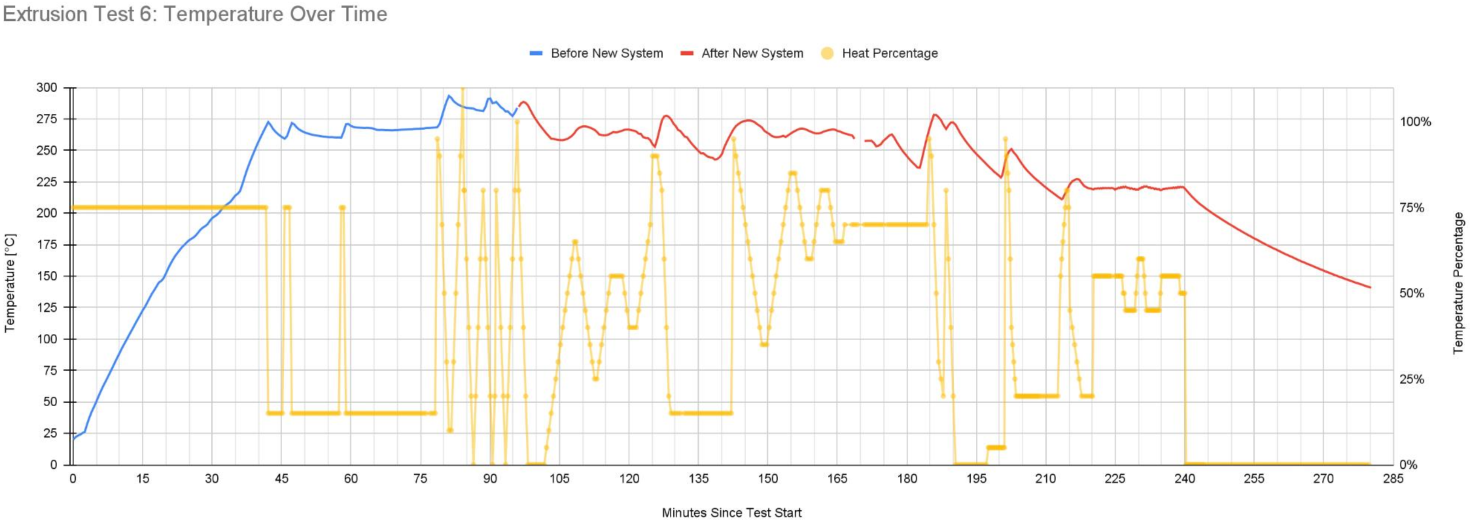


Figure 56: Extrusion Test 6 Temperature, Time, and Heating Percentage

Unlike Extrusion Test 5, the fans were drawing 12 volts which increased the cooling capacity. The spooling system was also mounted to the frame. The first variable we changed was the speed of the auger screw, we were initially spinning the stepper motor at 0.5 revolutions per second. We increased the speed incrementally up to 1 revolution per second.

A significant issue we encountered while performing this test was that plastic was still significantly hot by the time it cooled. Since it was significantly thicker than it should have been, around 3mm in many spots, it was difficult to cool evenly, and strands would cool together on the spool. To combat this, we increased the distance from the nozzle exit to spooler to give the plastic more time to cool. We increased the speed of the spooler up to 0.75 RPS to try and mitigate the filament sagging too quickly and hitting the ground.

With all the variables changing, this test did not yield successful results. The extruded plastic stuck together as it was spooled, and the diameter varied immensely. The feasibility of increasing the nozzle size to get a larger diameter proved to be not possible without advanced cooling. Filament results from this test are depicted in Figure 57.

Figure 57: Extrusion Test 6 filament results

5.0 Discussion and Recommendations

Our team identified many variables critical for successful repurposing of FDM material. With the machine having so many components and variables, we recommend separating them into stages and addressing them individually. With the success of our original machine achieving a constant diameter of filament, our team recommends the following improvements for its next iterations to attain printable filament. The major areas of improvement involve, the auger pitch, the oven, the cooling system, a drawing system, the nozzle, the spooler, better control tolerances, a Printed Circuit Board, frame improvements, and location / ventilation improvements.

In the current design, there is the use of a 3/4-inch diameter auger screw and with a 35° pitch and the most successful tests yielded 0.8mm thick extruded filament. We recommend experimenting with different auger screw pitches to test whether the pitch of the auger dictates the flow rate and diameter of the filament. This is something that our team did not explore, but with this auger variable it could help pinpoint gaining the correct constant diameter.

The oven presented many difficulties that we recommend changes to combat. We recommend that the hole in the top of the oven lid be sealed with a bearing and ring assembly to allow the auger screw to spin freely but prevent any heat or smoke from escaping. Fixing this safety issue will allow for tests to be run anywhere, not just in a ventilated lab. We also recommend creating an openable door in the lid of the oven, which will allow plastic to be entered into the system without needing to disconnect the auger screw. Maintaining a full basin was necessary to have a constant flow to the auger screw. Our team had to remove the entire lid to add more material, and the ventilation was not strong enough to remove all of the smoke that was expelled. This door will also need to be sealed when shut and thermally insulated, along with the rest of the lid. Our final oven recommendation is to design a system to rigidly mount it to the frame in a manner that is level and stable to prevent the auger screw from hitting the sides of our funnel. During testing, we found the auger screw became unstable, and our team had to carefully reposition and fasten it while the oven was hot.

Outside of the oven assembly, we believe that the post extrusion phase of the process needs to have tested and controlled variables. Many commercial filament extruders have long post-extrusion paths consisting of many pulling wheels, cooling fans, and diameter measuring devices. We recommend that future post-extrusion processes take inspiration from these extrusion paths and implement better pulling and cooling systems.

With the cooling system, we recommend exploring and testing the variation of the distance from the exit of the nozzle and the spooler. In between, we recommend looking into the possibility of forcing cooling through larger high-power fans or an ice bath. Our experiments found that fans can often blow filament around unpredictably, which can especially complicate the filament path. Commercial setups also use ice baths to quickly cool the filament as-is without blowing it around. If the ice bath was implemented, it would be crucial that the diameter of the filament is at desired width before entering the bath.

To continuously move the filament and to prevent sagging, we recommend implementing a pulling process with a few points of contact between the pulling motors and the filament. This will allow the filament more time to cool but will also prevent it from touching the ground or sagging. Many pulling processes consist of rolling filament through two wheels to pull it through the machine but are also careful not to compress it. Putting one before and after the ice bath could prevent filament from hitting the ground or drooping too low. During this pulling process we also recommend taking the filaments diameter and modifying parameters such as pulling speed, auger speed, temperature, and more to maintain consistent diameter.

After implementing a consistent widening and drawing mechanism which can achieve a constant diameter output, we recommend experimenting with the nozzle geometry. We have estimated that successful extrusion nozzle diameters may be in the range from 2mm to 8mm due to our success with the 4mm nozzle. To get the most accurate estimation of a successful nozzle size, we recommend testing within this range of nozzle diameters and creating a regression plot to find where the target for 1.75mm filament falls.

With the active pulling systems moving filament, we recommend also having the spooler be connected to this loop. Having these systems work together should yield a more constant diameter and eradicate the need for spooler speed to be manually adjusted based on the filaments flow rate. We recommend investigating commercial spoolers and creating a design that varies the location on the spool that filament goes to produce an efficient pattern of filament on the spool. These systems would add more control over the post extrusion phase.

Lastly there are recommendations we have for the ease of the users and testers. The first improvement we recommend would be the design, manufacture, and implementation of a Printed Circuit Board (PCB). This PCB would ultimately consolidate all electronics to one main board, which would eliminate the probability of wires and solder separating or becoming loose during operation. There is the ability to make a custom PCB with the WPI Makerspace with their LPKF ProtoLaser S4. With this board, we also recommend considering an easier human-machine interface. At its current state, changing any parameter such as motor speed or temperatures requires sending new code to the two Arduinos. Combing to one larger Arduino, such as the Arduino Mega, will simplify everything onto one program, and it will have plenty of pins for buttons to change parameters without sending new code. Combining everything into one program will also allow for the machine to contain one large feedback loop, changing parameters such as resistive wire wattage, auger speed, pulling speed, and spooling speed based on input parameters such as temperature, diameter, and user input.

We recommend putting the frame on wheels to facilitate transport of the assembly. We encountered issues associated with an appropriate place to perform tests in an area with optimal ventilation. We strongly recommend a permanent location to test on campus with good ventilation and safety precautions.

Our final recommendation is to enter this project with a multifaceted team of engineers with different knowledge levels. We recommend having members specializing in mechanical design, manufacturing, thermal analysis, electrical engineering, and computer science. This multifaceted team would be able to start immediately without having to learn many different skills necessary for this project.

We believe our overall design has significant merit. With these and other improvements, we hope that future teams will find success in achieving printable recycled filament.

6.0 Conclusion

To combat the increasing environmental strain that single-use plastics put on the environment, our team created a system to directly recycle PLA 3D prints and extrude plastic filament with a constant diameter without the need for grinding and drying. The relative and promising success of our system demonstrated the feasibility of a compact, low-cost, low-maintenance system for hobbyists and small businesses. Though we were not able to extrude a constant 1.75mm diameter, the promising 1mm diameter sample made it evident that this goal could be achieved.

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8.0 Appendices

Appendix A: Extrusion Test Code

```
/**
 * @file   Extrusion_Test_6.ino
 * @brief  MQP Team Phoenix from WPI
 *          Operate Phoenix MQP Plastic Recycling with ease
 * @version 0.2
 * @date 2022-02-23
 *
 * @copyright Open Source 2022
 *
**/
#include <Adafruit_MAX31856.h>
#include "PhoenixStepper.h"
// Place PhoenixStepper.h in the same folder as this .ino file.

// Define the Thermocouple
Adafruit_MAX31856 maxthermo = Adafruit_MAX31856(3, 4, 5, 6);
float tempMid;

// Set up Steppers with pinout StepPin, DirectionPin, EnablePin, Microstepping
PhoenixStepper augerStepper(11, 10, 12, 16);
PhoenixStepper tempStepper(8, 7, 9, 16);
// positive spin (false) moves in +percent


// CONFIGURATION
int desired_temp = 220;  // The temperature it tries to get

int temp_above = desired_temp + 5;
int temp_below = desired_temp - 5;
int temp_off = desired_temp + 15;
float current_percent = 0.5;
float increment = 0.05;

bool augerEnable = false;  // Enable Auger Screw.


void setup() {
  Serial.begin(9600);

  // Ensure Thermocouple is set up.
  if (!maxthermo.begin()) {
    Serial.println("Could not initialize thermocouple.");
    while (1) delay(10);
  }

  // Set up Thermocouple settings:
  maxthermo.setThermocoupleType(MAX31856_TCTYPE_K);
  maxthermo.setConversionMode(MAX31856_CONTINUOUS);

}
```

```
void loop() {
  // Take temperature; assign to tempMid float
  tempMid = maxthermo.readThermocoupleTemperature();
  Serial.print(tempMid);

  // if Temperature is between +- 1 degree of desired:
  if (desired_temp -1 < tempMid && tempMid < desired_temp+1){
    // Do not do anything. Temperature is in a happy range.
  }

  // if Temperature is above this range:
  else if (tempMid > desired_temp && current_percent >= 0){
    // if temp is greater than 10 degrees away, move 20% down.
    if (tempMid > desired_temp + 10) {increment = 0.2;}
    else {increment = 0.05;}  // Otherwise move 5% down.

    current_percent += -increment;

    // Move Temperature Stepper
    tempStepper.enable();
    tempStepper.runSteps(increment*tempStepper.stepsPerRev, tempStepper.stepsPerRev, false);
    tempStepper.disable();

    Serial.print("  Turning heat to ");
    Serial.print(current_percent, 2);
  }

  else if (tempMid < desired_temp && current_percent <= 0.875){
    // if temp is greater than 10 degrees away, move 20% up.
    if (tempMid < desired_temp - 10) {increment = 0.2;}
    else {increment = 0.05;}  // Otherwise move 5% down.

    current_percent += increment;

    // Move Temperature Stepper
    tempStepper.enable();
    tempStepper.runSteps(increment*tempStepper.stepsPerRev, tempStepper.stepsPerRev, true);
    tempStepper.disable();

    Serial.print("  Turning heat to ");
    Serial.print(current_percent, 2);
  }


  else if (tempMid < 1.01) {
    // If temperature is below 1 C, something is wrong
    if (tempStepper.getAngPosition() != 0) {
      tempStepper.enable();
      tempStepper.runPos(0, tempStepper.stepsPerRev);
      tempStepper.disable();
      Serial.print("  Temperature is too low, turning off stepper");
    }
  }
```

```
  Serial.println(); // Print an empty line

  // Auger
  if (tempMid > desired_temp - 15 && augerEnable) {
    for (int i = 0; i < 15; i++){ // Run Auger for 30 seconds, 15 revolutions at half a rev
per sec
      augerStepper.enable();
      augerStepper.runSteps(augerStepper.stepsPerRev, augerStepper.stepsPerRev*1, true);
    }
  } else {
    delay(30000);
    augerStepper.disable();
  }
}
```

Appendix B: PhoenixStepper Code

```
/**
 * @file   PhoenixStepper.h
 * @author Dominick Gravante (DJGravante@WPI.edu)
 * @brief  MQP Team Phoenix from WPI
 *          Move NEMA-17 Steppers with ease
 * @version 0.2
 * @date 2022-02-19
 *
 * @copyright Open Source 2022
 *
 */
#ifndef PhoenixStepper_h
#define PhoenixStepper_h

#include "Arduino.h"
#include "AccelStepper.h"

class PhoenixStepper
{
    public:
        int stepsPerRev;    // # of steps to make one revolution
        int microstepping;  // Microstepping:
        bool enabled = true;
        long absPosition = 0;    // Absolute Position from now until restart

        /**
         * @brief Construct a new Phoenix Stepper object
         *
         * @param stepPin  Arduino Pin for STP
         * @param dirPin   Arduino Pin for DIR
         * @param enPin    Arduino Pin for EN
         * @param microsteppingInput    Microstepping; 1=full, 2=1/2, 4=1/4...
         */
        PhoenixStepper(int stepPin, int dirPin, int enPin, int microsteppingInput){
            // Create AccelStepper Object
            // Define Microstepping, max speed
            // Set rpm, rev, etc

            // Set Pins:
            _stepPin = stepPin;
            _dirPin = dirPin;
            _enPin = enPin;

            // Create Stepper Object
            stepper = AccelStepper(1, _stepPin, _dirPin);

            // Set Microstepping
            microstepping = microsteppingInput;
            stepsPerRev = 200 * microstepping;  // 200 steps per full rev

            stepper.setMaxSpeed(8*stepsPerRev);
            Print();
        };
```

```
/**
 * @brief Disables the motor for an amount of time. Waits for the
 * whole time.
 *
 * @param milliseconds How many ms to disable for
 */
void disableTime(int milliseconds){
    digitalWrite(_enPin, HIGH);
    delay(milliseconds);
    digitalWrite(_enPin, LOW);
};


/**
 * @brief Disables motor indefinitely
 *
 */
void disable(){
    digitalWrite(_enPin, HIGH);
    enabled = false;
}


/**
 * @brief Enables motor indefinitely
 *
 */
void enable() {
    digitalWrite(_enPin, LOW);
    enabled = true;
}


/**
* @brief Runs a specified number of steps in a specified direction
*
* @param steps  Number of steps to move (pos or neg)
* @param speed  Speed to move in steps per second
* @param dir    Direction (false = forward). Optional based on steps.
* @return long  Returns absolute position
*/
long runSteps(long steps, long speed, bool dir = false) {
    // Convention: dir=0 is the default positive speed

    if (dir){
        // if specified negative direction, make steps negative
        steps = -abs(steps);
    }

    // The desired position is the current one, plus the pos or neg
    // steps required to get there.
    long desiredPosition = stepper.currentPosition() + steps;

    // If it needs to go backwards, flip the speed.
```

```
            if (steps < 0){
                speed = -speed;  // flip speed to go in opposite direction
            }

            // Loop until we reach the desired position
            while (stepper.currentPosition() != desiredPosition) {
                stepper.setSpeed(speed);
                stepper.runSpeed();
            }
            // Set the object's absolute position to the current position.
            absPosition = stepper.currentPosition();

            return absPosition;
        };

        /**
         * @brief Runs the stepper motor for a specified number of revolutions
         *          at a specified RPM
         *
         * @param rev   Number of revolutions to move (can be fractional)
         * @param rpm   Speed to move (based on Microstep)
         * @param dir   false = CCW. Optional
         * @return long
         */
        long run(long rev, long rpm, bool dir = false) {
            runSteps(rev*stepsPerRev, rpm*stepsPerRev, dir);
        }


        /**
         * @brief Runs the motor to a specified angular position
         * Angular position is from 0 to 1 revolution of steps
         *
         * @param pos       Desired position (angular)
         * @param speed     How quickly to move (steps/sec)
         * @param runShortDir   Defaults to running the shortest Direction
         * Set to False to run the long direction.
         * @return long  Returns absolute position
         */
        long runPos(int pos, long speed, bool runShortDir = true) {
            // pos is the angular spot we want to be at
            // angPosition is the anguler spot we are at
            long angPosition = getAngPosition();

            // difference > 0 = needs to move forwards
            // difference < 0 = needs to move backwards
            long difference = pos - angPosition;
            long opp_difference = (difference > 0) ? difference-stepsPerRev :
difference+stepsPerRev;

            // So now we have two directions, one that's larger than the other.
            // by default, let's go the smaller speed:
            if (runShortDir){
                if (abs(difference) < abs(opp_difference)){
                    runSteps(difference, speed);
                } else {
```

```
            runSteps(opp_difference, speed);
        }

    } else {
        // Run in long direction
        if (abs(difference) < abs(opp_difference)){
            runSteps(opp_difference, speed);
        } else {
            runSteps(difference, speed);
        }
    }

    return absPosition;
};


/**
 * @brief Sets the current absPosition and angPosition as zero
 * Also sets stepper current position to zero
 *
 */
void Zero(){
    absPosition = 0;
    stepper.setCurrentPosition(0);
};


/**
 * @brief Get the Angular Position.
 * Angular Position is defined as from 0 to one full revolution
 * Analogous to (0, 360) degrees, but (0, stepsPerRev)
 *
 * @return long Positive Angular Position (0 to full step)
 */
long getAngPosition(){
    // define _tempPosition as a variable holding the position to be
    // manipulated
    long _tempPosition = absPosition;

    // Continuously subtract stepsPerRev from absPosition
    while (_tempPosition >= stepsPerRev) {
        _tempPosition -= stepsPerRev;
    }

    // if absPosition is negative, this will bring it to positive:
    while (_tempPosition < 0) {
        _tempPosition += stepsPerRev;
    }

    // Now we have the _tempPosition between 0 and stepsPerRev.
    return _tempPosition;
}


void Print() {
    // Prints all aspects of the class out to Serial Console
```

```
            Serial.println("======\nPrinting Class:");
            Serial.print("\nStep Pin: "); Serial.print(_stepPin);
            Serial.print("  Dir Pin: "); Serial.print(_dirPin);
            Serial.print("  Enable Pin: "); Serial.print(_enPin);

            Serial.print("\nAbsolute Position: "); Serial.print(absPosition);
            Serial.print("\nAngular Position: "); Serial.print(getAngPosition());
            Serial.println();

        }


    private:
        AccelStepper stepper;   // AccelStepper Object
        int _stepPin;   // Step Pin on Arduino
        int _dirPin;    // Direction Pin on Arduino
        int _enPin;     // Enable Pin on Arduino

};

#endif
```

Appendix C: Type J Code

```
#include <Adafruit_MAX31856.h>

#include <Adafruit_MAX31856.h>
#define DRDY_PIN 5

Adafruit_MAX31856 maxthermo = Adafruit_MAX31856(10, 11, 12, 13);

void setup() {
  Serial.begin(9600);
  while (!Serial) delay(10);
  Serial.println("MAX31856 thermocouple test");
  pinMode(DRDY_PIN, INPUT);
  if (!maxthermo.begin()) {
    Serial.println("Could not initialize thermocouple.");
    while (1) delay(10);}
 maxthermo.setThermocoupleType(MAX31856_TCTYPE_K);
  Serial.print("Thermocouple type: J ");
  switch (maxthermo.getThermocoupleType() ) {
    case MAX31856_TCTYPE_K: Serial.println("J Type"); break;
    case MAX31856_VMODE_G8: Serial.println("Voltage x8 Gain mode"); break;
    case MAX31856_VMODE_G32: Serial.println("Voltage x8 Gain mode"); break;
    default: Serial.println("Unknown"); break;}
maxthermo.setConversionMode(MAX31856_CONTINUOUS);}


void loop() {
  // The DRDY output goes low when a new conversion result is available
  int count = 0;
  while (digitalRead(DRDY_PIN)) {
    if (count++ > 200) {
      count = 0;
      Serial.print(".");} }
  Serial.println(maxthermo.readThermocoupleTemperature());}
```

Appendix D: Diamatron Code

```
/**
 * @file   Diamatron.ino
 * @brief  MQP Team Phoenix from WPI
 *          Operate Phoenix MQP Plastic Recycling with ease
 *          Also has SLR manually-coded in.
 * @version 0.5
 * @date 2022-02-19
 *
 * @copyright Open Source 2022
 *
**/
// Needs an ADC to run - best to use the Adafruit ADS1015 board.
#include <Adafruit_ADS1X15.h>
#include <wire.h>

Adafruit_ADS1115 ads1115;    // Construct an ads1115

// Use this to define your Analog Pin. Default is A0.
#define ANALOGPIN A0

float slr_slope;
float slr_intercept;
float input_voltage;
float temp;

void setup() {
  Serial.begin(9600); // Turn on Serial Monitor

  // CALIBRATION DATA - add it all here
  float calibration_diameters[] = {1.57, 1.95, 2.35}; // Known Diameters
  float calibration_voltages[] = {27042, 29348, 30845};  // Known Output Volts
  float m = 3;  // Number of calibration diameters used

  // Perform Simple Linear Regression.
  slr_slope = slope(calibration_voltages, calibration_diameters, m);
  slr_intercept = intercept(calibration_voltages, calibration_diameters, m);

  pinMode(ANALOGPIN, INPUT);  // Define ANALOGPIN as an input.

  ads1115.begin(0x48);  // Initialize ads1115 at address 0x48
  ads1115.setGain(GAIN_TWO);
}

void loop() {
  int16_t adc0;
  adc0 = ads1115.readADC_SingleEnded(0);

  temp = slr_intercept + slr_slope * adc0;


  Serial.print(adc0);
  Serial.print(" -> ");
  Serial.print(temp,3);
```

```
  Serial.println();
  delay(100);
}


float diameter(float voltage){
  // uses the simple linear regression model to return a diameter for a given voltage
  return slr_intercept + slr_slope*voltage;
}


float sum(float samples[], int m) {
  // Sums all items in the list samples
  float total = 0.0;
  for(int i=0; i<m; i++){
    total += samples[i];}
  return total;
}

float average(float samples[], int m) {
  // Averages all items in the list samples
  return sum(samples, m)/m;
}

float sd(float samples[], int m) {
  // finds standard deviation of all items in the list samples
  float temp_mean = average(samples, m);
  float difference_square_sum = 0.0;

  for(int i=0; i<m; i++){
    difference_square_sum += sq(samples[i] - temp_mean);}
  return sqrt(difference_square_sum/(m-1));
}

float slope(float x[], float y[], int m){
  // Calculates the slope of SLR:

  // B1 (slope) = sum((xi-X)(yi-Y))/sum(Xi-X)^2
  float mean_x = average(x, m);
  float mean_y = average(y, m);

  float numerator = 0.0;
  float denominator = 0.0;

  for(int i=0; i<m; i++) {
    // Numerator = (xi-X) * (yi-Y)
    numerator += (x[i] - mean_x) * (y[i] - mean_y);

    // Denominator = (xi - X)^2
    denominator += sq(x[i] - mean_x);
  }

  return numerator / denominator;
}

float intercept(float x[], float y[], int m){
```

```
  // Calculates the intercept of SLR

  // B0 (intercept) = Y - B1*X
  float mean_x = average(x, m);
  float mean_y = average(y, m);
  float given_slope = slope(x, y, m);

  return mean_y - (given_slope * mean_x);
}
```