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3D ReFil

The Future of Sustainable 3D Printing

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ABSTRACT

Plastic waste poses a significant global challenge, necessitating innovative recycling solutions. This report presents the elements needed to create an integrated plastic recycling system that turns thermoplastic waste into 3D printer filament, focusing on polylactic acid (PLA), the most common 3D printing material. The system comprises essential components such as a grinder, extruder, cooler, quality control tester, and spooler. Two objectives guide this project: recycling plastic and serving as a teaching guide at the Applied Engineering Center (AEC). The report evaluates different design solutions, balancing cost, and size with ease of use and performance. Notably, the project yielded promising results, producing plastic of superior quality compared to certain commercially available filaments, as confirmed by microstructure analysis. Additionally, the report includes a detailed system design, discussion of its current state, steps for innovation and scalability to other plastics, and analysis of project budgeting in comparison with market alternatives.

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3D ReFil: The Future of Sustainable 3D Printing

1.0 Introduction

3D printing is a broad term usually describing the process of laying down layers of material one on top of another until a 3D object is made. (Britannica) While 3D printing can be used to print metal and other exotic materials, the most common material are thermoplastics. (Stratasys) A thermoplastic is a plastic that softens and liquifies when heated and hardens when cooled; both processes that are totally reversible and may be repeated. The major difference between this way of manufacturing compared to most others is that it is an additive process, unlike processes like milling or other subtractive processes where material is removed to generate the required geometry.

In recent years the 3D printing industry has grown significantly and while it often produces much less waste than subtractive manufacturing it still generates waste. Waste in a typical 3D print is created from purge lines and supports. Purge lines are essential to 3D printing because it primes the nozzle just before a print starts to ensure smooth flow on the first layer. Support is another integral part of 3D printing; supports are automatically generated to support the part as it is being printed. This feature prevents the user having to spend valuable time and resources designing tooling that would be required to hold the part. Modern printers such as the Bambu Lab X1C have the ability to print with multiple colors or materials in the same part (Bambu) which has increased the usefulness of 3D printing drastically although it comes at the cost of even more waste material created every time the material changes. Plastic must be purged out of the nozzle to prevent mixing creating significant waste. However, the ability of thermoplastics to be repeatably melted and hardened make them a perfect candidate for recycling.

Plastic waste presents a significant environmental concern, contributing substantially to global pollution. A prime illustration is the Great Pacific Garbage Patch, primarily comprising plastics and microplastics, with an estimated 80% sourced from land-based origins (National Geographic). The escalating global population corresponds with increased plastic consumption and subsequent waste production, exemplified by a study estimating that the UK discards around 349,000 kg of 3D printed plastic annually (Toor). Although addressing such vast quantities may appear daunting, even small efforts can yield meaningful results. For instance, students at USI generate approximately 7.2 kg of 3D printer waste annually, demonstrating the potential to recycle all this waste into new filament.

This project focuses on recycling 3D printed parts and making new filament that can be easily re-used. In the 3D printing world, 3D prints are often used as making test trails of things and there tend to be various variations made. With all these extra prototypes, people tend to just through them away. In addition to this, support material and purge lines are plastic waste from the printing process. The goal of this project is to take those prototypes, grind them up, and extrude new filament so it can become a new part.

The process begins with a grinder that will grind the parts into small shavings. From there, it will be fed into an extruder that will heat the plastic up and extrude it to the desired thickness. The plastic will then travel over an air-cooling system that will harden the plastic. Next the plastic will go through a quality control test and check the thickness of the plastic to make sure it is to the industry standard of 1.75 mm. Once it passes through quality control, it will then go onto its spooling system that will wind the plastic up onto a roll. Everything will be controlled by a PLC, and it will resemble a manufacturing line. The sub systems will be color coded for clarity: the grinder in red, extruder in grey, cooling in blue, quality assurance in orange, and spooling in green.

The other objective of this project is to serve as a teaching guide in manufacturing. The PLC control will allow the project to be completely customized. The motors for the grinder, extruder, and spooling system will have adjustable speeds. The heating element of the extruder will have a varying temperature range. The cooling system fans can speed up or slow down. These adjustable settings are an example for how manufacturing lines can tailor their production processes to specific requirements, offering valuable insights into industrial manufacturing practices.

1.1 Big Picture

The machine operates in a step-by-step manner, beginning with the feeding of plastic waste into the grinder for fragmentation into smaller pieces. Following this, a predetermined quantity is measured using a scale and added into the extruder for further processing. Within the extruder, the plastic waste is subjected to heat-induced melting and shaping, resulting in the formation of a filament with a diameter of 1.75 mm. This filament is then directed over a cooling system to solidify its form before undergoing scrutiny in the quality control segment to determine if diameter meets the industry specifications. Finally, the processed filament is wound onto a spool via the spooling system, allowing it to be used by any common 3D printer. Figure 1 shows how the components are laid out and integrated together.

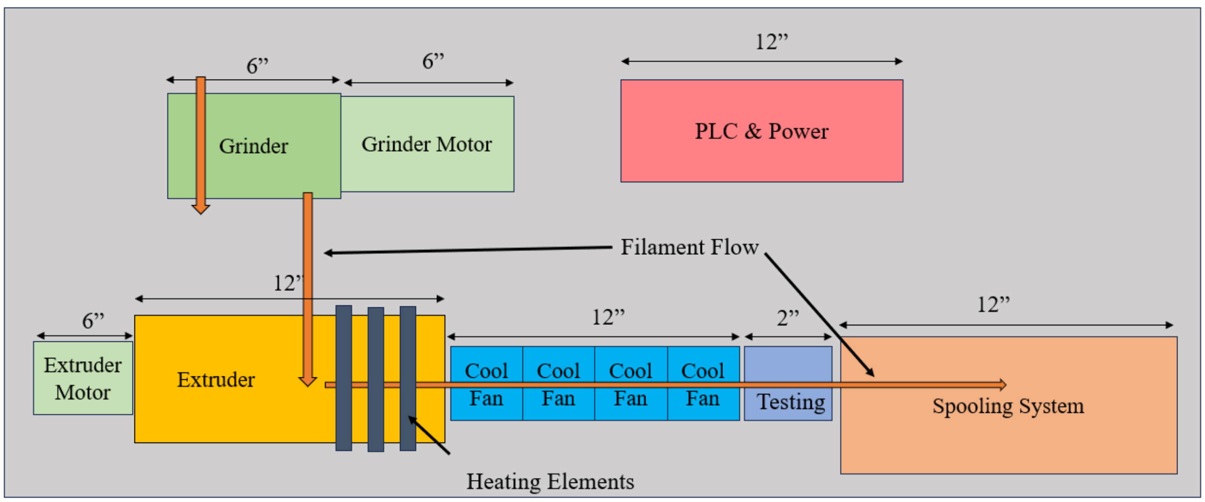

Figure 1. Project Big Picture

1.2 Objective

The objective of this project is to make a fully functioning plastic recycling system to produce 3D printer filament for the AEC and serve as a teaching guide in manufacturing processes.

1.3 Deliverables

The Deliverables for this project are the following:

- Functional plastic recycler for 3D printer filament.
- CAD drawings to show the planning and placement.
- Calculations to validate the specifications for mechanical and electrical components.
- 3D printed item from recycled plastic.
- Report, Presentation and Poster.

This project will be fully functional upon completion to produce 3D printer filament in the AEC. It will contain all CAD drawings, operational instructions, and maintenance guidelines for replacing parts and keeping it operational. Figure 2 shows the completed 3D ReFil project.

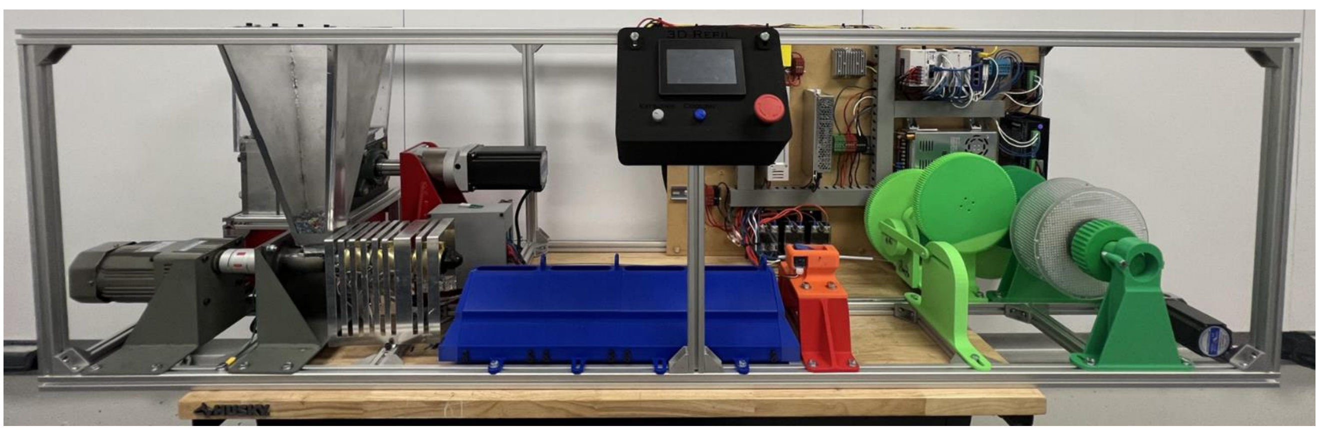

Figure 2. 3D ReFil

2.0 EXISTING SOLUTIONS

Due to the rapid growth in the 3D printing world, there has been a lot of research and projects done of small-scale 3D printer filament recyclers. The research conducted for this project has yet to find an exact replica project consisting of all the components in this project. Although, there are many partial designs out there that have similar components and can be used as a reference point in this project.

A similar joint project constructed by a school in Germany and India was made for recycling plastic. Plastic waste could be turned into 3D printer filament by melting it down and extruding it into a spool of the proper diameter. The schools of TU Braunschweig in Germany and Birla Institute of Technology and Science (BITS) Pilani in India created a project called 3-CYCLE [1]. The project was an integrated system that was fed plastic and produced 3D printer filament. The worked, and the filament was used to 3D print various items.

Santa Clara University had a team of engineers develop a plastic recycler for 3D printer filament for the country of Uganda [2]. The idea was to reduce the use of kerosene and increase the use of solar lamps. The casings for the solar lamps were to be 3D printed to increase their quality, and the plastic recycler was made to recycle plastic trash into the source for the printers. The team's design included a shredder and extruder and would be fueled by plastic water bottles from the country.

A small desktop size plastic recycler was developed for educational purposes by a team at Drexel University [3]. It was tested with recycled plastic and had the intent of persons to regain value from failed prints or plastic waste. The device was implemented at several high schools that used 3D printing. The average print failure was 30%, and by recycling this plastic, saved an average of $1600 per year. This project was successful in reducing plastic waste and having a monetary value reassigned, but it lacked automation and the ability to adjust the settings for different types of plastics. It had one setting for extrusion and would run until it finished [3]. Our team's design project has a goal of being a teaching guide in manufacturing, so motor speed and temperature need to be varied to show the effects in manufacturing.

The University of Akron had a senior design project that resembled our team's objective. An excess of plastic waste was identified, and the University's 3D printer section could benefit from custom-made filament [4]. This team's project consisted of a grinding device, and extruder with heating elements, a cooling system, and spooling system. This project did not have a quality control aspect to the project. The project was conducted in 2019-2020, and Covid prohibited them from completing the actual project. Calculations were performed instead to verify the quality and functionality of the newly made filament with their known variables. Specifics were not shared on what the calculations were over [4].

The next project comes from Indiana University – Purdue University Fort Wayne. This project focused on just the extrusion aspect of recycling plastic into filament [5]. Their project consisted of a screw and casing, heating elements, and a motor. The project eventually extruded a solid line of filament that could be fed into a printer. Initially, they had an inadequate motor to turn the screw and extrude the plastic. Uneven heating also led to issues in the plastic and caused it to break [5].

Another project comes from solving a pollution issue in the Philippines, Vietnam, and Indonesia. Dated in 2010, the Philippines was the third-largest producer of plastic waste, with each person making half a kilogram a day [6]. A team of researchers devised that plastic molding was an adequate solution to this problem by producing plastic flowerpots. The system was aimed at collecting low density polyethylene (LDPE) bottle caps. The system has a grinder and extruder. From the extruder, the melted plastic was inserted into the mold. One mold was estimated to require 128 bottle caps and the whole system was estimated at $2700 [6].

3.0 BUDGET AND SCHEDULING

3.1 Budget

The proposed budget was $3600. This money came from the engineering department and from the awarding of the Barnett Research Grant. The project ended up requiring a sum of $3171.36 to build to completion. The project came in under budget and comparing this project to similar plastic recyclers can be an effective and affordable device to produce 3D printer filament.

A Company known as Filabot makes a full recycling system for turning plastic trash into 3D printer filament for approximately 21 thousand dollars [7]. This system consists of a Reclaimer and Pelletizer to grind up plastic. The extruder is called a Filabot EX6 which flows to their Filabot Airpath cooler. Lastly a spooler is included. The extruder module for this system can be seen in Figure 3. The main difference between this machine and the one in this project is the integration and automation of the subcomponents.

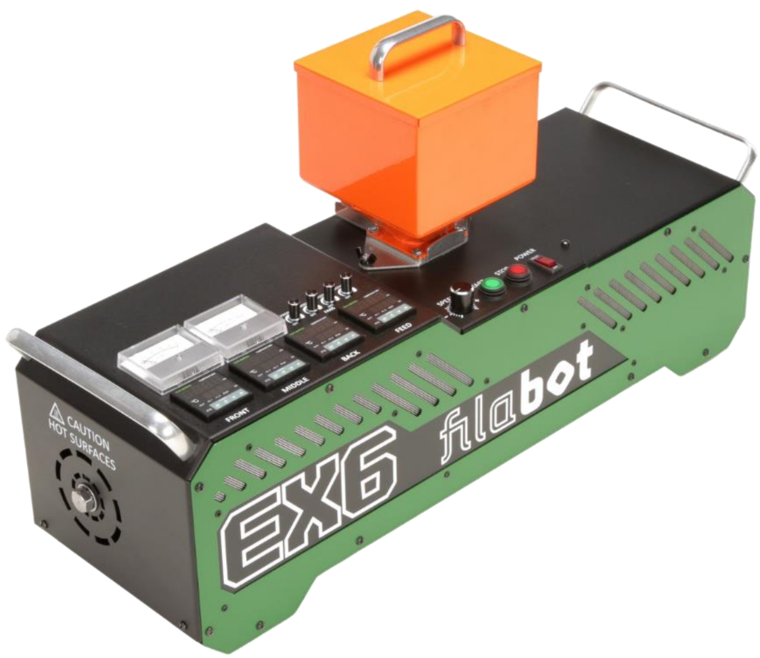

Figure 3: Filabot Extruder

3.2 Schedule

The proposed schedule for designing and completing this project is displayed in Table 1. The proposed schedule was not met in full. Part orders and fabrication did not begin until January of 2024. The frame was completed in mid-January, and the extruder was mounted shortly after. The cooling system was redesigned and fabricated in late January. The spooler was optimized and printed in early February. While the programmable logic controller (PLC) wiring and troubleshooting was completed in mid-February. The grinder fabrication was finished late in March, afterwards the Quality measurement system was redesigned and built. Ultimately, the project completed construction by April of 2024. The initial project schedule is shown in Table 1 and helped the team to complete the project on time.

Table 1. Project Schedule

Date	**Task**
2023	
Monday, August 21	First Day of Class
Monday, September 11	Library Instruction
Friday, September 29	First Draft of Senior Design Proposal
Friday, October 6	Final Senior Design Proposal Due
Monday, October 16	Senior Design Proposal Oral Presentation
Friday, October 27	Have first draft of Design for Construction
Mon/Wed November 13,15	Preliminary Design Review Oral Presentation
Mid November	Purchased framework, Power Supply, and PLC
Beginning of December	Purchase of Extruder and Grinder Parts
Mid December	Begin Fabrication for Framework, Grinder, Extruder
Thursday, December 7	Pre-Senior Design Report Due
End of semester	Order All Other Components Needed
2024	
Monday, January 8	Spring Semester Begins, Set up Weekly Meetings with Advisor
Mid-January	Have Grinder and Extruder Running

Start of February	Have QA and Spooling System Running
Thursday, February 8	Critical Design Review
End of February	Have Project Running and Work on Any Errors That Occurred
March	Complete Any Other Projects Request by Advisor
Friday, March 22	Entire Project Must Be Completed
Friday, March 29	Design Presentation Reviews Complete
Friday, April 5	Draft report Due to Advisor
Friday, April 19	Senior Design Presentation
Thursday, April 25	Senior Design Poster Session
Friday, April 26	Final Report, Due to Adviser, Shared Drive
Friday, May 3	Final Report Submitted to SOAR

4.0 GRINDER

The first component of this project is the grinder. This is where plastic waste will first enter the system for the filament production process. Preliminary knowledge on grinder design was acquired for the design and construction of the grinder in this project.

4.1 Literature Review

Due to the rapid growth in the 3D printing world, there has not been a lot of research and senior design projects done of a small-scale 3D printing filament recycler. Although, there are many hobbyists designs out there. These following reviews give insight to various aspects of the grinder design.

4.1.1 Plastic Waste Management System Using Metal Shredder for Clean Environment

This design that will be used for inspiration will be from a senior design project that was done over the "Plastic Waste Management System Using Metal Shredder for Clean Environment" that was located at Mattu University, Mattu, Ethiopia [8]. This project was done by a group of students who wanted to help fix the plastic issue that is being faced. They had to design and build a robot that would be able to drive around via a remote control. It would use its robotic arm and pick up any plastic it found and then put it into its grinder system that would grind up the plastic and hold it until it got full. Then it would dispose of it at its approved disposal area and return where it left off to continue its plastic waste management. A photo of this project can be seen in Figure 4.

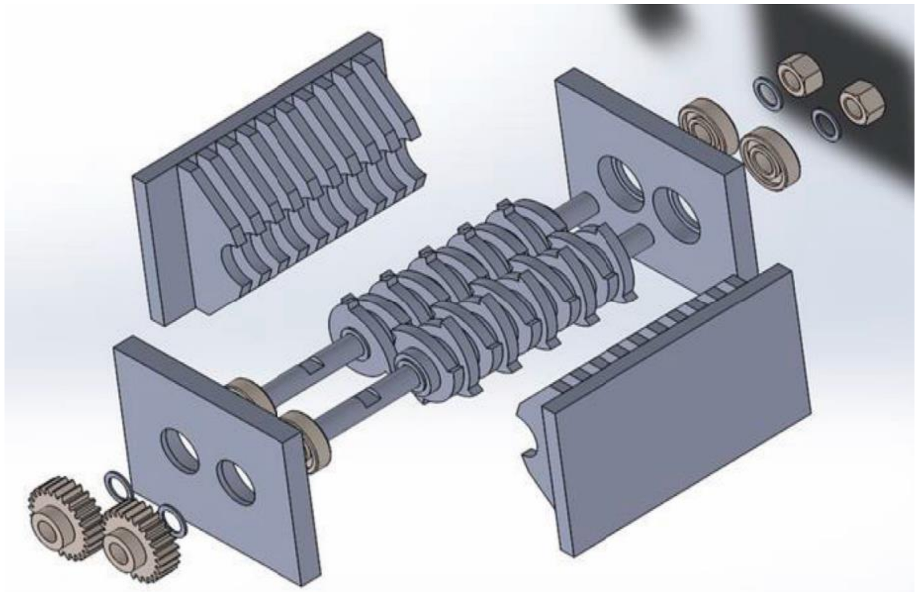

Figure 4. Mini Shredder Design [8]

4.1.2 Building a Community-Scale Plastic Recycling Station

Another project that was able to solve the design goals for a grinder that has been set for this project was the case study of "Building a community-scale plastic recycling station to make flowerpots from bottle caps" [6]. This group set out to solve a plastic waste issue in their local area by designing a system that can recycle plastic bottle caps and injection molding them into a flowerpot to be reduced. From this project, they achieved some of the engineering and design constraints set for this project. A photo of this project can be seen in Figure 5.

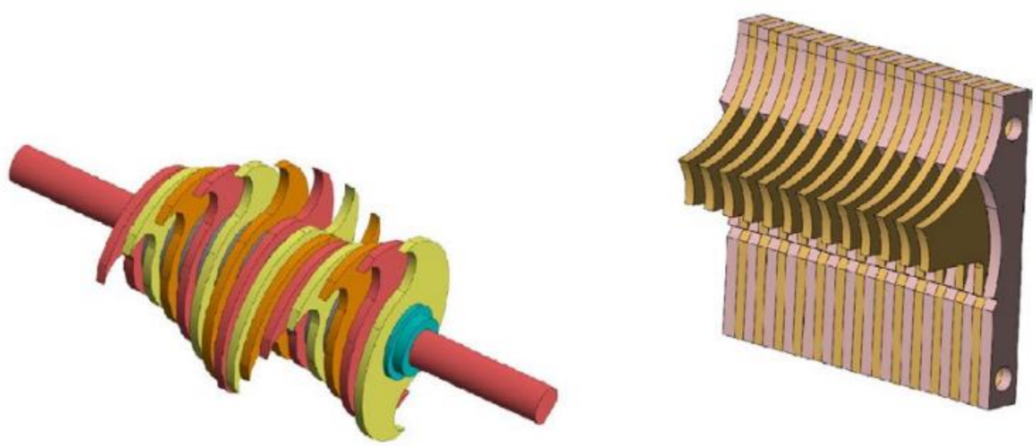

Figure 5. Bottle Cap Shredder Design [6]

4.1.3 Senior Design Report of the Paper Shredder Design

An additional project that was evaluated was the "Senior Design Report of the Paper Shredder Design" [9]. Although this project was done for the shredding of paper, a lot of similar aspects can be applied and used. What went wrong with their overall design would have been with their material selection as well as their cooling system. For the material selection, the team had gone with stainless steel shafts and cutters which resulted in the overall price to shoot up which resulted in the overall project to not be cost effective compared to others that are on the market. This team had decided to go with plastic gears, which in the end yielded due to having too many papers inserted at once, which is another design element that should be considered for this project. Although this project will not be shredding paper, it shows that the strengths of parts need to be considered when selecting and making components for the project. Finally, the last part that can be used to learn from this team is that they had problems with the motor overheating. A photo of this project can be seen in Figure 6.

Figure 6. Paper Shredder Design [9]

4.2 Information Learned

4.2.1 Plastic Waste Management System Using Metal Shredder for Clean Environment

This project was able to design and build a small and compact grinder system and was able to grind up plastic into smaller pieces as well as being light enough to transport. The motor selection that this group used struggled to cut the plastic due to the robot having a limited battery life. The team mentioned in their report that with the grinder size being so small, they were only able to grind up tiny amounts of plastic. From this report, the information that has been obtained is that a proper cutting tooth size needs to be determined and a strong and reliable motor will need to be selected.

4.2.2 Building a Community-Scale Plastic Recycling Station.

This project had decided to go with a fixed wall cutting edge and a rotating. In this design, they have offset grinder teeth to grab and cut through the bottle caps. Although the system is an innovative idea and would work well, the overall design of the grinder system is a lot larger than the size constraints for this project. The grinder system does have a few flaws due to the teeth being so large. A limit tray was placed at the bottom to only allow the correct size pieces to fall through. If the parts were too large, then they were returned into the system to be re-grinded until they were the desired size. Although the design and concepts worked out, the overall size of the grinder is too large and would need to be redesigned to fit the current project.

4.2.3 Senior Design Report of the Paper Shredder Design

This Project had decided to go with a plastic gears train system. Although the engineering design was done for the gears, the material selection resulted in failure. The group has decided to use plastic gear over metal, which in the end yielded due to having too many papers inserted at once, which is another design element that should be considered for this project. Although this project will not be shredding paper, it shows that the strengths of parts need to be considered when selecting and making components for the project. Another issue that was faced in this project was motor overheating. This was due to an improper motor selection.

4.3 Knowledge Gained

Some of the key information that has been obtained from the literature review is the following: Ensure that proper cutting tooth size is determined based on the desired object to enter the grinder system, spec out a motor that can handle any load being put into the shredder and add a safety factor to ensure no struggle will occur. Design the grinder to cut parts into desired sizes to fit end goal requirements. Finally, material selection should be considered for all components of the grinder to ensure that any weak points can be fixed and ensure that the system will hold up to design.

4.4 Conceptual Desings

Now that a literature review has been conducted and knowledge has been gained. A preliminary design phase has begun which takes into consideration all the knowledge that has been gained to come up with some ideas. The designs can be seen in the sections below along with what the design looks like as well as the pros and cons of each design. All images provided have been designed in SolidWorks.

4.4.1 Preliminary Concept 1 – Intermeshing Rotating Blades

The first preliminary concept that was determined was shown in Figure 7 below.

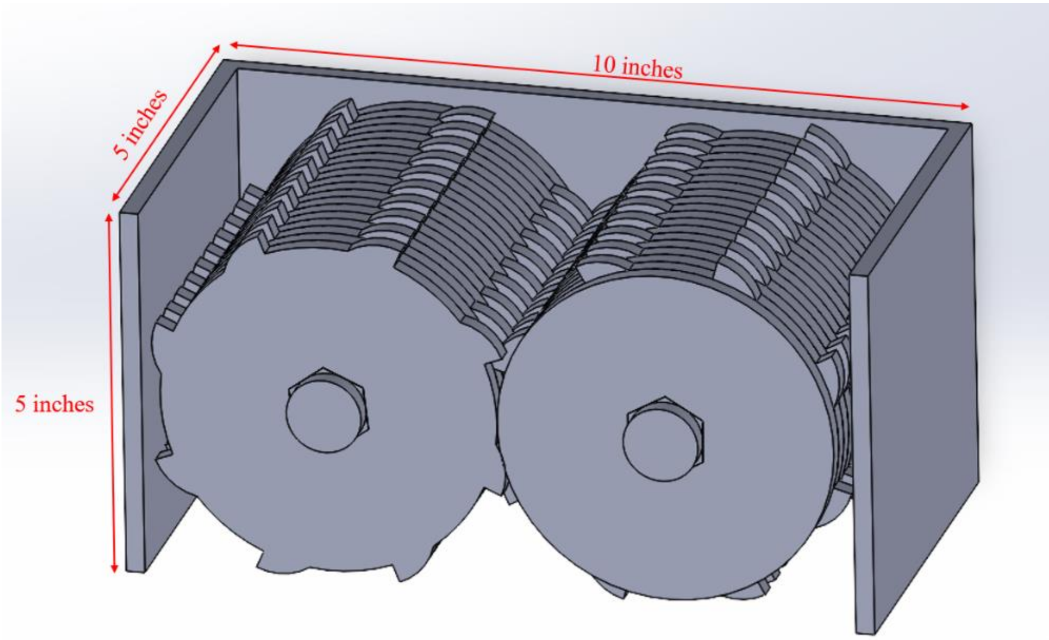

Figure 7. Preliminary Concept 1 - Intermeshing Rotating Blades

This style of grinder shows two sets of grinder teeth which are spinning in opposite directions. The set of grinder teeth on the left are spinning clockwise while the set of teeth on the right are spinning counterclockwise. By having these teeth spin together, they grip onto the desired object and shear it apart as the blades spin. This setup would require a powerful motor as well as some sort of gear setup to allow the motors to spin uniformly. It spins at a low RPM such as 20 RPM. It will require a motor that can produce high torque at low speed. Table 2 below shows the positive and negative aspects of this design.

Table 2. Pros and Cons of Intermeshing Rotating Blades

Pros	Cons
Slow Rotating Speed	Alignment issues
	Large Size
	Gear system required

4.4.2 Preliminary Concept 2 – Fixed and Rotating Solid Blade

The second preliminary concept that was determined was shown in Figure 8 below.

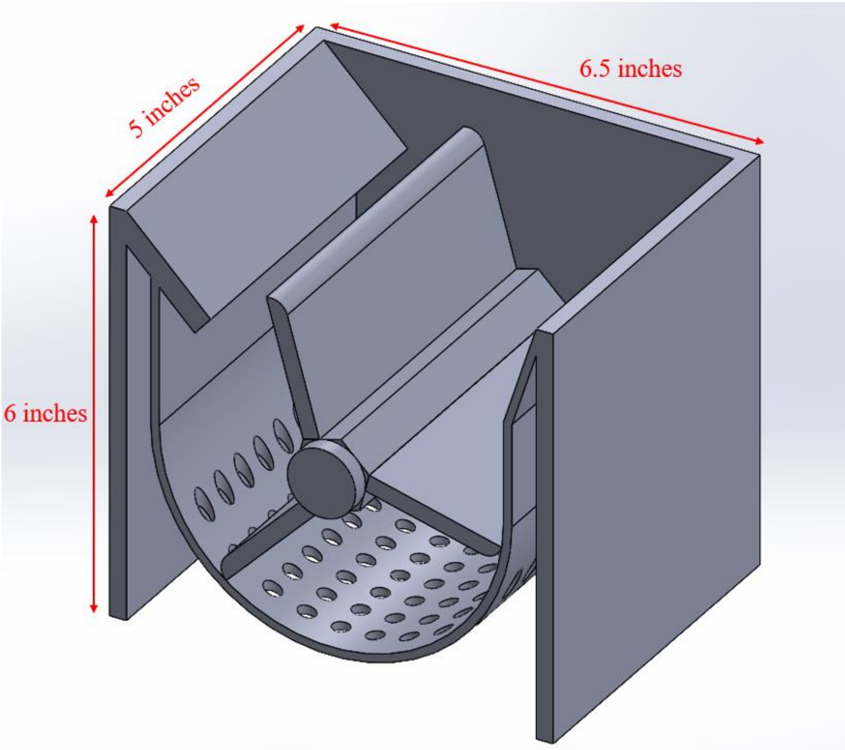

Figure 8. Preliminary Concept 2 - Fixed and Rotating Solid Blade

This style of grinder is typically used in the manufacturing setting to grind up plastic. This design works by having several spinning blades rotating at a high RPM and then having a fixed blade where the spinning blades will be able to shear the plastic. The spinning blade spins at a high rpm roughly around 400 RPM. By doing this it keeps cutting up the plastic until it is cut small enough to fall through the circular grate at the bottom. It will require a motor that has high speed as well as high torque to ensure that it can cut through the desired plastics. Table 3 below shows the positive and negative aspects of this design.

Table 3. Pros and Cons of Fixed and Rotating Solid Blade

Pros	**Cons**
Plain design	High cutting speed required
Common grinder in plastic manufacturing	Special Tool Steel need for cutter blades
	Difficult to alight properly

4.4.3 Preliminary Concept 3 - Fixed and Rotating Intermeshing Blade

The final preliminary concept that was determined was shown in Figure 9 below.

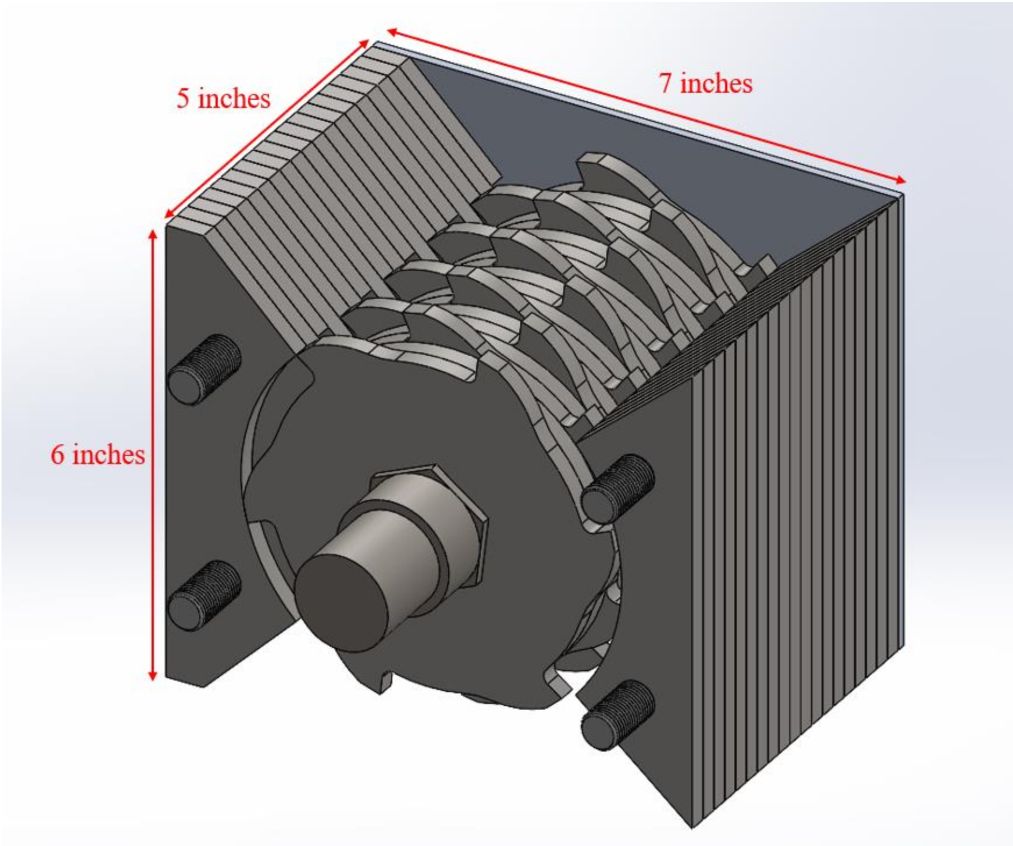

Figure 9. Preliminary Concept 3 - Fixed and Rotating Intermeshing Blade

This grinder design takes parts from the previous two grinders designs and combines it into one. It takes the slow rotating grinder teeth from Concept 1 and combines it with the fixed cutting edge from Concept 2. By combining these two concepts together, a controlled grinding size can be designed as well as its speed. Table 4 below shows the positive and negative aspects of this design.

Table 4. Pros and Cons of Fixed and Rotating Intermeshing Blade

Pros	Cons
Slow speed required	Alignment issues
Proper cut size given	
Fits Size requirements	
Easily manufacturable	

4.5 Chosen Design

By looking at the three different conceptual designs and comparing the pros and cons of each, a design will be chosen for the project. Concept 3, the Fixed and Rotating Intermeshing Blades appears to be the best design out of the three. It can incorporate the different pros from the other two concepts and combine them to make a better functioning design.

4.6 Overall Preliminary Engineering Design

To begin the Overall Preliminary Engineering Design for the grinder, a set of technical requirements must be set to help with the design.

The following requirements are:

- The grinder shall be able to grind PLA plastic with a 4-inch x 4-inch base.
- The grinder shall grind PLA plastic pieces into ¼-inch x ¼-inch x ¼-inch.
- A motor shall be specked out to exceed max shearing force.
- The grinder shall have finger projection on all moving parts per OSHA regulations.
- The grinder shall be hand fed with plastic parts.
- The grinder will have a catch tray to collect all the grinded material.

Now a set requirement has been determined. The design process can begin. The first step in the design process is to figure out what will be the largest piece of plastic that this grinder will be grinding up. From the requirements it shows that it needs to have an area of ¼-inch x ¼-inch. It also states in the requirement that this grinder should be able to grind up a piece of plastic that has a base of 4-inch x 4-inch. From these set requirements, several calculations need to be made on the overall design of the grinder.

4.6.1 Max Force Needed to Shear Plastic

To begin the calculations, the force needed to shear the PLA must be found. To do this, the yield strength of PLA must be found as well as the cross-sectional area that the force is being applied to. The yield strength of the PLA is 35MPa. The max area that the teeth can cut through will be an area of 1/4 by 1/4in by 1.1 in long. All these units are converted to metric system to keep everything standardized. The equation below is the force needed to shear the plastic.

$$\tau_{Plastic} = \frac{F_p}{A_{Plastic}} \quad (1)$$

Where:

τ_p = Force Needed to shear the PLA (N/m^2)

F_p = Applied force on the member (N)

A_p = Cross-sectional Area (m^2)

Where A_p can be found from the following equation

$$A_p = h * l + w * l * 2 \quad (2)$$

Where:

A_p = Cross-sectional Area (m^2)

h = Height of the cutting tooth (m)

l = Max length of plastic that will fit in tooth area (m)

w = Width of the tooth (m)

From this, we can modify the equation into

$$\frac{1}{2}\sigma_p = \frac{F_p}{A_p} \quad (3)$$

Then we can solve for F_p

$$F_p = A_p \frac{1}{2}\sigma_p \quad (4)$$

Where:

σ_c = Force Needed to shear the PLA (N/m^2)

F_p = applied force on the member (N)

A_p = Cross-sectional Area (m^2)

The σ_c is 35 MPa and the A_p = 0.0005322 m^2. With these given values, the force needed to shear the plastic is found to be 9315 N. Now that the max force needed to shear the largest piece of plastic that will fit in the grinder has been calculated, let's see if shearing will occur along the grinder tooth.

4.6.2 Max Force on Tip of Grinder Tooth

From finding the shear forces needed to shear the largest plastic that will fit, we need to see what the max load applied to the tip of the grinder tooth will be and compare it to the material yield strength to determine if the material will hold or shear. We can find this by looking at the following equation, found in *"Roark's Formulas for Stress and Strain"* of the max force that is applied on the tip of the grinder tooth. The following equation below solves it.

$$\sigma_t = \frac{2\mathrm{Fp}cos\emptyset}{\pi r_s} \quad (5)$$

Where:

F_p = Force calculated to shear plastic (N)

$\emptyset$ = Pressure angle (rad)

r_s = radius (m)

σ_t = total pressure needed to shear plastic (Pa)

From the equation, many of the values are given. F_p =9315 N, $\emptyset$ = 0 rad, r_p =0.060325. After plugging these values into the equation, we get the value for σ_t to be 98,297 Pa for the max load that will be applied on the tip of the grinder. We can compare this number to the yield strength of the selected material, 4140 steel, which is $4.6\text{x}10^8$ Pa. So, this means that the plastic will yield way before the grinder tip yields. This ensures that there is no worry on the grinder breaking due to yielding on the tip of the tooth. This can be verified by running a SolidWorks Simulation as shown below.

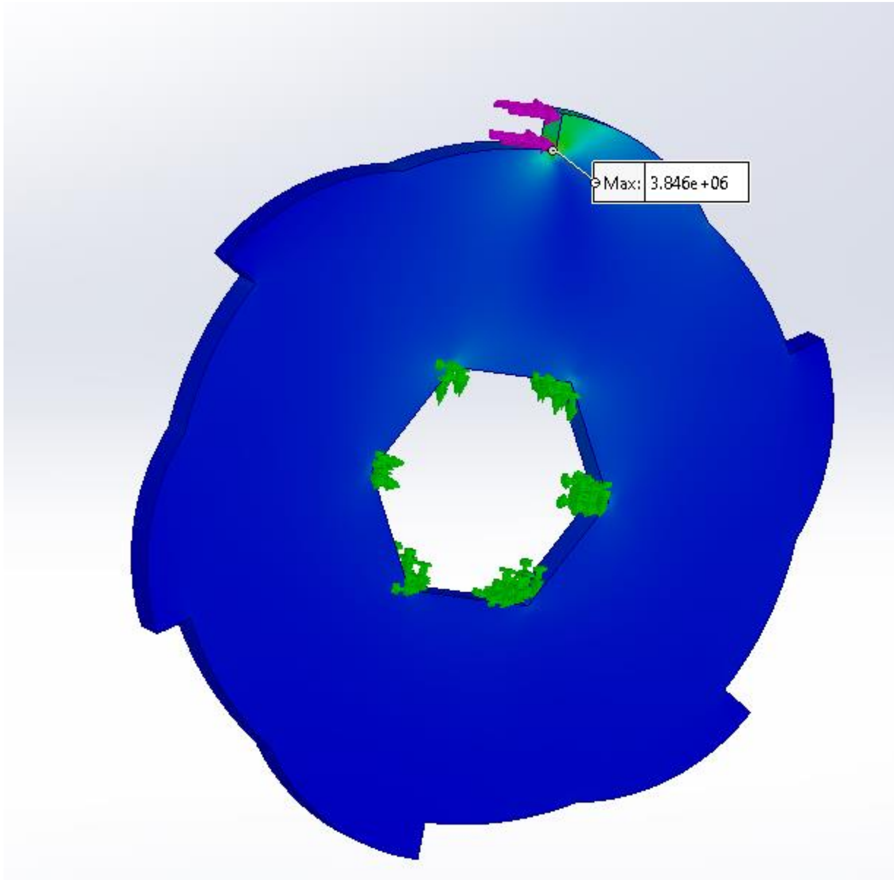

Figure 10. Edge of Grinder Blade SolidWorks Simulation

As shown above, the SolidWorks simulation has helped prove the calculations to be accurate.

4.6.3 Max Shear Force Applied to Grinder Face

Next up, the max force that will be applied to the face of the tooth needs to be calculated. By doing this, we can see if the grinder tooth will yield and break or if it will be able to withstand the force that the plastic will put on it when it gets sheared.

$$\sigma_f = \frac{6F_p w}{hl^2} \quad (6)$$

Where:

σ_f = Max force (Pa)

F_p = Force calculated to shear plastic (N)

w = tooth width (m)

h = Tooth face length (m)

l =Length of overall tooth (m)

From the equation above, σ_f can be solved for. The following values are F_p = 6988.42 N, w = 0.003175, h = 0.003175, l = 0.04191. σ_f is found to be $2.39*10^7$ Pa to shear through the plastic. We can compare this number to the yield strength of the selected material, 4140 steel, which is $4.6x10^8$ Pa. So, this means that the plastic will yield before the grinder face yields. This ensures that there is no worry on the grinder breaking due to yielding on the tip of the tooth. This can be verified by running a SolidWorks Simulation as shown below.

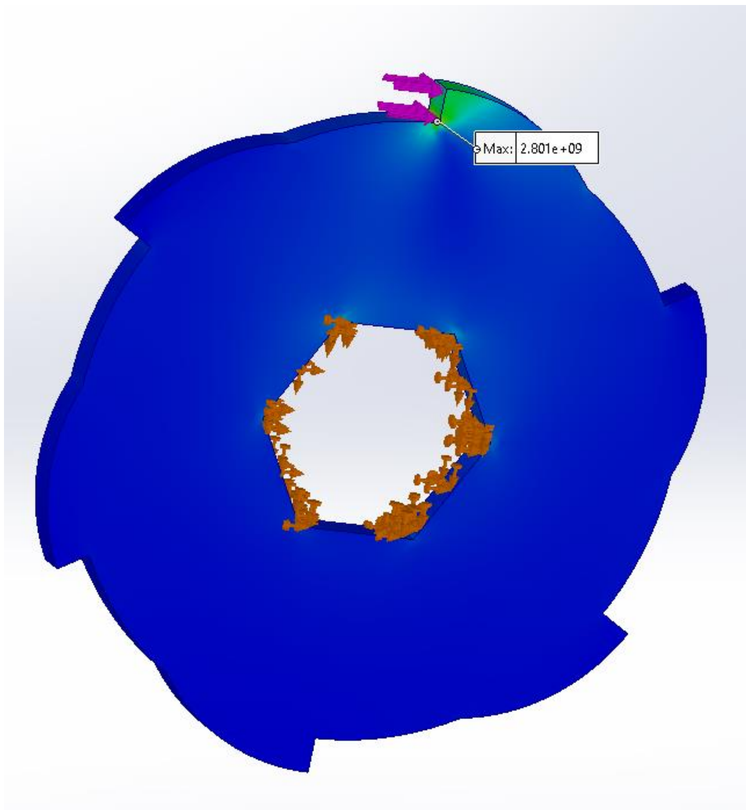

Figure 11. Face of Grinder Blade SolidWorks Simulation

As shown above, the SolidWorks simulation has helped proven the calculations to be accurate.

4.6.4 Force Applied for Deflection

Now that the calculations have been done to ensure that the grinder teeth can withstand the plastic and will be able to shear through the plastic. The deflection of the shaft needs to be checked to ensure that it will not bend while cutting through the plastic. The equation to determine the deflection is,

$$\sigma_d = -\frac{F_{pm} l_s^2}{48 E I_s} \quad (7)$$

Where:

σ_d = Deflection in shaft (m)

F_{pm} = Force calculated to shear plastic (N)

l_s = Total Length of shaft (m)

E = Elastic Modulus of 4140 steel

I_s = I of the shaft

Not all the variables are defined and need further equations to be fully resolved.

$$F_{pm} = \frac{F_p}{2} * 5 \quad (8)$$

Where:

F_{pm} = Force calculated to shear plastic (N)

F_p = Force calculated to shear plastic (N)

The reason we multiply it by 5 is because there will be 5 teeth max engaged at once. It is divided into 2 to get the max force applied to the center. The given value is F_P = 6988.42 N. From this, F_{pm} is found to be 17,768 N

$$I_s = \frac{\pi d_s}{64} \quad (9)$$

Where:

I_s = I of the shaft

d_s = Diameter of the shaft (m)

To solve for I_s, the value for d_s = 0.0381 M and when solved, I_s is found to be $1.65*10^{-6}$

Now that all the variables have been defined for equation 7, σ_d is solved to be $-2.79*10^{-7}$ m. This means that the deflection that will occur in the shaft will be so small that it can be negligible and will not be a concern for the overall project. This can be checked by running a SolidWorks Simulation as shown below.

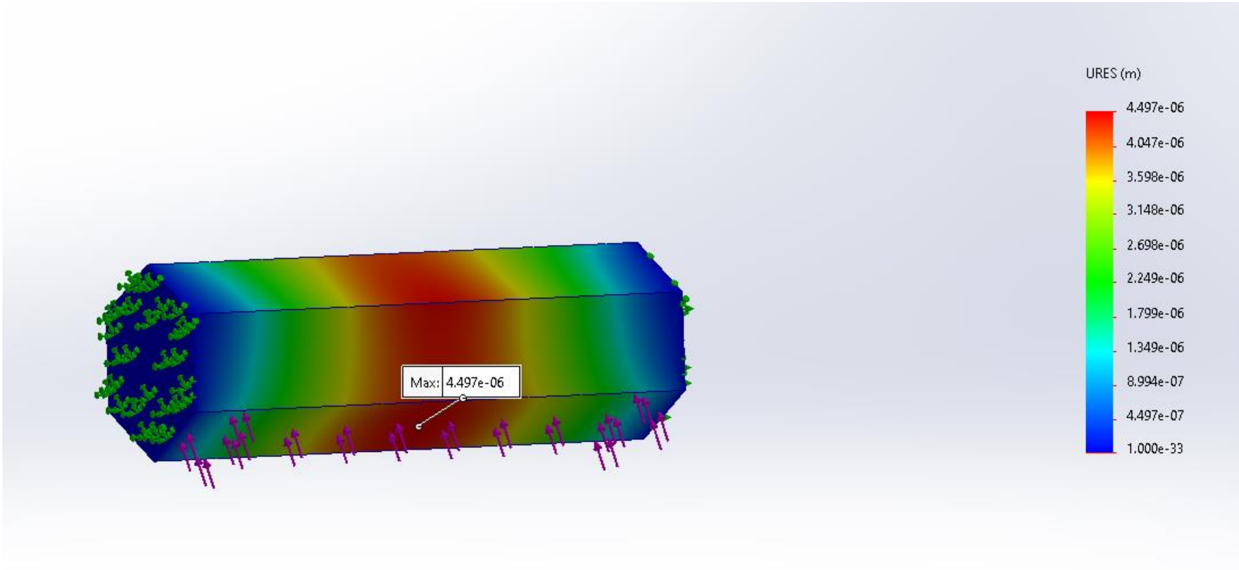

Figure 12. Shaft Deflection SolidWorks Simulation

4.6.5 HP Needed to Maintain Speed

Finally, it is proven that the shaft and the grinder teeth will be able to withstand shredding the plastic. It is time to find the horsepower needed to operate the grinder. The first step in this process is to find the torque needed to grind through all the plastic, then apply a safety factor to allow for the items that were not calculated such as friction and other miscellaneous items. Finally, the torque can be converted into Watts which can be used to find Horsepower.

Torque needed to grind through plastic:

$$\tau_L = F_{pm} r_g \tag{10}$$

Where:

F_{pm} = Force calculated to shear plastic (N)

r_g = radius of the grinder (m)

τ_L = Torque needed to grind through plastic (Nm)

From these known values, we can solve for τ_L to be 140.90 Nm

Torque with a safety factor:

$$\tau_{sf} = \tau_L Sf \tag{11}$$

τ_L = Torque needed to grind through plastic (Nm)

Sf = Safety Factor

τ_{Sf} = Torque needed to grind through plastic (Nm)

A safety factor (Sf) is applied to the torque required to account for all unaccounted factors such as friction and any other variables. τ_L is found from Equation 10 and the Sf will be 1.25. This gives us the max torque required to be 176.12 Nm.

Watts need to maintain max speed:

Finally, the power needed to calculate the motor can be found.

$$P = \tau_{Sf}\omega_g \tag{12}$$

Where:

P = Power (w)

τ_{Sf} = Torque needed to grind through plastic (Nm)

ω_g = Max Speed the grinder will be Spinning (rad/s)

To solve for the power, we need to first determine what the ω_g is going to be by deciding a max speed. The team has chosen it the max speed to be 15 RPM which can be converted to 1.57 rad/s. Now that the torque and max speed is known, it can be found that the total power needed to grind through the plastic is 276.64 Watts.

4.6.6 Supporting Diagrams

A system hierarchy for the grinder can be seen in Figure 13. This shows the five components of the project and the subcomponents for the grinder. Table 5 and Table 6 show a failure mode and effects analysis for prior and post project completion.

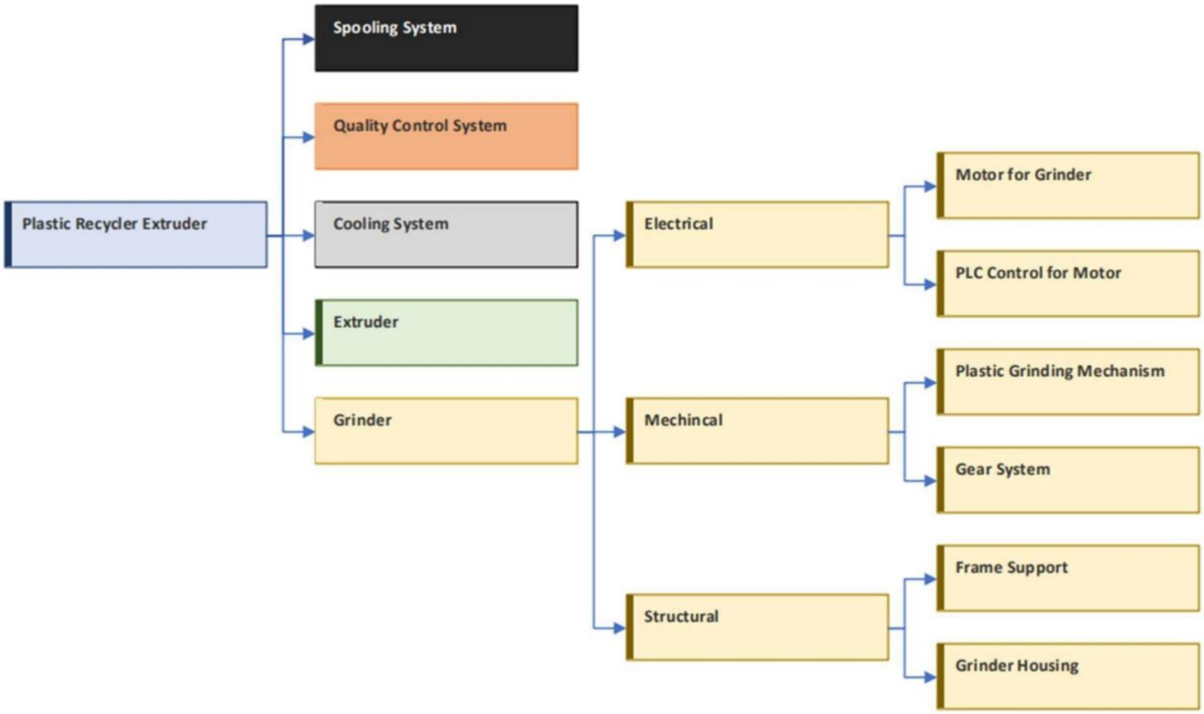

Figure 13. System Hierarchy - Grinder

Table 5. FMEA Grinder Prior Project Completion

Item	Failure Modes	Cause of Failure	Possible Effects	Prob.	Actions to Reduce failure
Electronics	Electrical Short	Wall Outlet Surge	System Will Not Work	Low	Check Electrical Load Calc.
		Power Supply			
		Drive Load Too Large			
	Under Powered	Power Supply	System Will Not Operate Properly	Medium	Check Electronics Rating
		Drive Load Too Large			
	Over Heating	Improper Fuses	Electronic Damage or Fire Hazard	Low	Check Electronics Rating
		Drive Load Too Large			
		Electronics Operating Past Rated Parameters			
Mechanical	Rupture	Alignment Issues	System Will Not Operate Properly and Failure	Medium	Measure twice/ Cut Once
		Deflection in Material		Low	Check Load Calc.
		Defective Material			Reliable Manufacturer

Table 6. FMEA Grinder Post Project Completion

Item	Failure Modes	Cause of Failure	Possible Effects	Prob.	Actions to Reduce failure
Grinder Teeth and Housing	Jamming	None Plastic Items	Plastic won't grind up properly	Low	Check Production settings
		Spinning to fast			
	Rupture	Wear And Tear	Broken Teeth	Low	Protective Wrapping
		Damage from Transport			

4.7 Critical Grinder Design

With the initial design of the grinder believed to be finalized, the selection of an extruder necessitated a modification in the grinder's particle size from ¼” to 1/8”. This adjustment prompted a comprehensive reassessment and redesign of the entire grinder.

Following thorough research and analysis, the team opted to retain the original design. However, they devised a solution to address the particle size requirement by incorporating a supplementary section into the grinder. This innovation transformed the grinder into a two-stage reduction grinder, as illustrated below in Figure 14.

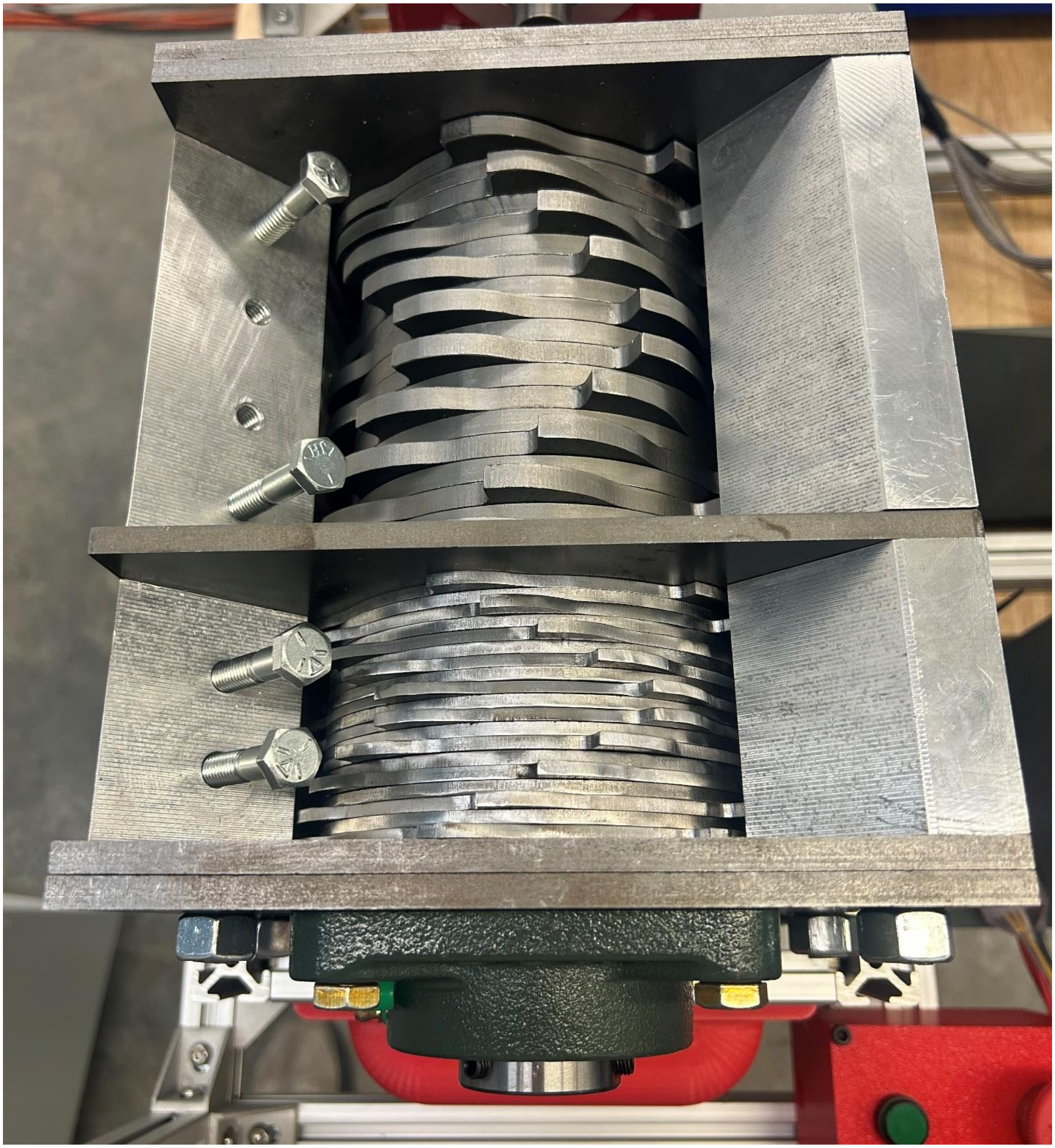

Figure 14. Two Stage Grinder Model

An analysis was conducted on the smaller 1/8” section to ascertain its capability to withstand similar loads, and it was found to be satisfactory. As the redesign progressed towards a two-stage grinder, the requirements for the grinder had to be reevaluated, leading the team to formulate the following updated requirements.

The following new grinder requirements are:

- The grinder shall be able to grind PLA plastic with a 4-inch x 4-inch base.
- The grinder shall grind PLA plastic pieces into 1/8-inch x 1/8-inch x 1/8-inch.
- A motor shall be specked out to exceed max shearing force.
- The grinder shall follow sound engineering design with safety for the used in mind.
- The grinder shall be hand fed with plastic parts.
- The grinder will have a Material Collection Bun with a Scale.

Now that the grinder's design has been refined to meet the updated requirements, the construction phase can commence.

4.8 Grinder Fabrication and Modification

The fabrication of the grinder was done in the Applied Engineering Center (AEC). It began by cutting out all the plates on the waterjet that were ¼" thick and 1/8" thick. This can be seen below in Figure 15

Figure 15. Waterjet Cutting out Grinder Parts

After cutting out all the grinder teeth and the frame, they were meticulously positioned in the mill for precision milling of the edges to ensure proper alignment. Every component was engineered with a tight tolerance of 0.005 inches to guarantee efficient cutting through the plastic without the risk of clogging or particle entrapment. The milling process is visually documented in the following two figures.

Figure 16. Milling of Grinder Tooth

The Figure 16depicts the refinement of the cutting edge of the grinder. Both the inner and outer edges of the grinder tooth underwent machining. The inner section was machined to attain a slip fit on the hex shaft, facilitating easy removal and installation. Meanwhile, the exterior of the grinder tooth was meticulously machined to ensure the attainment of a precise and effective cutting edge.

Figure 17. Milling of Grinder Frame

The Figure 16depicts the refinement of the cutting edge of the grinder. Both the inner and outer edges of the grinder tooth underwent machining. The inner section was machined to attain a slip fit on the hex shaft, facilitating easy removal and installation. Meanwhile, the exterior of the grinder tooth was meticulously machined to ensure the attainment of a precise and effective cutting edge.

Figure 17Figure 17 shows the edges of the frame being machined to the proper size as well as making sure all the holes are sized properly to be tapped.

Now that the frame and Cutting edges have been machines to the proper size and tolerance. The Assembly of the grinder can begin as shown in FIGURE below

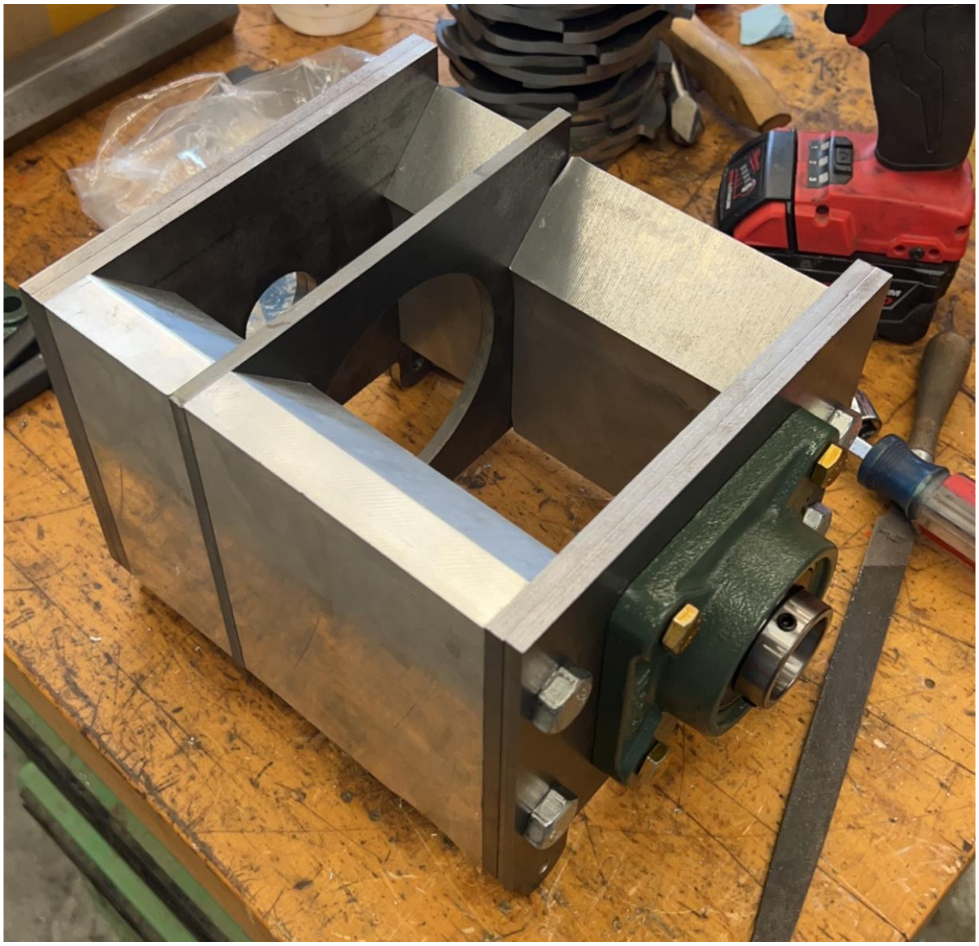

Figure 18. Frame of Grinder

As shown in Figure 18 above. The frame of the Two stage grinder is complete, and the grinder teeth can be inserted and have the shaft prepped for the whole system.

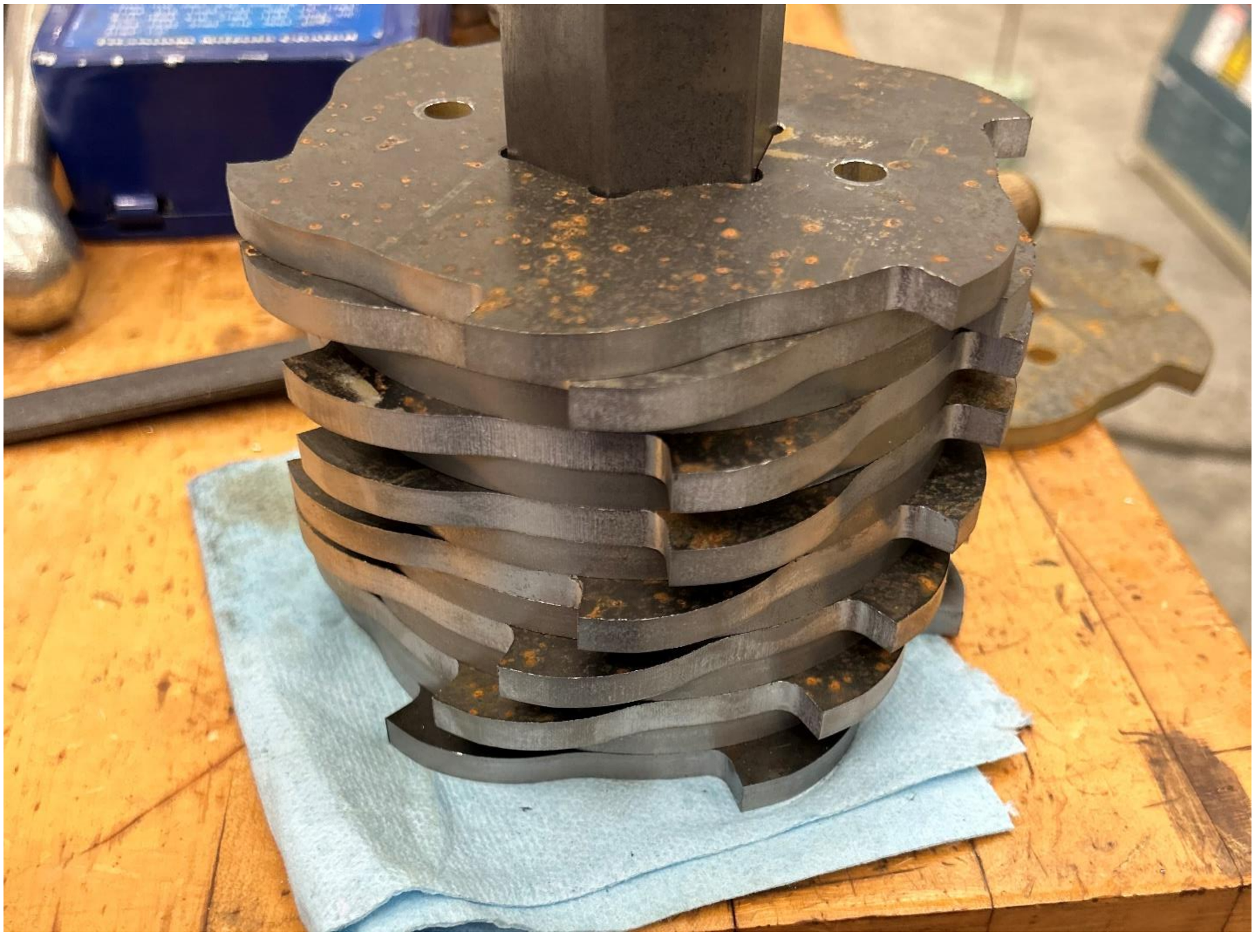

Figure 19. Grinder Teeth

Figure 19 shows the grinder teeth fitting on the shaft and are ready to be assembled. The next step in the grinder fabrication is to make the cutting edges that the grinder teeth will be cutting against. Figure 20 below shows the cutting edges fabricated and installed in the grinder housing.

Figure 20. Grinder Cutting Edge

Now that the grinder housing is assembled, it is ready to be mounted to the frame of the whole project. This can be seen in the Figure 21 below.

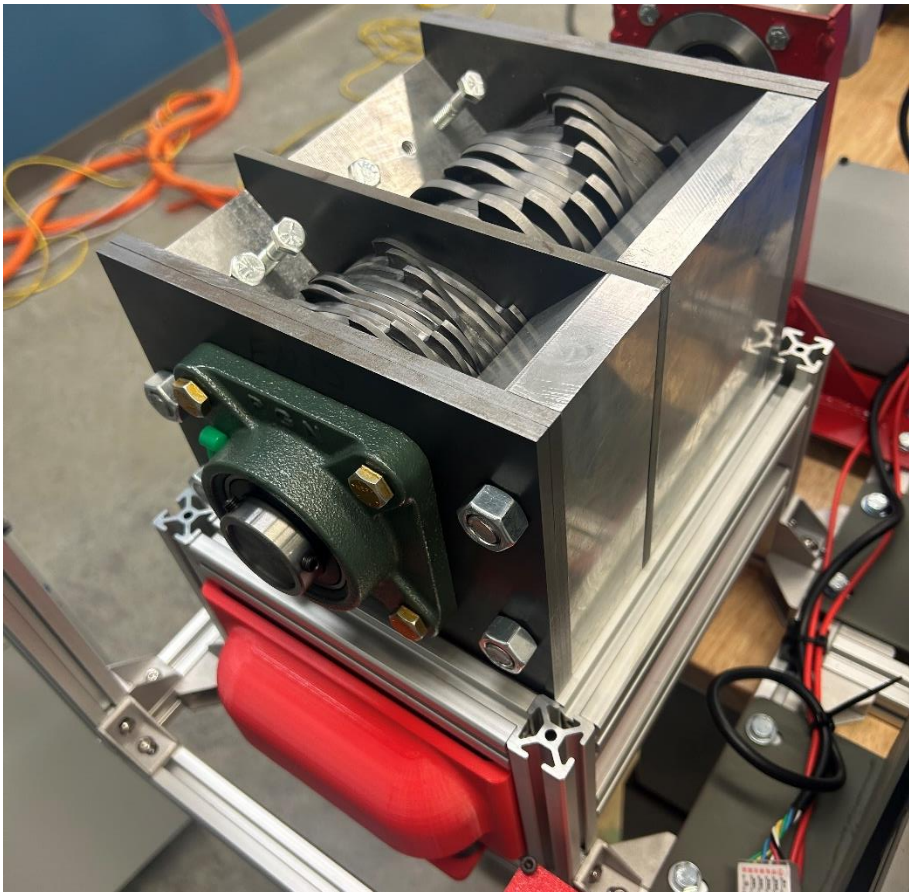

Figure 21.Grinder Mounted to frame

Once the grinder was properly mounted, the fabrication of the motor mount was done and installed. Can be seen in Figure 22 below.

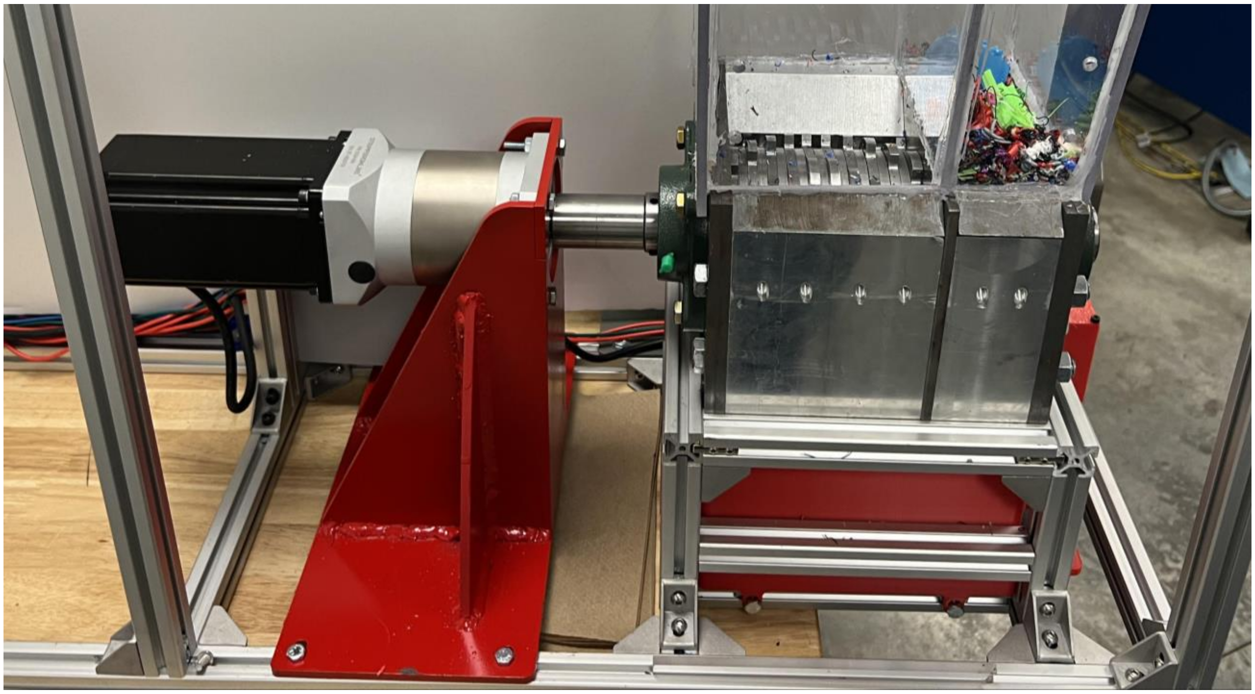

Figure 22. Full Grinder Assembly

After the grinder was fully assembled, testing commenced. During this phase, it became evident that the motor needed to operate at low revolutions to optimize torque output. This outcome was anticipated by the team, who understood that a slower grinding speed would minimize friction on the plastic, thereby preventing overheating and melting, given its low melting point.

The testing revealed that achieving the desired amount of ground plastic required several hours. However, despite the time investment, the team deemed it worthwhile as the grinder performed as intended. With functionality confirmed, attention now turns to commencing Filament production.

5.0 EXTRUDER

The next component in the project is the extruder. The extruder is made up of a barrel, screw, motor, and heating elements. The extruder will take the ground up plastic bits from the grinder and melt and extrude them through a 1.75 mm hole to produce 3D printer filament. Although a screw and casing can be fabricated for this project, an already pre-made package will be purchased to reduce errors in the production process.

5.1 Literature Review

Since a premade extruder will be purchased, there is not a lot of research to do on the ordering process. The requirements for the extruder will be discussed later and decide on which extruder gets purchased. The key components to look at will be the production speed of the extruder and power of the motor that accompanies it.

5.1.1 The Extruder Characteristic

This small document [10] discusses how fluids flow inside a screw. The fluid being liquid plastic will have various viscosities depending on the type of plastic and the coefficient of friction of the barrel is hard to determine. For the fundamentals, the document discusses velocity equations and volumetric flow equations depending on diameter, rotational speed, and thread pitch angles.

5.1.2 Dynisco Extrusion Processors Handbook

This handbook on extrusion processes [11] discusses material properties, how extruders work, and several topics related to extruders and dies. This book is centered around large industrial processes but is still relevant to this project's small-scale applications.

5.2. Information Learned

5.2.1 The Extruder Characteristic

This document discusses how to find the linear velocity of plastic as it exits the nozzle of the screw. This will determine the production speed of the project in length per hour and kilograms per hour. Since viscosities and friction coefficients are hard to determine, a safety factor will be applied at the end of the sizing calculations to ensure the motor can handle the manufacturing load.

5.2.2 Dynisco Extrusion Processors Handbook

The biggest piece of information from the Dynisco Handbook is the ratio of desired production speed to motor wattage. This ratio suggests that for every 10 pounds of plastic line to be produced per hour, the extruder motor should have a power of at least one horsepower.

5.3 Knowledge Gained

The most important engineering knowledge to know for the extruder would be thermodynamics, material properties of plastic and motor sizing for driving the screw. To keep energy costs low, the heating elements should heat up right to the melting point of the plastic. Going over is a loss in efficiency of the system. A look at the most common types of plastics in the world would be useful as well. The project will be tested around PLA. Eventually, having presets for various kinds of plastics' melting points will make the project more versatile for all kinds of plastic waste.

5.4 Conceptual Designs

The extruder only has one design, as the motor connects to the back of the screw. The whole project will sit on a table, but there are multiple ways to orient all the components. The table will be 4 ft x 6 ft.

The first one is a side view of the table. Every component has been labeled and flows horizontally from left to right. The pro of this design is that it best demonstrates a manufacturing line. The controller is off to the side and allows the user to monitor the filament as it goes down the line. The grinded plastic exits the grinder directly into the extruder. The con of this design is that the plastic extrudes horizontally and will need support to not deform under gravity. This will add additional pulleys to guide the plastic, and the possibility of them being motor controlled if the plastic needs to be pulled down the line. The first design is shown in Figure 23.

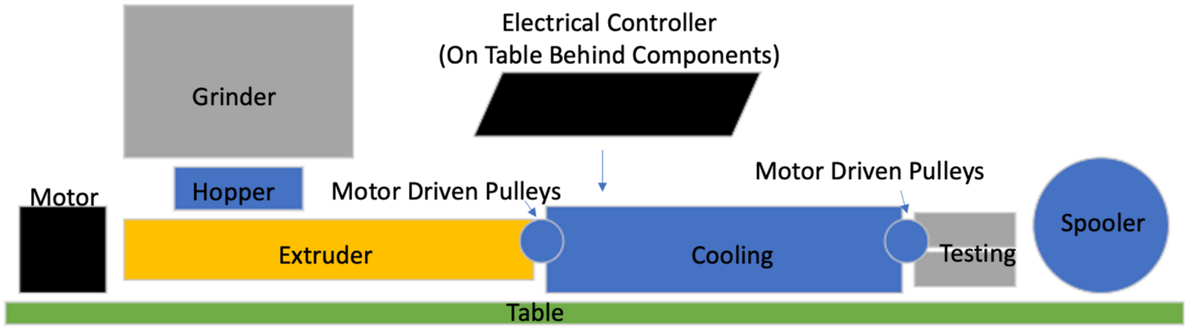

Figure 23. Extruder Concept 1

The second design is also a side view. This design changes the extruder from a horizontal position to a vertical position. The pro to this design is that the plastic gets extruded, and gravity pulls it down and out of the extruder. The controller is still off to the side and allows the user to monitor the production process. The table can also be smaller since there are less components spread out horizontally. The con to this design is that it becomes tall. The average table already sits about three feet off the ground, so an additional two to three feet are needed to stack the grinder on top of the extruder. Another con is the amount of guide pulleys needed to guide the plastic from vertical to horizontal to enter the cooling system. Enough railing and support would be needed to keep the grinder and extruder from moving during the production process. The second design can be seen in Figure 24**Error! Reference source not found.**.

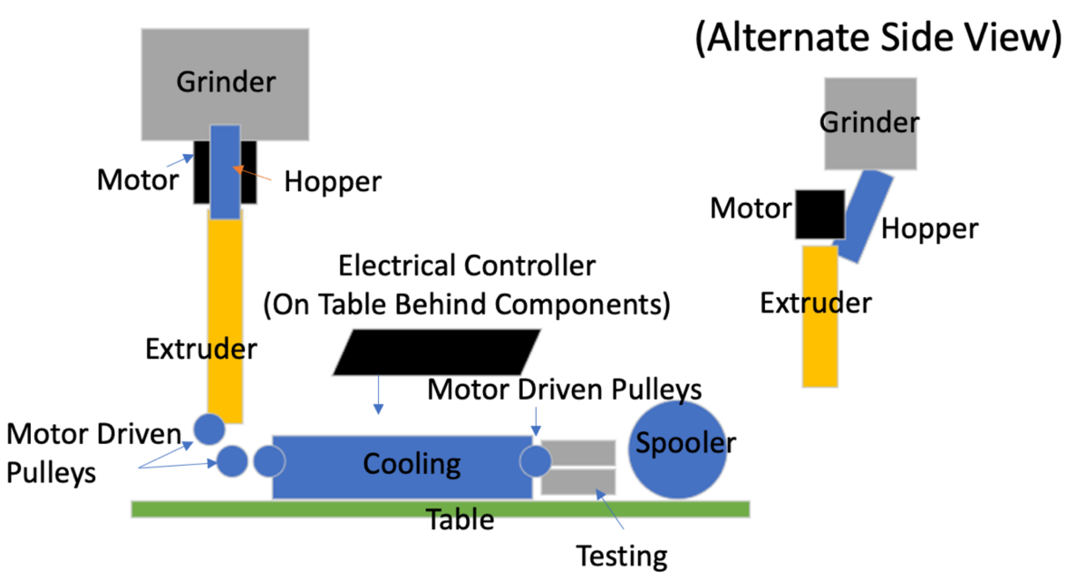

Figure 24. Extruder Concept 2

The third design is a top view and has the production line wrapped around three edges of the table. This design puts the operator in the center of a semi-circle of the production process. The pro of this design is that the user is centered around the manufacturing process, and even has room to store the spooled 3D printer filament. The con to this design is the curvature as the plastic exits the extruder. It is not ideal to have the project bend like it is oriented. Since it lays horizontal, guide pulleys are needed to guide it through the cooling system. The third design can be seen in Figure 25.

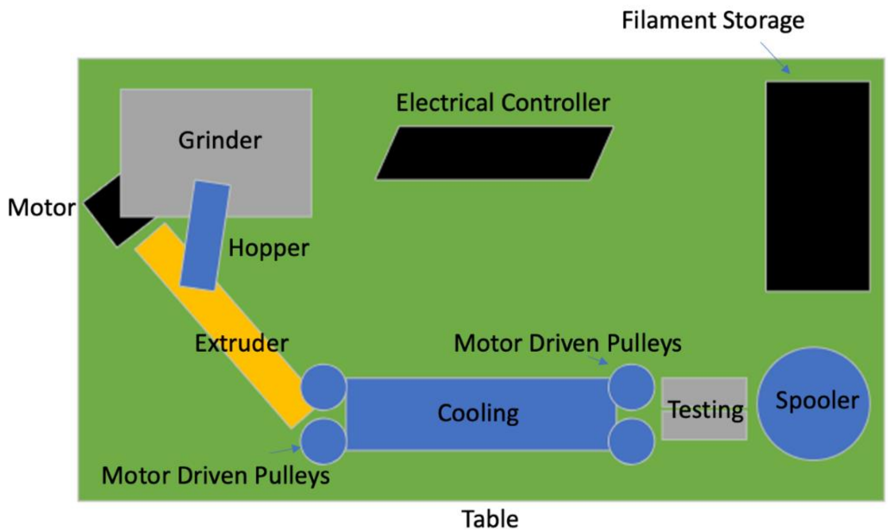

Figure 25. Extruder Concept 3

5.5 Chosen Design

The chosen design for the extruder configuration is concept 1. Design concept 2 is not ideal to have the grinder above the extruder. The height is not adequate for running a manufacturing line. Design concept 3 is not ideal because the plastic production must curve around the table. Design concept 1 has a linear layout for all the components to flow smoothly.

5.6 Overall Preliminary Engineering Design

Now that a design concept has been chosen, requirements for it can be established to guide the design process. These requirements were based on industry standards, material properties of common 3D printer plastics, other needs determined by the team. The requirements for the extruder are listed below.

1. The Extruder shall extrude the plastic at a speed no faster than 30 mm/s and no slower than 10 mm/s.
2. The Extruder shall melt the plastic at a temperature range of 190 ℃ - 300 ℃.
3. The Extruder shall extrude the plastic at a diameter of 1.75 mm with a +/- 0.5 mm tolerance.
4. The motor for the Extruder screw shall have a varying RPM control.
5. The Extruder screw casing with heating elements shall have a safety net to prevent injury.
6. The Extruder shall not be fed directly from the Grinder.
7. The Extruder shall be easily disassembled for cleaning and unjamming.

The extruder can be broken into three subcomponents: screw and casing, heating elements, and motor. The first aspect to look at is the screw and casing. This project is rather large and time-consuming. A prebuilt screw and casing will be ordered rather than fabricating one. For Requirement 3, the extruder shall extrude plastic at a diameter of 1.75 mm with a tolerance of +/- 0.5 mm. This diameter is industry standard for 3D printers. The project does not have a requirement on how much plastic is to be produced within a set amount of time, but selecting an extruder with a larger production rate would be more beneficial than a smaller one. A screw and casing have been selected for ordering. The output diameter is 1.75 mm, and its production rate is 0.5 kg/hr. The chosen screw is shown in Figure 26. This screw and casing include heating elements and their specifications will be checked next.

Figure 26. Pre-built Screw and Casing

For the heating elements of the extruder, they must be able to have an adjustable temperature. For Requirement 2, the heating elements must range from 190 ˚C to 300 ˚C. This project will be used to melt all types of plastics, and 300 ˚C is the higher end of those plastics. The chosen screw and casing in Figure 5 include heating elements as well as thermal couples. The heating elements are rated up to 450 ˚C, which meets the requirement. They are also adjustable as they come with controls and temperature monitors.

This chosen screw is rated to move at a maximum rotational speed of 60 RPM (2π rad/s). Using *"Single-Screw Extrusion, The Extruder Characteristic"* [10], Equation 13 can calculate the linear speed at which plastic is extruded, where D: diameter of screw (m), N: rotational speed (rad/s), $\cos\theta$: deflection of screw thread, V: plastic production speed (m/s).

$$V = \pi D N cos\theta \tag{13}$$

The screw has a diameter of 0.016 m and a rotational speed of 2π rad/s. The thread pitch angle θ is 60 degrees. The maximum plastic production speed is 157.9 mm/s. Since the motor will be adjustable on speed, this meets Requirement 1.

For the motor that drives the screw, it must be adjustable so that the speed can be changed. Sizing a motor for this project is an important aspect. It must be large enough to spin the mass of the screw against the frictional forces of the casing. In addition to that, it must push the plastic through the screw. The screws inside extruders have a slight slope, or in other words the screw shrinks in diameter as it goes from intake to output. Modeling it as a cylinder for its inertia can be seen in Equation 14, where I_x: inertia about the central axis (kgm^2), m: mass of the screw (kg), d_o: the outer diameter (m).

$$I_x = \frac{1}{8} m d_o^2 \quad (14)$$

The only unknown of this equation is the mass of the screw. There is not a listed mass of the screw itself, so the mass is estimated to be on the high side of 5 lbs, or 2.267 kg. The outside diameter is 0.02 m. The inertia is then 0.000134 kgm^2.

The acceleration of a motor is not typically known when ordering motors. Therefore, it has been estimated. The equation for the acceleration is shown in Equation 15, where α: angular acceleration (rad/s^2), ω_{max}: maximum angular velocity (rad/s), ω_{init}: initial angular velocity (rad/s), Δt: time elapsed from initial velocity to maximum velocity (s).

$$\alpha = \frac{\omega_{max} - \omega_{init}}{\Delta t} \quad (15)$$

The max rated speed of the extruder is 60 RPM, or 2π rad/s. Assuming the average motor can bring the screw from rest, to 60 RPM, in one second, the calculated angular acceleration is then 2π rad/s^2. This is assumed to be maximum acceleration.

There are two different torques to look at for motor sizing. There is the torque required to bring the screw up to its maximum rotational speed and there is the torque to keep it at that speed. The torque to start spinning the unloaded screw is in its general form below in Equation 16. Substituting the equations for inertia and angular acceleration gives Equation 17, where τ_L: load torque required to bring screw to rated speed (Nm).

$$\tau_L = I_x \alpha \quad (16)$$

$$\tau_L = \frac{1}{4} m d_o^2 \pi \quad (17)$$

Using the estimated inertia and acceleration from earlier, the load torque to bring it up to speed is then 0.000712 Nm. The torque required to keep the screw turning once it reaches its max speed of 60 RPM is less than the torque required to bring it up to that angular velocity. To determine the torque required to keep it at its max speed is a rather difficult task. Especially once it is loaded with plastic. There is resistance due to fluid flow of the liquid plastic. There is resistance due to friction of the screw thread and outside casing. A coefficient of friction can be estimated for the steel screw and steel casing. A frictional resistance from the liquid plastic can be estimated as well. However, estimating the area of the screw threads against the steel casing is rather difficult. A discussion with Dr. Nelson (USI Associate Professor) suggested estimating the necessary torque required to keep the screw at 60 RPM. This torque will be less than the required torque to get the screw up to speed. In a rather safe scenario, applying a safety factor will ensure the motor can handle this load. A minimum safety factor (sf) of 2 is applied. Equation 18 shows the constant speed torque required, where τ_c: torque to maintain max speed (Nm).

$$\tau_c = (sf)\tau_L \tag{18}$$

Therefore, a minimum torque of 0.0015 Nm is needed at 60 RPM.

Motors have a power rating in watts or horsepower. Now the torque and speed are known of the motor, the required power can be calculated. Equation 19 shows the power relation, where P: power (W), ω_c: constant, maximum rated speed (rad/s).

$$P = \tau_c \omega_c \tag{19}$$

This equation gives the power required to keep the screw rotating at 60 RPM. A discussion with Dr. Nelson also found literature [11] that suggests a general rule with plastic production. For every 10 pounds an hour being produced, the motor on a screw needs 1 hp. The chosen extruder is rated to produce 0.5 kg/hr, which converts to 1.10 lbs/hr, so this can be put into Equation 20 to determine the minimum horsepower needed based on the 10:1 ratio from the literature [11].

$$\frac{10\,\frac{lbs}{hr}}{1\,HP} = \frac{1.10\,\frac{lbs}{hr}}{j} \tag{20}$$

The value j is the power for the motor in horsepower. Solving Equation 20 for j gives a power of 0.11 HP, which is 82.1 Watts. The screw and casing chosen for purchase includes the heaters, as well as a motor with a built-in gearbox. The motor is rated at 90 W. This is a higher rating than what was yielded in Equation 20. The seller included this motor with the screw and casing to produce plastic at the 0.5 kg/hr rate, so it is assumed to be adequate.

Another aspect to look at with the extruder is a transformer for the heating elements. The system is to plug into a 120 V AC wall outlet to power all systems. The heating elements are 220 V input. When up stepping the voltage for the output, the input current is increased as well. Equation 21 is used to show the increased input voltage, where V_1: input voltage (V), V_2: output voltage (V), I_1: input current (A), I_2: output current (A).

$$\frac{V_1}{V_2} = \frac{I_2}{I_1} \tag{21}$$

The input voltage is 120 V, the output voltage is 220 V. Solving for I_1 gives $1.83I_2$. This means the input current will be almost doubled to achieve an output of 220 V. The concern of overloading the power supply or the wall outlet is discussed. Using Equation 22 below will give the current draw at the output for the heating elements, where P: power (W), V: voltage (V), I: current (A).

$$P = VI \tag{22}$$

The heating elements are rated at 450 W, with a 220 V voltage. Solving Equation 22 for the current yields 2.045 A current. Putting this into Equation 21, the input current draws 3.74 A. This is a suitable value since wall outlets can have 15 A drawn from them.

A hopper will need to be made to dump plastic trash into the extruder. A premade batch of plastic will be made from the grinder and dumped into the extruder. The hopper shall be able to hold a minimum of two of these premade batches. The volume of the collection tray for the grinder is 84 cubic inches. The volume of the hopper should be at least 168 cubic inches.

Looking at the requirements listed above, almost all have been met. Requirement 1 has been met as the extruder can be slowed to the minimum 10 mm/s and reaches a top linear extrusion rate of 23 mm/s. Requirement 2 has been met as the heating elements can reach up to 450 ˚C. Requirement 3 has been met as the screw is set for a 1.75 mm diameter. The tolerance will be measured after the extruder is running and creating filament. Requirement 4 is met as the motor that comes with the extruder has a controller to vary its speed. Requirement 5 will be discussed soon on safety measures for the extruder. Requirement 6 has been met as the extruder has an opening for dumping plastic, rather than being connected directly to some other component. Requirement 7 has been met as the screw and casing simply unscrew from each other and the screw can be retrieved from the casing.

Safety is an important factor in this design. This plastic recycler is to be used in the AEC, and this facility, and USI in general, are large enough that OSHA regulations are required to be followed. Hot objects are to be properly guarded to prevent injury in the workplace. A metal cover is to be made to prevent personnel from hitting the hot extruder. This cover will be fabricated in the AEC and can be seen in Figure 27 and Figure 28.

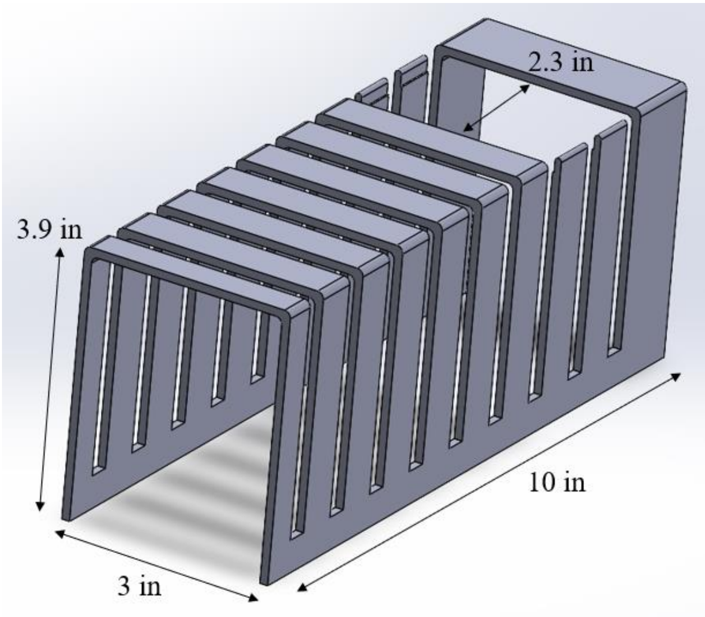

Figure 27. Safety Net View 1

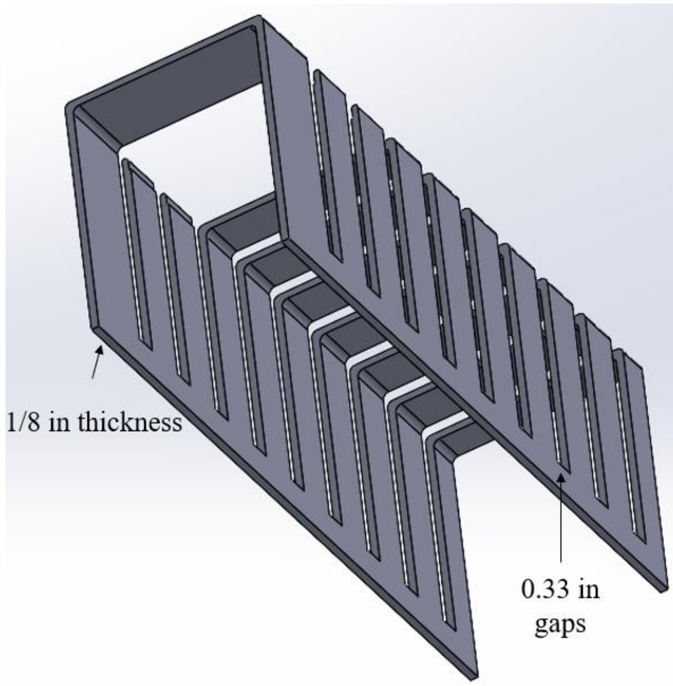

Figure 28. Safety Net View 2

Made from 6061 this will sit on top of the extruder mounted to the table. The extruder casing is 1.5 inches, so the minimum dimension for the cover is twice that at 3 inches. The heating elements are placed vertically and extrude past 1.5 inch, so additional room is added at 3.9 inches. The barrel is approximately a foot long, so the cover is 10 inches long, leaving some open room at the end where the plastic is extruded. The 0.33-inch gaps are chosen at random and allow the extruder to vent and not overheat. The possibility of someone sticking their fingers through the gap is low, but possible. The purpose of this cover is to prevent injury when someone accidentally contacts it. Long sleeves are not allowed on the shop floor of the AEC, so there is no protection on the arms. The extruder will approximately sit at this arm level on the table.

To fabricate this, a 1/8-inch sheet of 10 x 10.8 square inches will be cut out from a waterjet. All the gaps in the design will be cut out as well, and then the sheet is bent twice to make it into its shape in Figure 27 and Figure 28. A drawing of the sheet that will be cut out is shown in Figure 29. All dark lines are what the waterjet cuts out. The two tall vertical lines are where the sheet will be folded at a right angle.

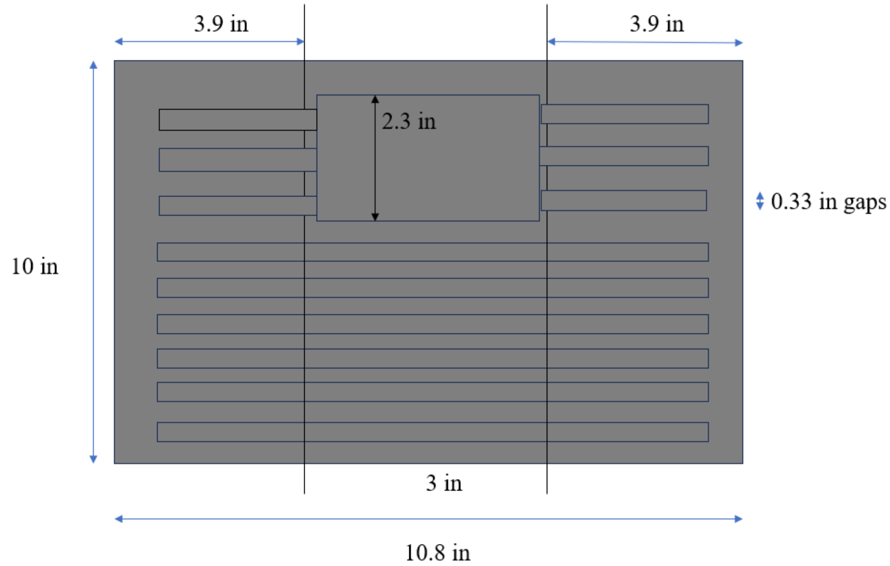

Figure 29. Safety Net Fabrication Design

The final product placed on top of the extruder and motor is shown in Figure 30. This fulfills Requirement 5.

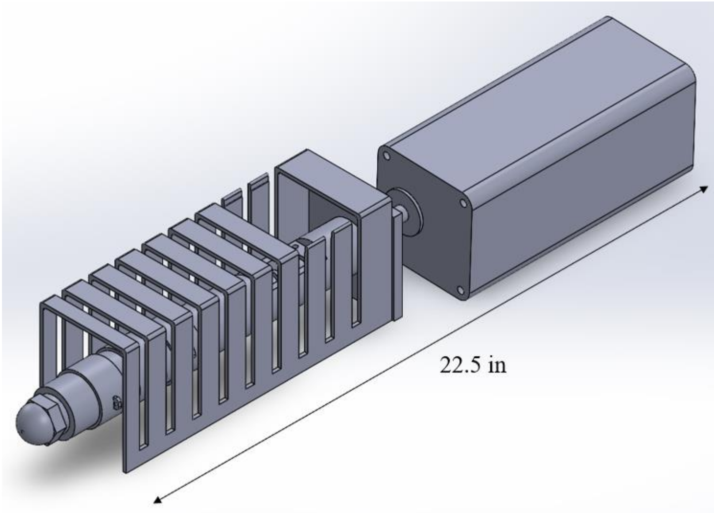

Figure 30. Safety Net with Extruder

5.6.1 Supporting Diagrams

A system hierarchy for the extruder can be seen in Figure 31. This shows all the subcomponents that make up the extruder. Table 7 and Table 8 show a failure mode and effect analysis for prior and post project completion.

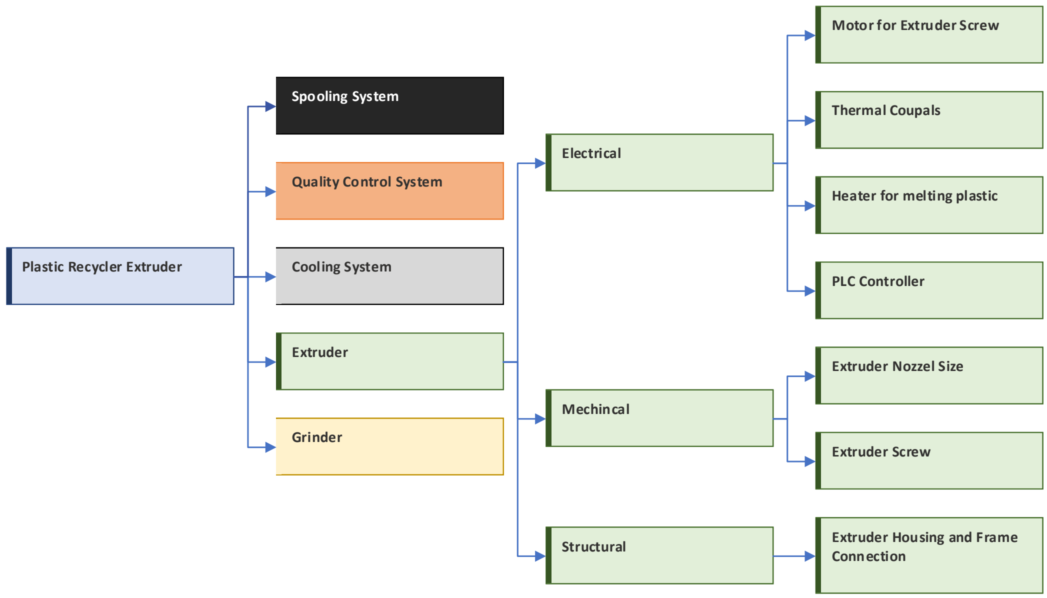

Figure 31. System Hierarchy – Extruder

Table 7. FMEA Extruder Prior Project Completion

Item	Failure Modes	Cause of Failure	Possible Effects	Prob.	Actions to Reduce failure
Electronics	Electrical Short	Wall Outlet Surge	System Will Not Work	Low	Proper Fuses
		Power Supply			
		Drive Load Too Large	Broken Motor		Check Electrical Load Calc.
	Under Powered	Power Supply	Inproper Voltage to Items	Medium	Check Electronics Rating
		Drive Load Too Large	Inproper Working Speed		
	Over Heating	Improper Fuses	Electronic Damage or Fire Hazard	Low	Check Electronics Rating
		Drive Load Too Large			
		Electronics Operating Past Rated Parameters			
Heating Elements	Bad Product	Bad Seller	No Heating	Medium	Check Seller Rating
	Burnout	Too Much Current	Improper Heating	Low	Check Fuses and Calc.
	Underheating	Not Enough Current			Wall Outlet Insufficient
General Construction	Table Breaks	Too Much Weight	Project Cannot Be Completed	Low	Check Table Rating
	Frame Breaks				Check Ratings and Mounting Methods
		Components Mounting			
	Anything Breaking	Welding/Bolt Connections			Check Mounting Methods

Table 8. FMEA Extruder Post Project Completion

Item	Failure Modes	Cause of Failure	Possible Effects	Prob.	Actions to Reduce failure
Screw & Casing	Jamming	Uneven Heating	Plastic Won't Extrude	Low	Check Production Settings
		Fast Extrusion Rate			
	Rupture	Wear And Tear	Broken Extruder	Low	Operate At Rated Values
		Damage from Transport			Protective Wrapping
	Extrusion	Lack of Material	lament Will Have Air Pocke	Low	Provide Adequte Material
		Heating Failure	Plastic Won't Melt		Check Heating Element Rating
Motor	Burnout	Load Too Large	Motor Will Burn Out	Medium	Run Screw At Rated Values
		Wrong Electrical Supply		Low	Proper Wall Outlet & Fuses
Heating Elements	Burnout	Life Epectancy Reached	Heating Elements Broken	Low	None
	Overheating	Transformers, Power Supply	Improper Plastic Melting	Low	Set Temperature According to
	Underheating				

5.7 Critical Extruder Design

The extruder order arrived as advertised and position placing began. The aluminum frame that contains the project has slotting in it for easily mounting anything anywhere. The extruder sits in the front left of the project relevant to facing the HMI screen. The extruder required to be elevated slightly to pass over the cooling system. A mount was fabricated to connect to the frame at the base and connect the screw and casing and motor to each other. Figure 32 shows this mount and how the extruder and motor connect to it.

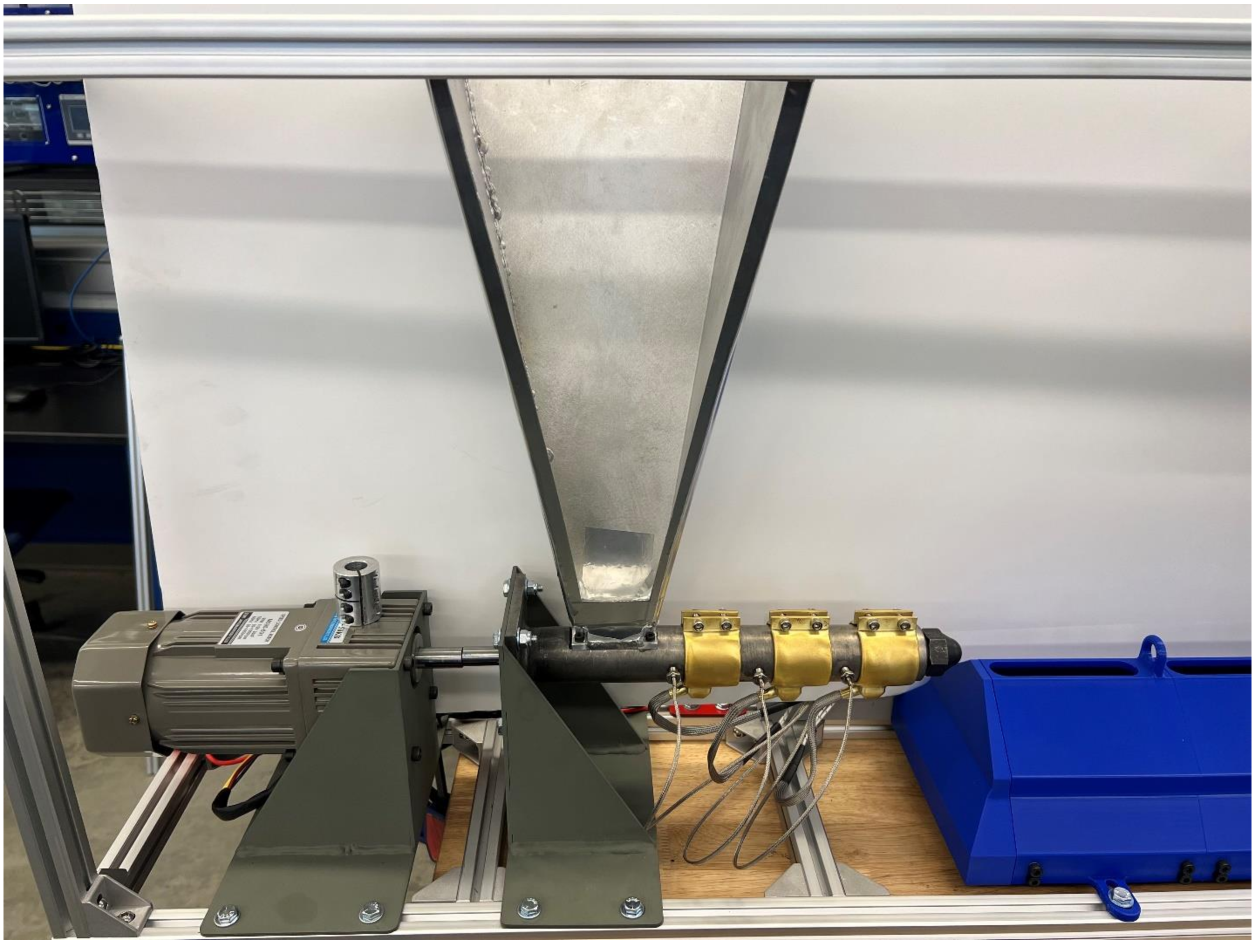

Figure 32: Extruder

The extruder has a flat face with mounting holes that were matched on the mounting plate to hold the extruder. The same was done for the motor mount and it was connected to the extruder screw. There is a small moment placed on the mount, but it is insignificant based on the slow speed of the motor. The mount was made of 1/8 in sheet steel and was designed with tabs and slots for ease of manufacture. The components were cut on a water jet then MIG welded together before adding a coat of paint.

The extruder kit was sold with a controller for the motor, three solid state relays for the heaters, and three temperature control modules. The temperature of each zone can be set and read on the HMI while the speed of the motor is controlled by a dial on the control panel. The integration of these components is discussed in section 9.

A hopper was fabricated next to allow plastic trash to be dumped into the extruder opening after a preset amount was made from the grinder. This hopper is a large rectangular opening that condenses down to the small rectangular opening on the barrel. One side of this hopper is plexiglass so that the amount of plastic in the hopper can be seen. Premade batches of plastic trash are made for this project, so the hopper needs to be large enough to hold one of these. The hopper was designed to fit inside the aluminum frame rather than matching the volume of the collection tray. The hopper was designed in SolidWorks and integrated into the rest of the project model. The extruder and grinder models were placed where they currently sit on the project, and the hopper was placed into the extruder barrel. Dimensions for the hopper were modified until an adequately sized hopper fit inside the frame without interfering with other components. Figure 33 shows the hopper CAD model placed into the system. Figure 34 shows the fabricated hopper.

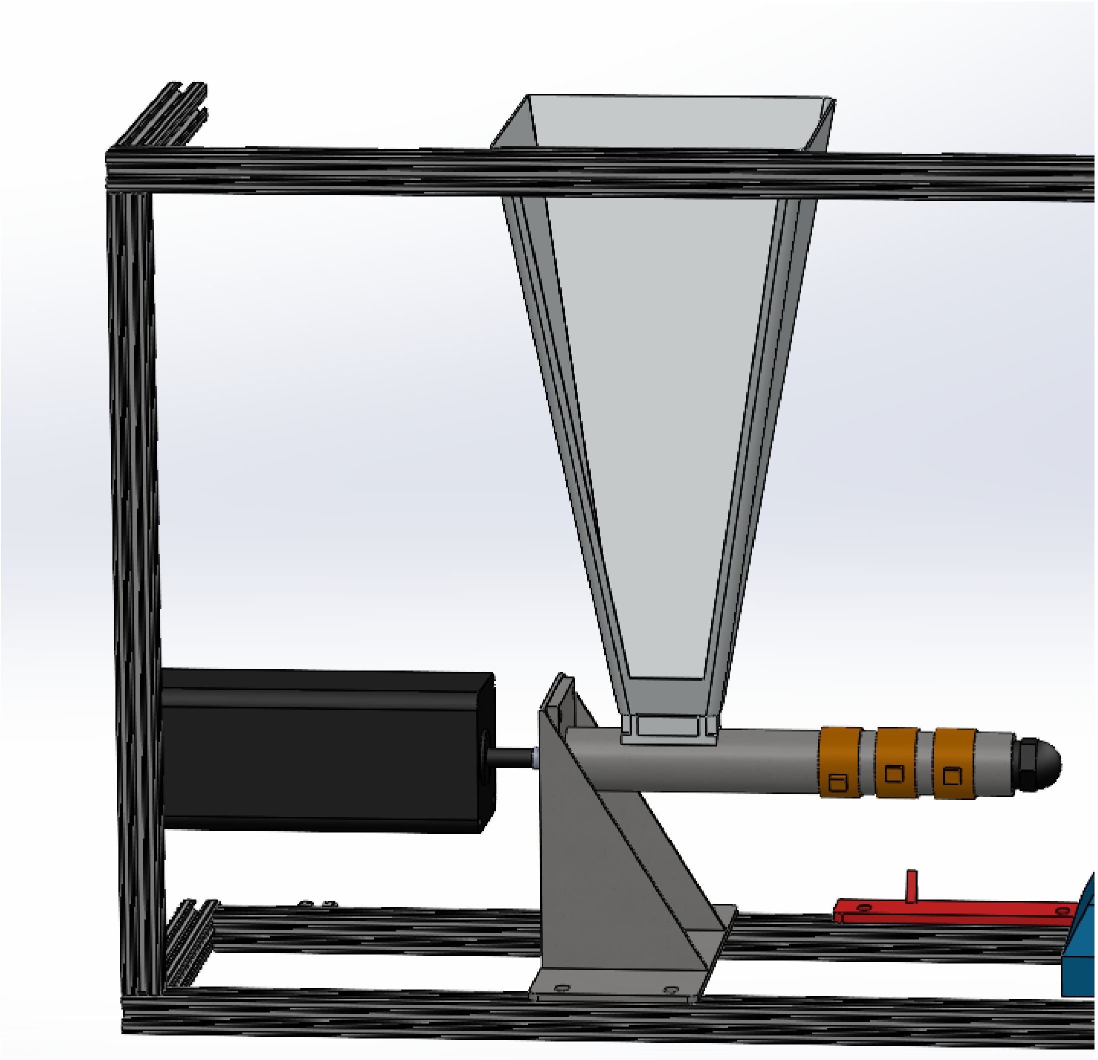

Figure 33: CAD Model of Extruder and Hopper

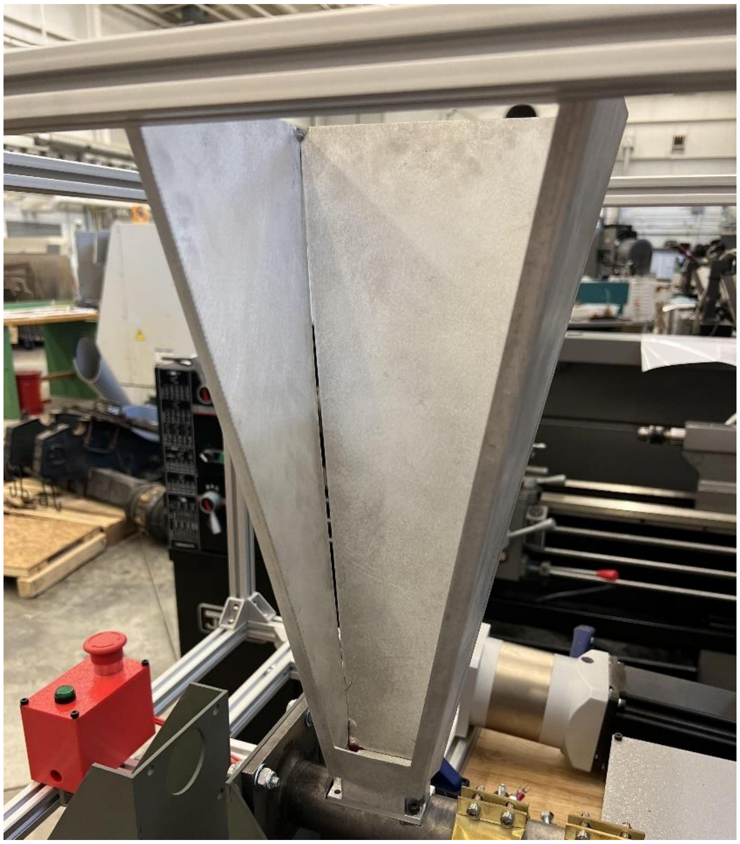

Figure 34: Fabricated Hopper

The heat shield was fabricated last after every other aspect of the extruder was placed. Its design was altered slightly from the preliminary design. With the hopper in place as well as the mount that holds the extruder, the full shield design could not be made. As a counter, the shield size changed to cover only the heating elements. This brought its original 10-inch length to 7 inches. The surrounding materials like the hopper and mount become warm to the touch when the extruder is running at high temperatures, but nothing that seriously injures someone. Figure 35 shows the new CAD model of the sheet metal that will be cut out of one-eighth inch steel.

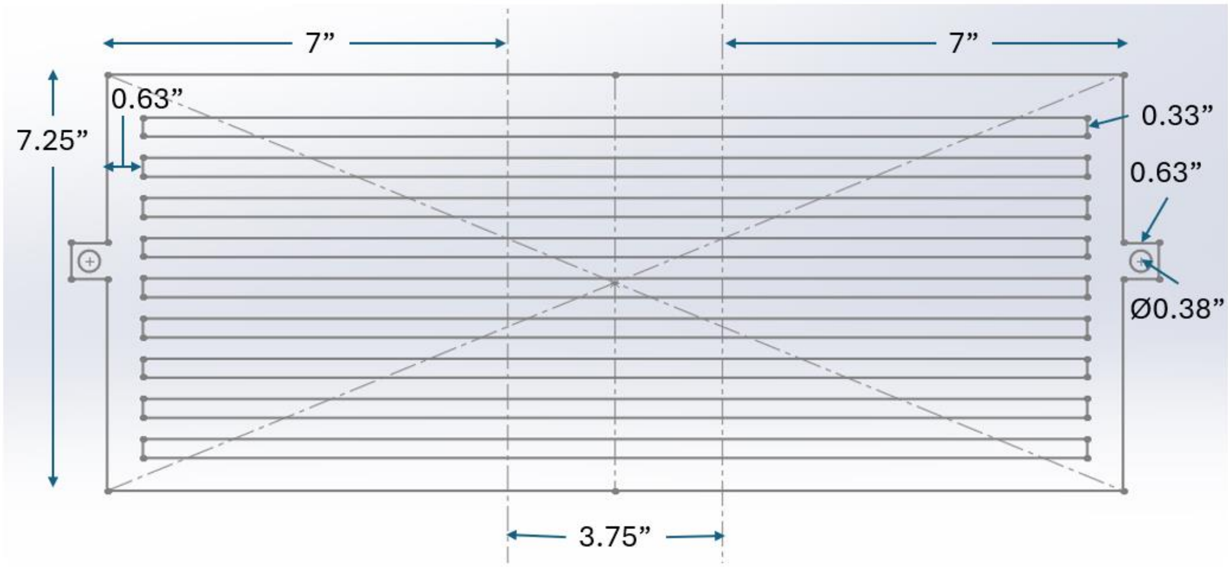

Figure 35: Updated Extruder Guard

The section of heating bands that needs to be covered on the barrel spans 7.25 inches. The square tabs on each side of 0.63” length are bolt holes for mounting the cover to the aluminum frame. From where it mounts to the top of the extruder is 7 inches. The width of the barrel with heating bands is 3.75 inches. Once cut out, the sheet will bend on the two vertical lines at a right angle as well as the square tabs on the edge of the sheet. The gaps for airflow are a third inch and spaced evenly along the sheet at a third inch. The finished product can be seen below in Figure 36. The entire extruder with motor, hopper and safety shield can be seen in Figure 37.

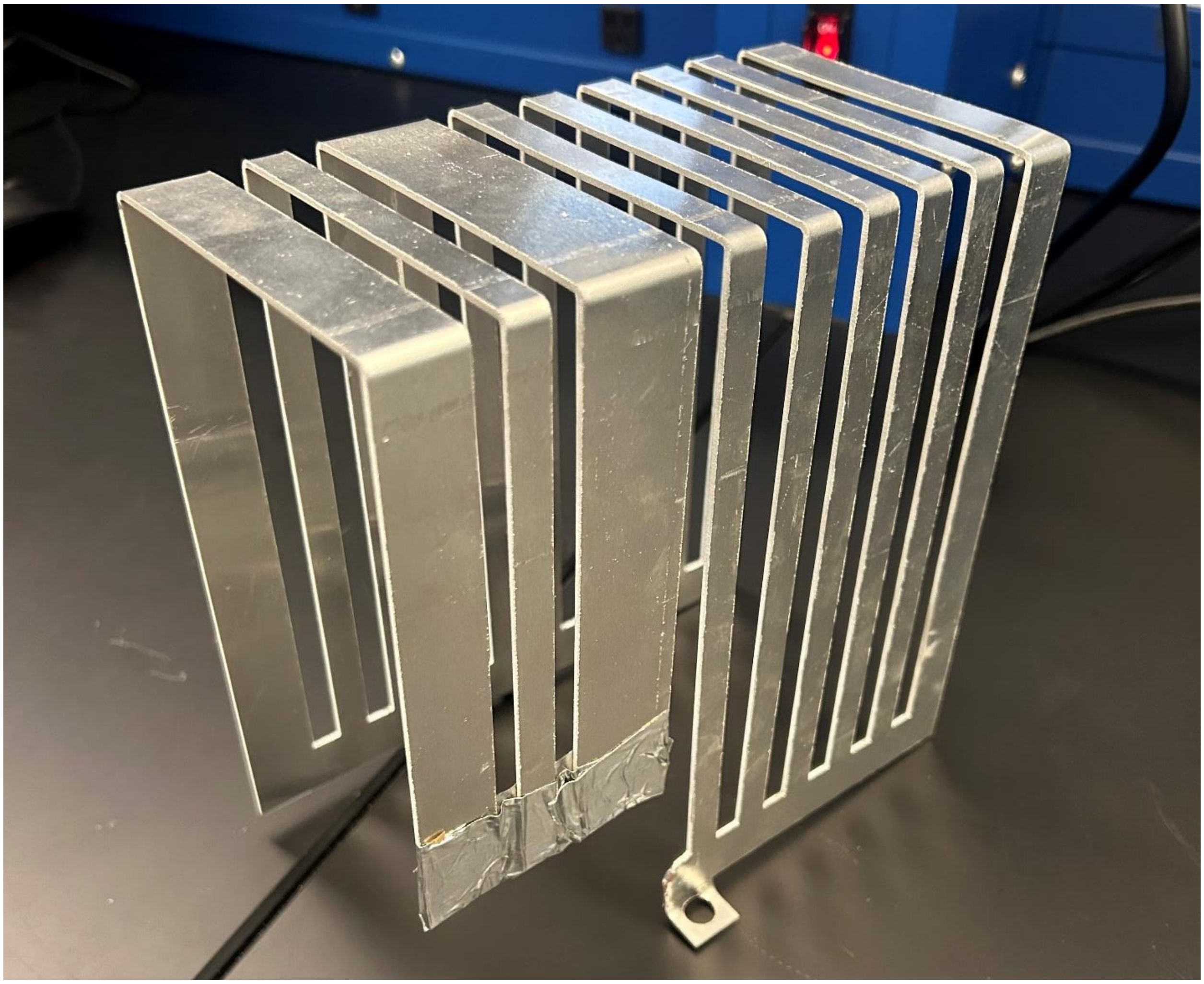

Figure 36. Extruder Heat Sheild

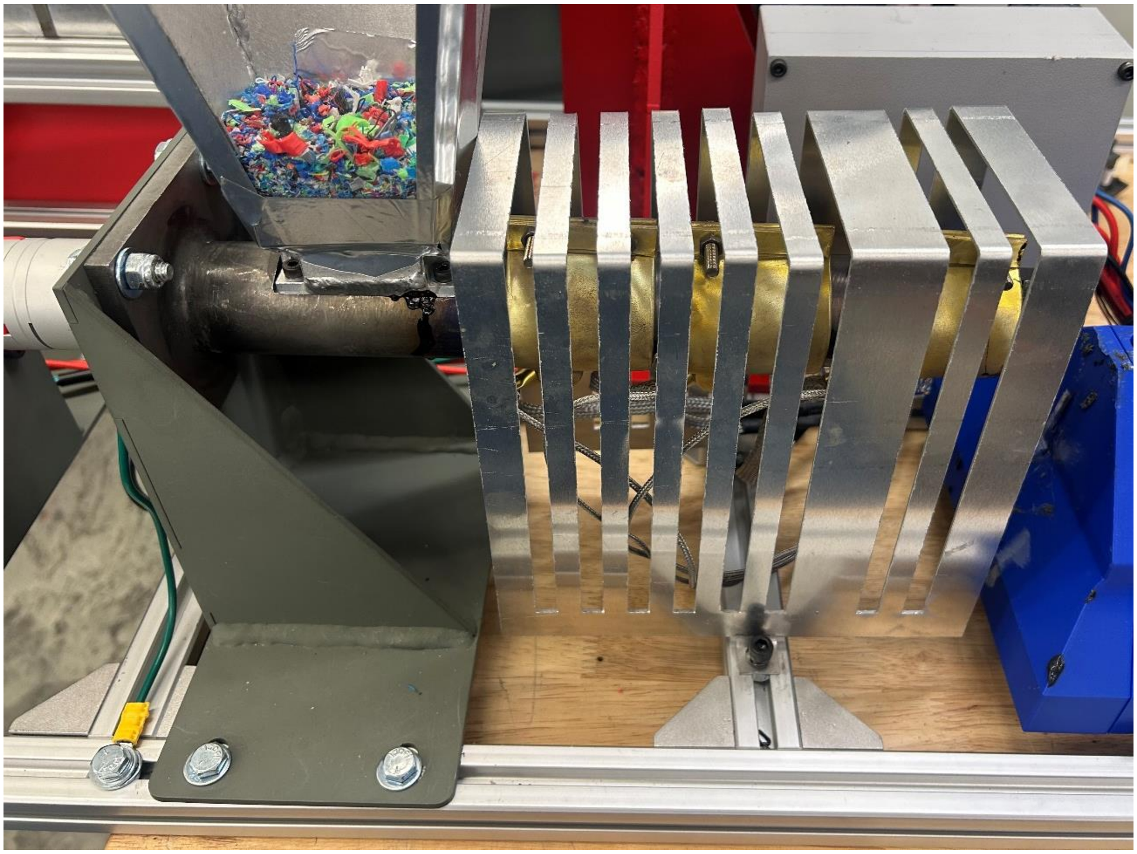

Figure 37. Entire Extruder Assembly

The section of metal missing on the cover near the mounting hole was cut away to allow the thermocouple wires to pass through. The wires could not be stretched around the cover, so this section was cut away. This missing section is on the inside of the extruder and does not compromise protection from the user.

6.0 COOLING SYSTEM

Following the exit of the extruder is the cooling system. This system brings the temperature of the plastic down well below the melting point. The plastic must reach a lower temperature before entering the quality tester and into the spooling system. There were two considerations for the type of cooling system. The first is a water bath that has the temperature regulated through a radiator. The second one is an air-cooled system using a line of fans that the plastic travels over.

6.1 Literature Review

An article called *"A review of Thermal Cooling Systems"* [12] discusses various heat exchangers and the theoretical and experimental results from their applications. There are absorbers, adsorbers, desiccants, ejectors, and hybrid systems. All of these pertain to using chilled water or a refrigerant called R123. This article [12] mainly refers to using these heat exchangers in large industry settings.

Another article called *"Air-cooled Heat Exchangers and Cooling Towers"* [13] discusses cooling towers for power plant applications. The cooling towers are wet heat exchangers and are used to disperse water vapor as well as change temperature. Dry heat exchangers are used in electronics, vehicles, and air-conditioning. This uses fans and is for applications in dropping temperatures of 60 degrees Celsius or more.

6.2 Information Learned

There are multiple types of heat exchangers that involve water cooling systems. They are used in large scale operations and can be scaled appropriately to use on the project. Dry cooling systems can be used for large temperature differences and is simpler to create than a wet heat exchanger.

6.3 Knowledge Gained

A small-scale wet heat exchanger can be made with a small water bath and circulation system to keep the water at low temperatures. Using small sized fans that can be found in electronics or vehicles can serve as dry cooling system.

6.4 Conceptual Designs

6.4.1 Water Cooling System

The first idea of a cooling system is a water bath. This method would be very effective as a water bath is a great heat exchanger. A water bath would require a radiator to regulate the temperature of the water and keep it low enough to continuously cool the plastic. The first complication of this method is that this project has multiple electrical components. The project is well kept in a small area and keeping a water bath near these components will be problematic. It was decided that a water-cooling system would not be adequate for this project.

6.4.2 Air Cooling System

The other idea for a cooling system was using air fans to cool the plastic. It is not as effective as a heat exchanger as the water bath but serves good protection against the electrical components on the table.

6.4.2.1 Air Tubing

The first iteration of the cooling system was to make a tube with several holes cut into it. This will be where the air is blown into the tube. The plastic would travel through the tube and be cooled uniformly as the holes will be scattered across the entire surface area of the tube. The pro to this build is that once the plastic enters the tube, there will be no other support required to guide it. The con to this build is that the plastic could jam itself on one of the air holes unless the holes were made a smaller diameter than the 1.75 mm filament.

6.4.2.2 Linear Fan Line

The second iteration of the cooling system would be to make a line of fans that cooled the plastic as it traveled over them. The pro to this build is that the plastic cannot jam on anything as it will travel through mounts set an adequate height above the fans. The con to this build is that cooling will only happen on half of the filament, so it won’t be uniform. The other con is that multiple guide mounts will be needed, and the plastic will have to be manually fed through each of them at the start of production.

6.5 Chosen Design

The team decided that no amount of water needs to be near the electrical components of the board. So, of the two cooling system ideas, the air-cooling system is chosen. The debate between the air tube and fan line took some designing. The big decision was that the plastic should always be visible from the end of the extruder to the spooling system. Both iterations were very viable as 3D printing offers many options in design. The linear fan line is the chosen design.

6.6 Overall Preliminary Engineering Design

This design needed to find a PC fan to use that had simple electrical connections so it could be incorporated into the PLC control system. The PLC will send digital signal to a relay that will control the power to the fans. The fan control speed would depend on what voltage is supplied to the two power pins. The voltage is varied by an adjustable power supply. The voltage of this power supply is controlled by a potentiometer mounted to the control panel.

Calculating the amount of air that needs to travel across the plastic filament at its high temperature range to bring it to its desired temperature range can be difficult to achieve. Factors such as room temperature and specific heat play a part in how the heat is dissipated. A discussion with Dr. Rad (USI associate professor) suggested that calculations would be difficult and to design a heat exchanger that is more than capable of lowering high temperatures. A not as adequate heat exchanger would require the filament to travel through the cooling system for a longer amount of time.

The chosen PC fan can be seen below in Figure 38. This fan is a 12 Volt fan. It can reach a maximum speed of 1800 rpm. The linear fan line design will include four of these fans. This will ensure that an adequate amount of air can pass around the filament to bring it to a low enough temperature to harden the exterior. These fans will be placed inside a 3D printed housing that can easily mount to the frame of the project. Dimensions of the fan are provided and will allow a CAD model to be made.

Figure 38. Noctua PC Fan

The proposed CAD model of the housing can be seen below in Figure 39. The loop at the top is for the filament to flow through. The height of these fans are based on where the extruder nozzle sits.

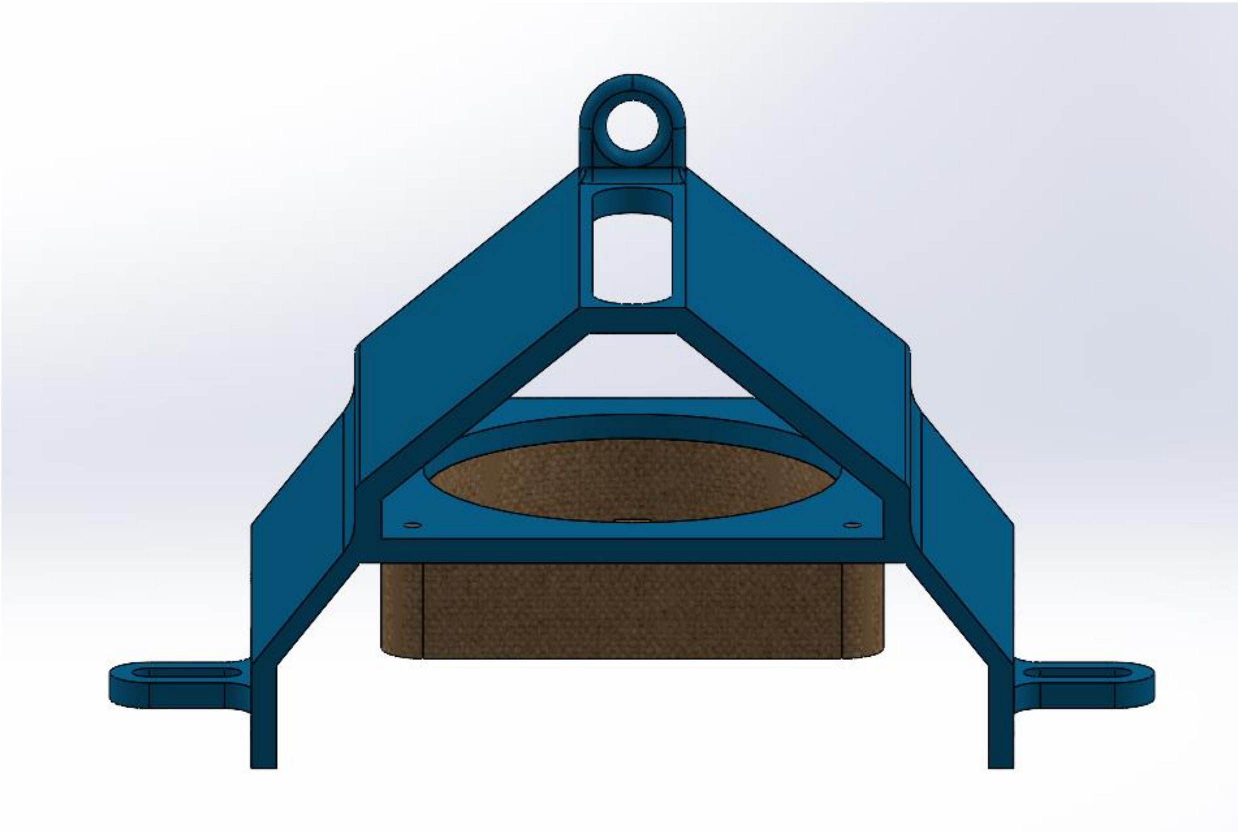

Figure 39: Side View of Cooling Module

6.7 Critical Cooling System Design

The fan housings were printed and verified that the bolt holes matched the project frame. Once the fans order came in, they were placed in the housing to ensure fitment. No modifications were needed at this point. All four housings and fans were bolted into place in front of the extruder and behind the quality testing area. The fan testing led to underpowered results. The fans did not give off the amount of power they were expected to. Inside the housing, there was little airflow that came towards where the filament line would be. The fan housing was redesigned.

Using the conservation of volumetric flow in equation **, the outlet at the top of the housing was decreased in surface area. This comes from the fact that volumetric flow is constant, so a change in area will cause an inverse change in speed. By decreasing the area, the air flow speed will increase.

$$Q = A_1V_1 = A_2V_2$$

The new model was redesigned accordingly and can be seen below in Figure 40 . This new housing was implemented, and the flow speed was significantly more powerful.

Figure 40. Full Cooling System

7.0 QUALITY ASSURANCE

The industry standard for filament in the 3D printing world is 1.75 mm. The quality testing component of this project will test the diameter of the filament right before being spooled into a roll. A constant 1.75 mm diameter is not always plausible, so a tolerance is labeled on spools of plastic that show its deviation from the 1.75 mm standard. Maintaining a consistent diameter of 3D printer filament is paramount for achieving high-quality prints and ensuring reliable performance of 3D printing processes. The diameter of the filament directly affects various aspects of the printing process, including extrusion, layer adhesion, dimensional accuracy, and overall print quality.

Consistency in filament diameter is critical for achieving uniform extrusion during the printing process. If the filament diameter varies, it can lead to uneven extrusion rates, resulting in inconsistencies in layer height and deposition. This can cause issues such as gaps or over-extrusion in printed parts, compromising their structural integrity and surface finish. Figure 41 shows an example of what a print can look like if the filament does not have a consistent diameter.

Figure 41: Under Extruded 3D Print

Furthermore, consistent filament diameter is essential for ensuring proper layer adhesion in printed parts. Inconsistent filament diameter can result in variations in material flow and deposition, leading to weak bonding between layers. This can result in delamination or splitting between layers, compromising the strength and durability of printed parts.

Dimensional accuracy is another crucial factor influenced by filament diameter consistency. Inaccuracies in filament diameter can lead to dimensional inaccuracies in printed parts, affecting their overall size and geometry. Parts may end up being larger or smaller than intended, leading to fitment issues or assembly problems in final products.

Overall print quality is significantly impacted by the consistency of filament diameter. Variations in diameter can result in visible defects such as surface irregularities, blobs, or stringing in printed parts. Consistent filament diameter ensures smooth and uniform material deposition, resulting in high-quality prints with precise details and smooth surfaces.

7.1 Initial Design

The initial design of the Quality Control subsystem consisted of a dial indicator that pinched the filament between two bearings. The CAD model and physical parts can be seen in Figure 42 and Figure 43 respectively. The dial indicator selected was advertised to output data over the RS 232 protocol, a protocol that the PLC selected supported. However, when the item arrived and was tested it did not use this protocol, so this design was abandoned.

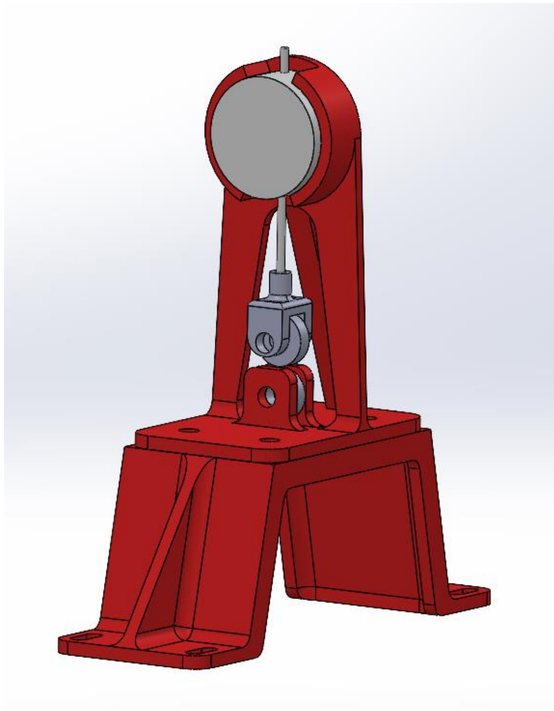

Figure 42: Initial Design of QA System

Figure 43: Dial Indicator QA System

7.2 Final Design

A complete redesign needed to be done on the QA system and after much research it was decided to use a Hall effect sensor to indirectly measure the diameter of the filament. A Hall effect sensor is a type of transducer that detects the presence of a magnetic field and converts it into an electrical signal. It operates based on the Hall effect, which describes the generation of a voltage difference (Hall voltage) across a conductor when it is subjected to a magnetic field perpendicular to the direction of current flow.

The basic principle behind a Hall effect sensor involves the interaction between the magnetic field and the charge carriers (electrons or holes) within the semiconductor material of the sensor. Typically, Hall effect sensors consist of a thin strip of semiconductor material, often made of gallium arsenide or indium arsenide, through which a current flow. When a magnetic field is applied perpendicular to the direction of current flow in the semiconductor material, it exerts a force on the charge carriers due to the Lorentz force. This force causes the charge carriers to accumulate on one side of the semiconductor strip, creating an imbalance of charge carriers and resulting in the generation of a voltage difference across the strip. This voltage difference, known as the Hall voltage, is directly proportional to the strength of the magnetic field and the current flowing through the sensor.

The Hall voltage produced by the sensor is typically very small, in the order of millivolts. To make it usable, the sensor includes an amplifier circuit that amplifies the Hall voltage to a measurable level. This amplified voltage signal can then be processed by external circuitry to determine the presence, strength, and polarity of the magnetic field. The board shown in Figure 44 shows such a circuit.

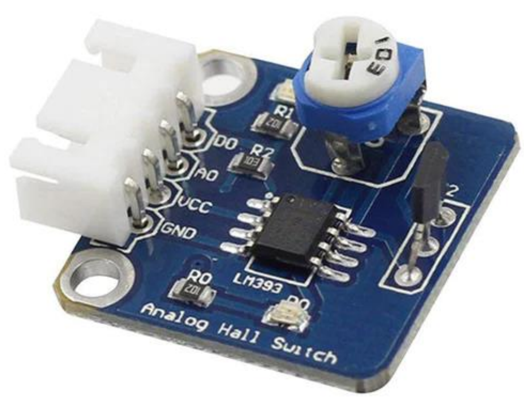

Figure 44: Analog Hall Switch Board

A widget was designed to move a magnet as the diameter of the filament changes. The magnet is attached to a lever arm, so the change is diameter is amplified, this effectively increase the resolution of the sensor. The lever arm is spring loaded and pinched the filament between two roller bearings. The model can be seen in Figure 45 and the completed subsystem can be seen in Figure 46.

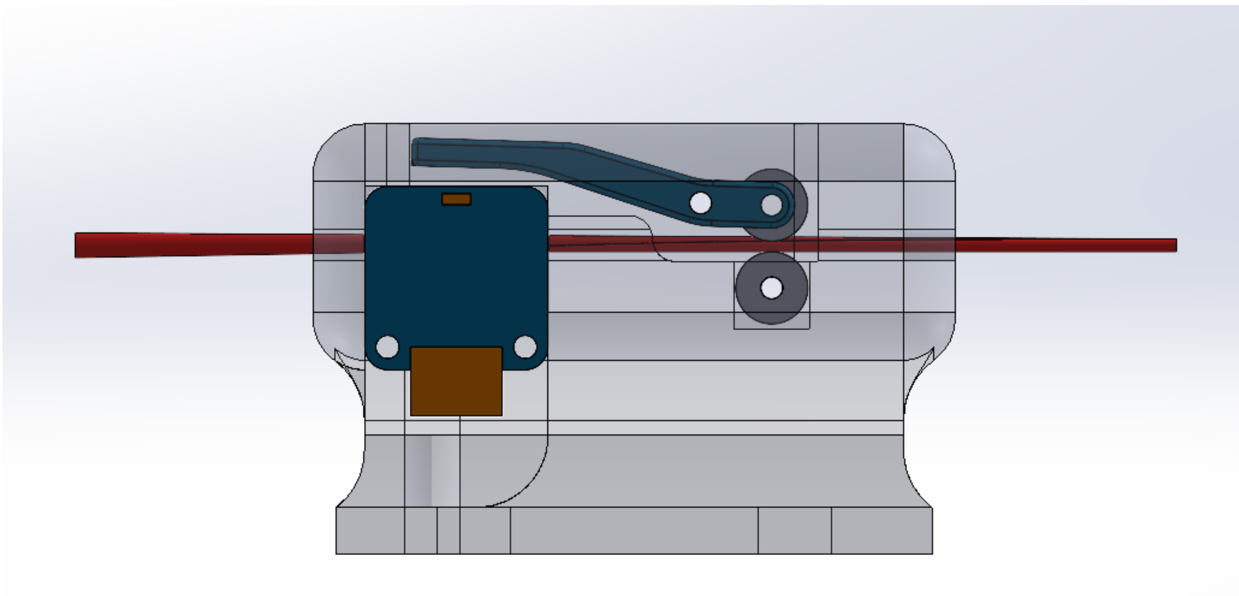

Figure 45: CAD Model of QA System

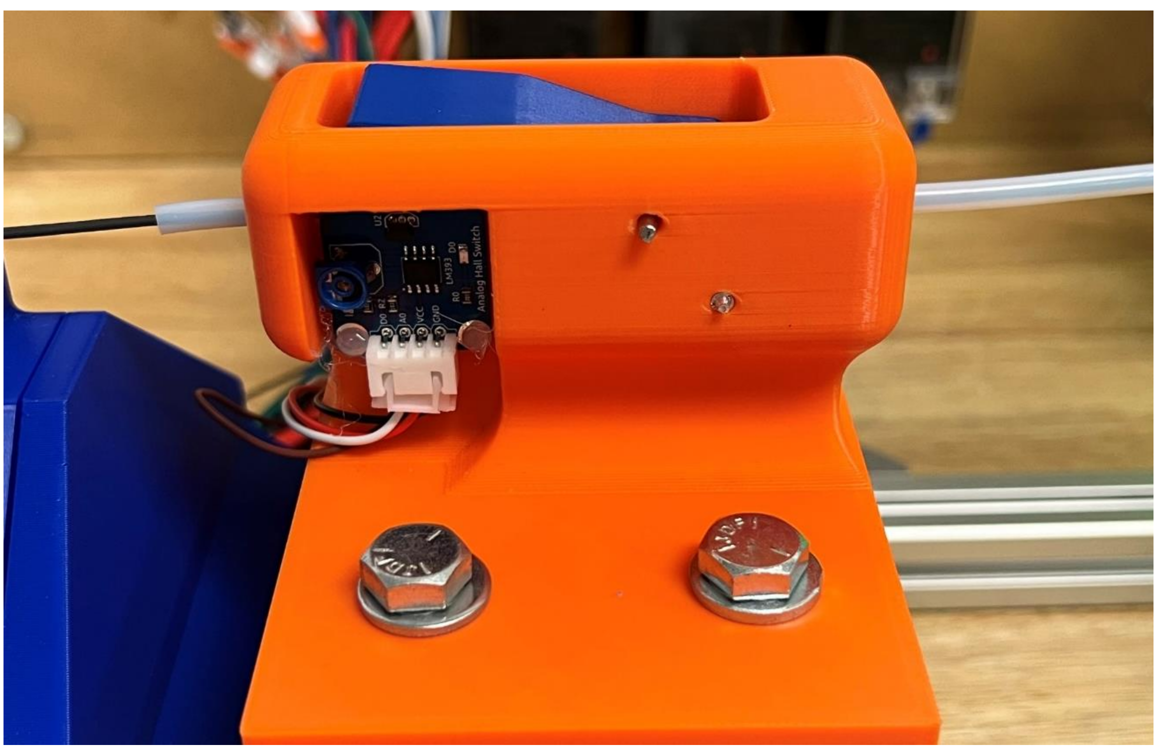

Figure 46: Image of Final QA System

8.0 SPOOLING SYSTEM

The last step in the recycled plastic's path is being spooled into a roll to be placed on a 3D printer. Plastic spools are circular and unroll the plastic as the printer pulls plastic for printing. Wrapping the filament neatly onto a spool is necessary to avoid tangling which can cause problems when printing. Based on the requirements of the machine a mechanism that can neatly spool 3D printer filament onto a standard size spool so that it can be used in most common printers must be designed and built. The system must be able to keep up with a production rate of 1.6 meters of filament per minute. The mechanisms must withstand 500,000 cycles with a static failure safety factor of at least 3.

8.1 Requirements

The device must fit into a 16 cubic inch volume and be able to consistently spool filament at a rate of 1.6 meters per minute. It must use the standard spool size shown in Figure 47. The spool needs to be removable from the shaft it rides on but also not slip on that shaft when in use. The system must use only one motor for the rotation of the spool and the tracking of the filament. Gears will transfer movement from the motor to the spool to wind it up as well as sending power to the system that will track the filament. Gear ratios will need to be evaluated to ensure there is enough torque at the spool to overcome the inertia. A shaft will be designed to hold a 1kg spool of filament and not allow it to slip. To make sure the spool does not slip elements of fastener design will be used to clamp onto it. A system to track the filament across the spool as the filament is being wound needs to be designed as well. This system will ensure that the filament does not tangle and cause issues when being fed into a printer. A frame is needed to support all components.

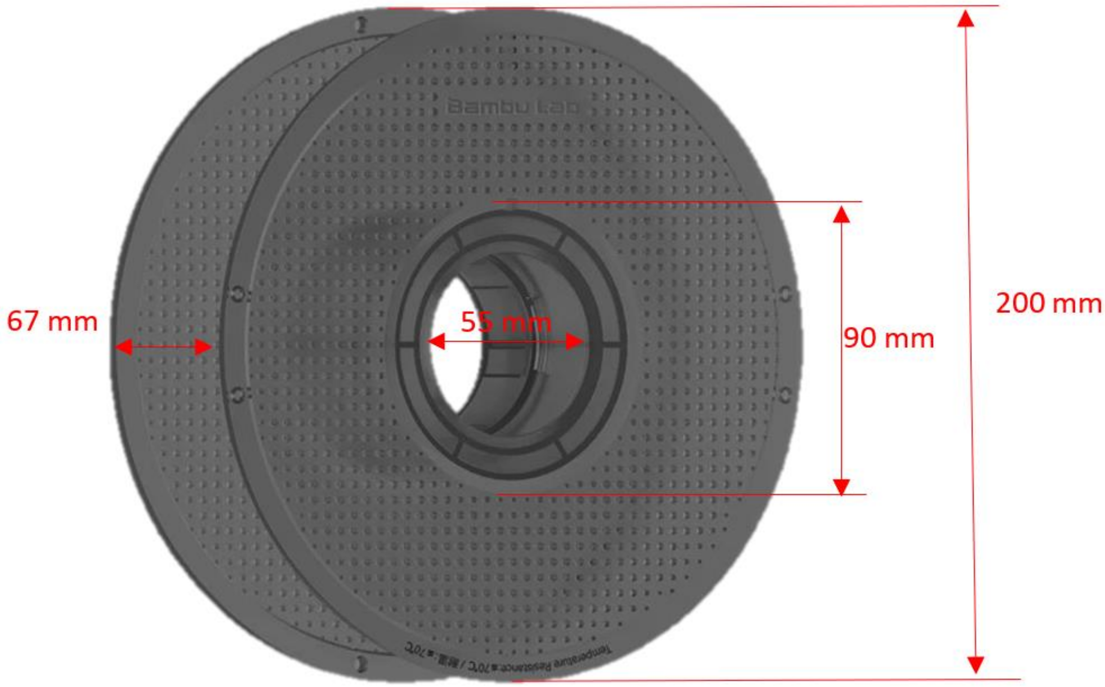

Figure 47: Bambu Lab Reusable Spool

8.2 Preliminary Design

An initial design of the system can be seen below in Figure 48. The motor will be behind the spool so that it is not in the way of the filament or tracking subsystem. There will be a set of gears that transfer the rotation to the spool.

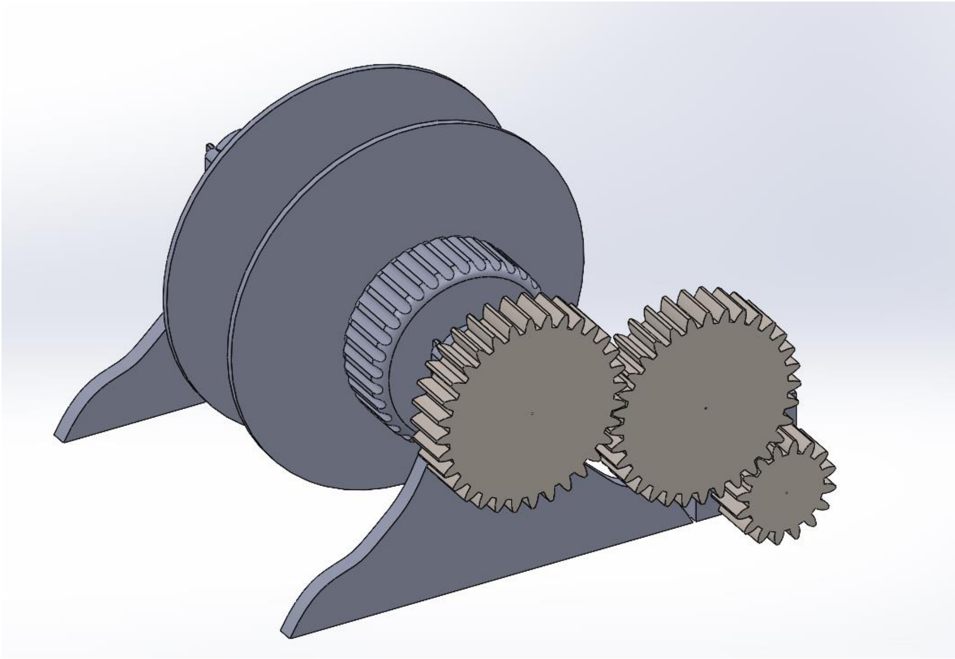

Figure 48: Spooling Conceptual Design

A shaft holds the spool in place and support the 1kg of weight from the filament. The shaft rides on two bearings surfaces. The bearing surfaces are shown in Figure 49.

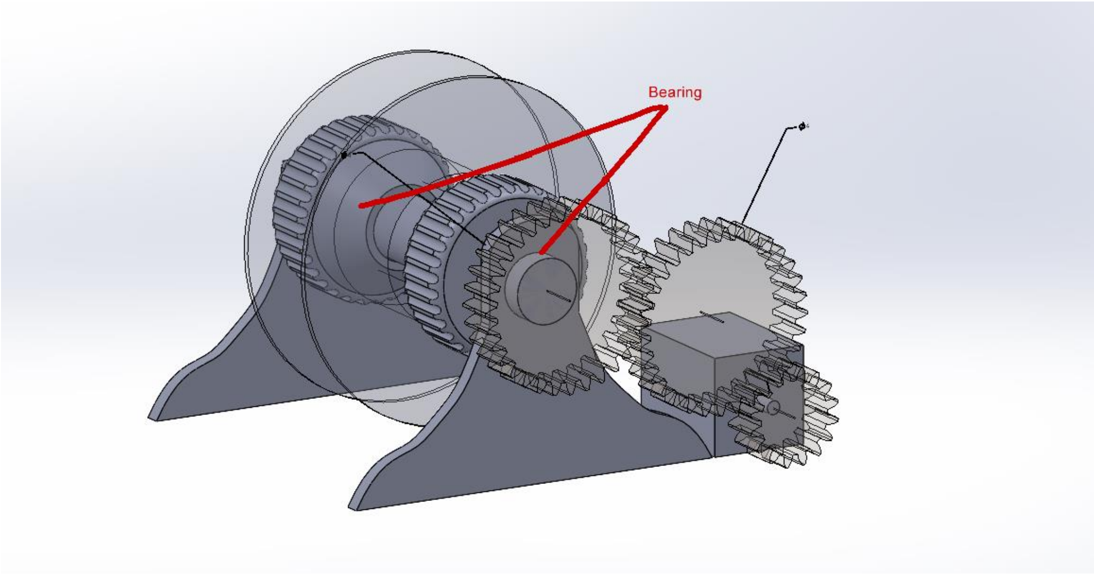

Figure 49: Location of Bearing Surfaces

The shaft itself is shown in Figure 50. It has 2 threaded sections for the shaft nuts. The shaft nuts are internally threaded to allow for centering the spool in the frame left and right. They are tapered to locate the spool concentric to the shaft. The thread also provides the clamping force to prevent the spool from slipping on the shaft.

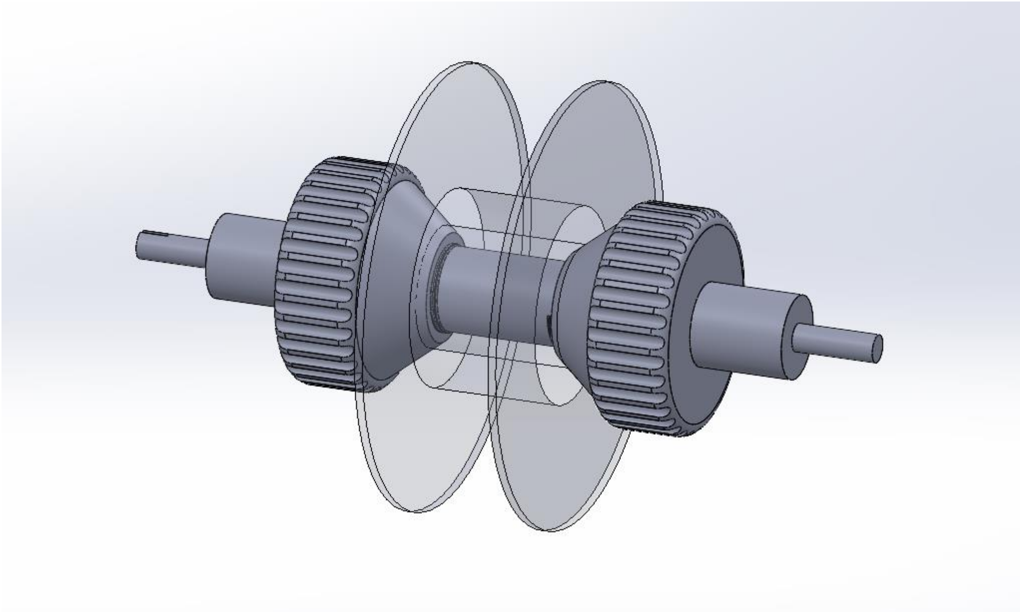

Figure 50: Spooler Shaft and Nuts

The tracking mechanism is shown in Figure 51. It runs off the same gear train as the spool and guides the filament along the width of the spool right to left, in 180 deg of rotation and left to right in the other. By doing this it will ensure that the spool will remain consistent and spool uniformly throughout the system regardless of the speed of the spool.

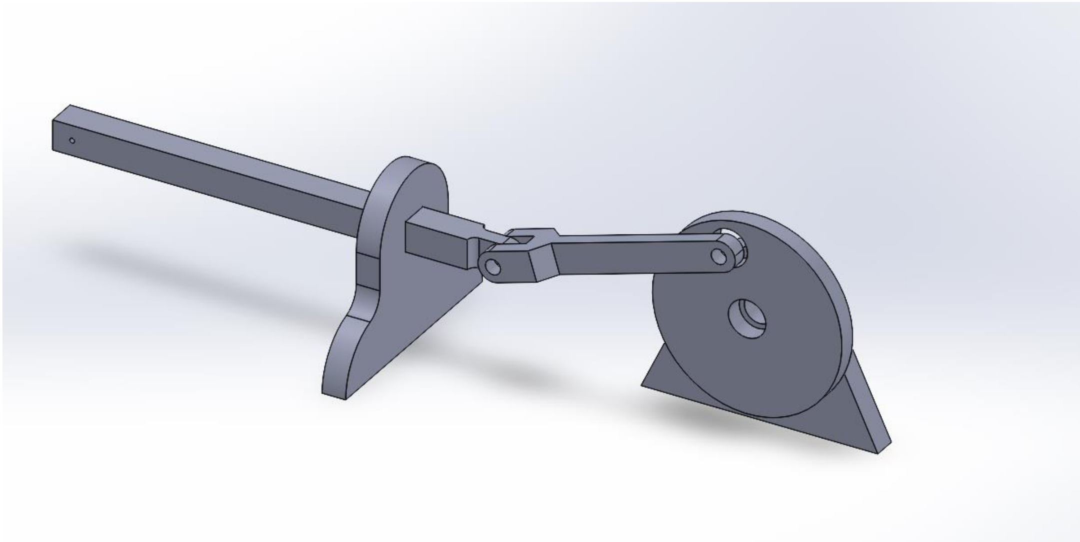

Figure 51: Preliminary Tracking Mechanism

8.3 Detailed Design

The frame that supports the spool and shaft will need to be resistant to static failure with a safety factor of 3. To analyze the complex, a SolidWorks simulation was performed. The maximum load on the system will be just over a kilogram and because there is a frame member on each side the load applied in the simulation was .5Kg.

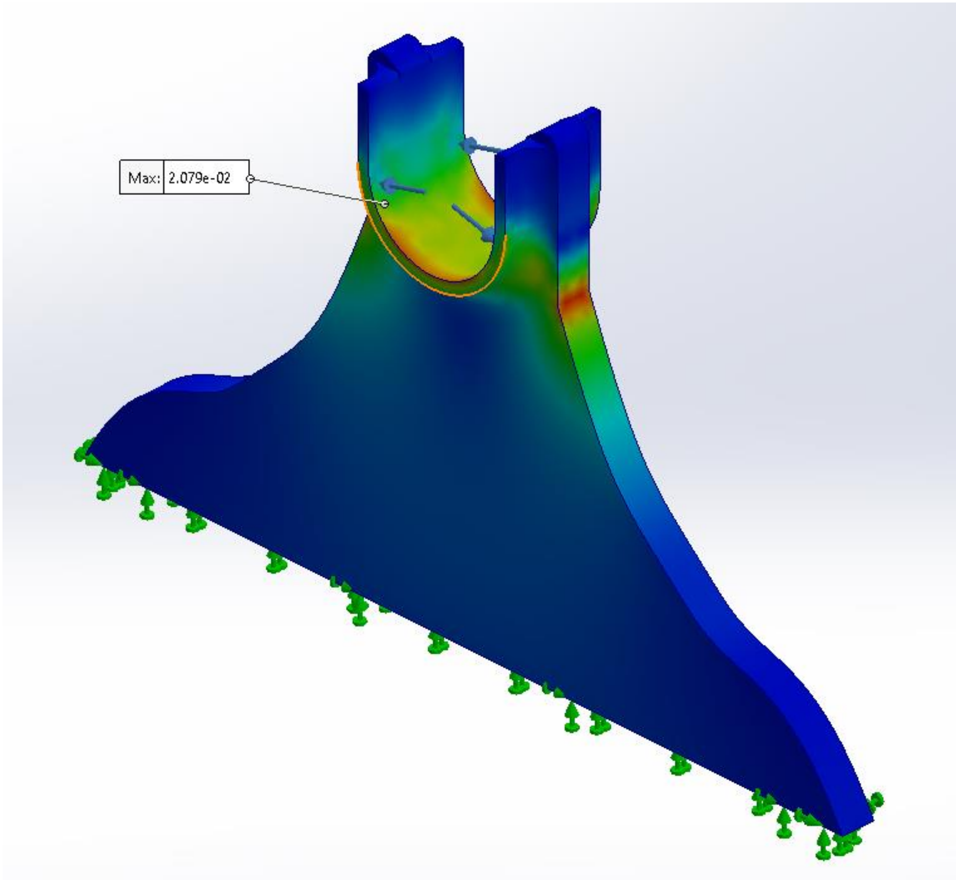

Figure 52: FEA of Spooler Frame

The simulation gave a resulting maximum Von Mises stress of 2.079x10^-2 MPa. To calculate the safety factor, we need to find the Tensile yield strength for Poly Latic Acid, 8Mpa, this value was obtained from Mat Web [FEA]. The safety factor was calculated below.

$$Sf = \frac{\sigma}{\sigma_f} \tag{1}$$

Where:

σ = 2.079x10^-2 MPa

σ_f = 8 MPa

When plugging in the values for σ and σ_f, the safety factor is found to be 2954. With such a large safety factor, it ensures that the frame will be able to handle the load.

The required rotational speed can be calculated based off of the production rate of the extruder. The outer and inner circumference will be used to find the RPM shown in the equation below.

$$RPM = \frac{Rate}{Circumference} \quad (2)$$

Where:

Rate = 1.6 (m/min)

Circumference of ID = 207 mm

Circumference of OD = 628 mm

Using the equation above, the inner part of the spool the RPM is found to be 7.716 RPM. As the spool begins to fill up the spool will slow down until it reaches the outer diameter which will then have an RPM of 2.54 RPM when the spool is spooled all the way.

The shaft was analyzed to design against fatigue. The shaft is supported by two bearing surfaces one on each end and will have a 1 Kg load, and there will be a torque of .8 Nm calculated from 4N at 200 mm applied towards the center of the shaft and be taken off at the at the and where the gear attaches. Figure 53 is a free body diagram of the shaft shown below.

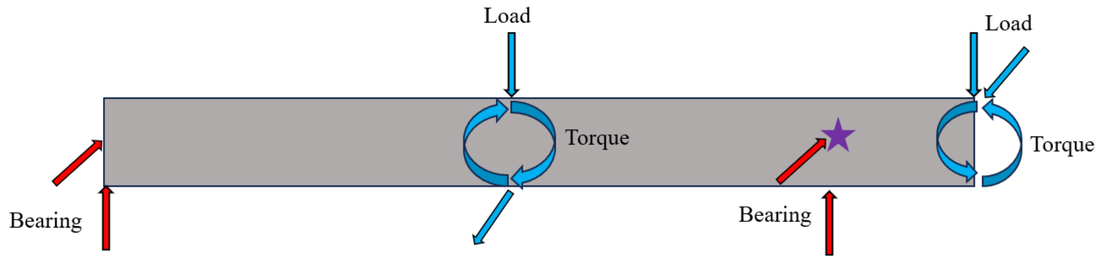

Figure 53: Free Body Diagram of Spooler Shaft

The shaft was analyzed at x = 12.5 inches, this is where there is the smallest diameter with a large change in geometry. There is also a torque active at this point. The moment at this point was calculated using the attached shaft defection MATLAB code[Appendix B – Spooler Shaft Deflection MATLAB Code] and was found to be .000214 Nm. These stresses were input into a fatigue safety factor excel sheet [Appendix C – Spooler Fatigue Calculations]. The ultimate tensile strength of PLA is 8.54 Ksi and the yield strength is 6.08 Ksi. Ka was calculated as an as forged part to assume maximum surface roughness. Kd was assumed to be 1 because the shaft will operate at room temperature. Ke was calculated based off 99% reliability (.814). Stress concentration factors were determined based on a fillet radius of 1/8th inch and visual interpretation of the graphs in the book. Kt is 1.4, Kts is 1.6, Qs is .3, and Q is .4. After inputting all the values into the excel sheet it was found that Goodman safety factor is 3.62, the Gerber safety factor is 3.621, and the static yield safety factor is 3.04 which all exceed the requirements for this system.

An analysis of the gear train was done to calculate the stress that will be on the teeth of the gears. The most critical gear set was identified as the 12 to 1 ratio right off of the motor, this set was the only one analyzed. These calculations can be seen in the attached Excel Sheet [**Appendix D – Spooler Gear** Ration **Calculations**]. Hardness ratio values were based off the lowest possible hardness on the provided scales. All the other assumptions that were made are mentioned in the sheet. From the Excel Sheet, it shows the system will have a bending Safety Factor of 3.3 and a Contract Safety factor of 7.862. From this, it is safe to assume that the gears will be able to handle the loads that will be placed on them.

8.4 Final Design

After evaluating the specification of the motor that drives the spooling system. The exact gear train could be calculated and modeled. It was calculated that the ratio between the motor and the spool should be 12 to 1. And the ratio between the spool and the tracking mechanism crank disk should be 768 to 1. Given these ratios a design was created shown in Figure 54.

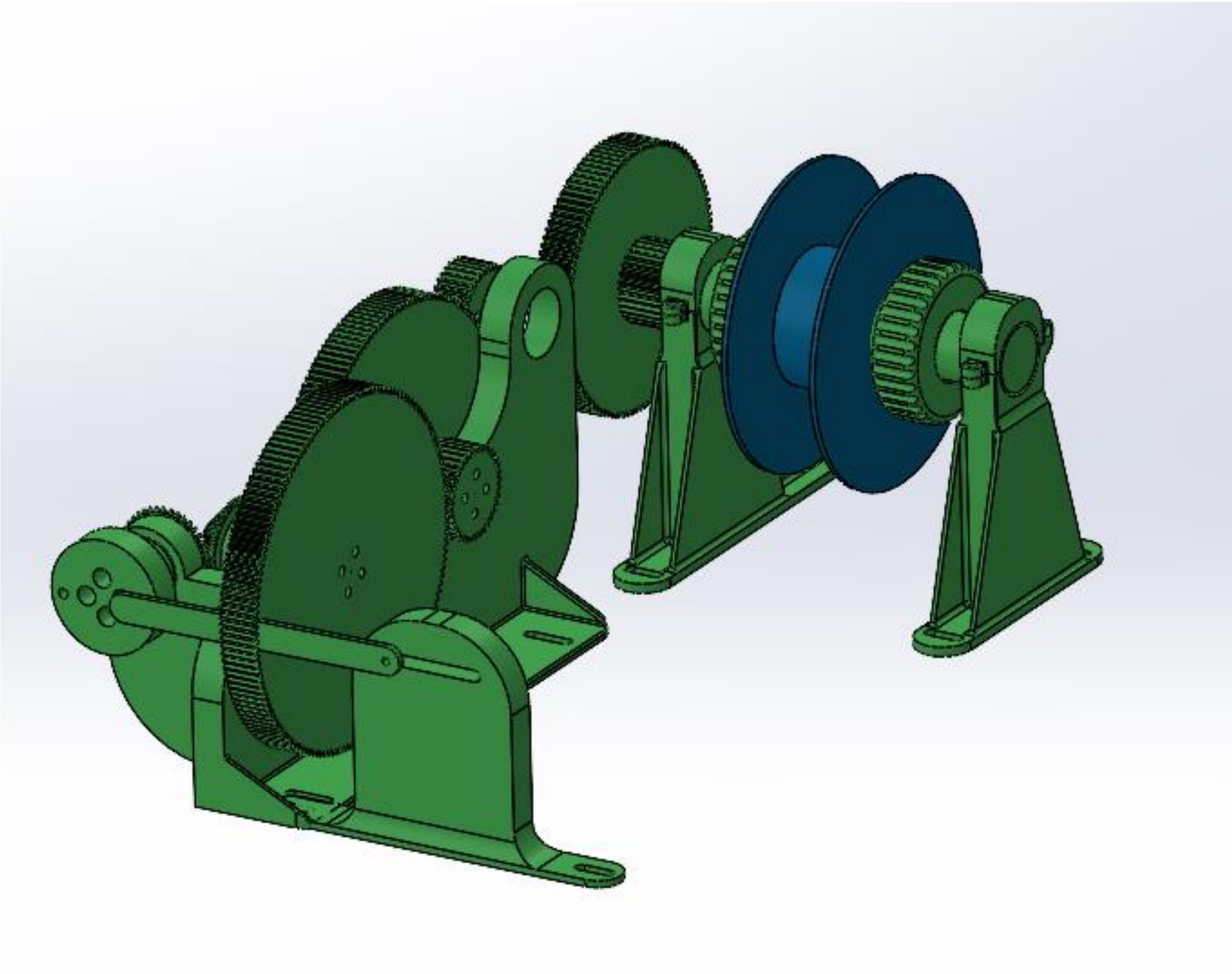

Figure 54: Spooler Design V2

This design was determined to be too long to fit into the overall design requirements so the third and final design was created to shorten the gear train. This design is shown in Figure 55.

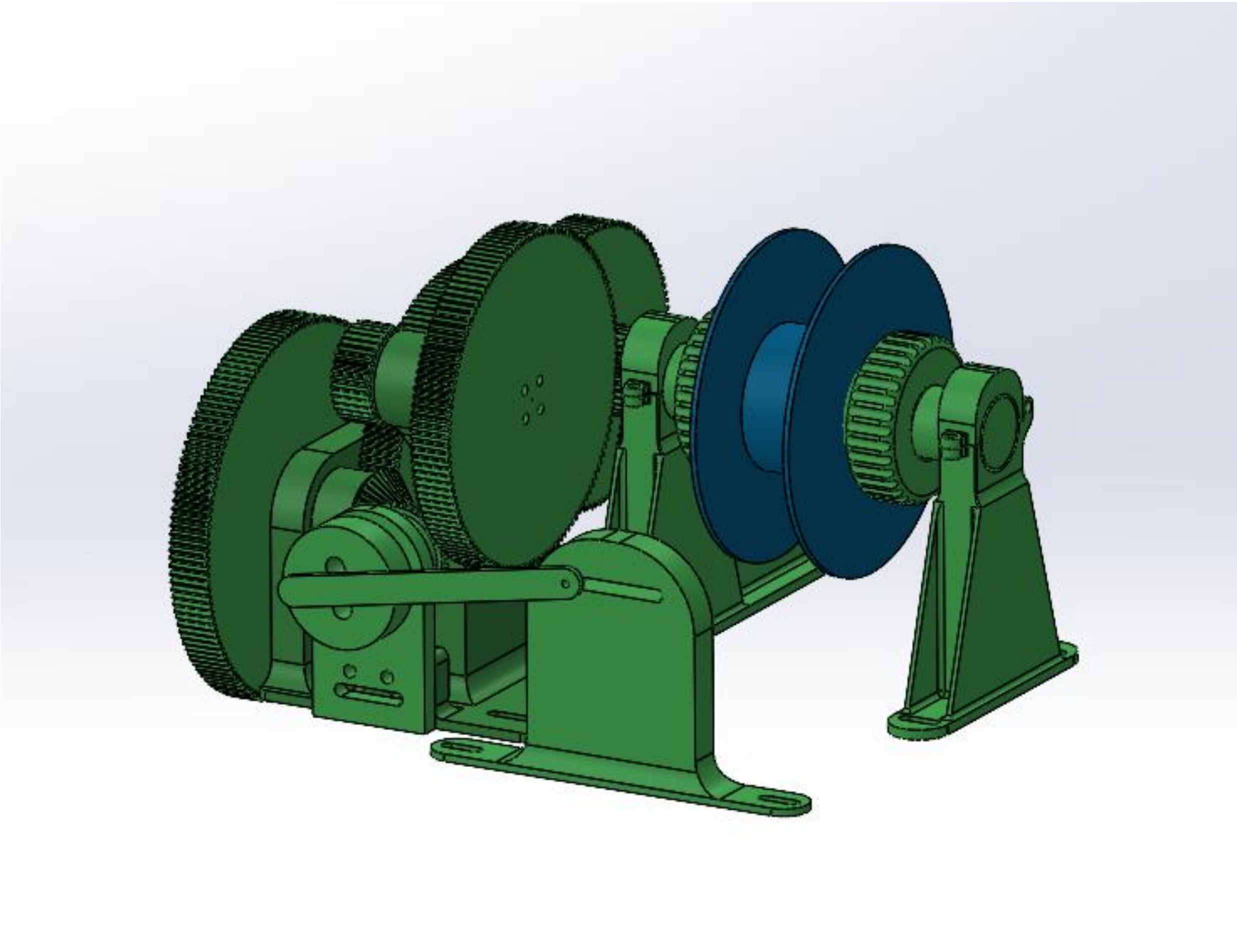

Figure 55: Final Spooler Design

8.5 Spooler Fabrication and Modification

Fabricating and modifying a 3D printer filament spooling mechanism involved a meticulous process, with a primary focus on leveraging 3D printing technology for cost-effective production. The spooler itself was entirely 3D printed, utilizing approximately 4 kg of filament for its fabrication. This approach proved advantageous, as traditional fabrication methods would have incurred significantly higher costs. By utilizing 3D printing, the team was able to achieve the desired design intricacies and functionalities while maintaining cost efficiency. The parts printed can be seen in Figure 56.

Figure 56: Printed Parts for Spooler

Throughout the fabrication process, key modifications were implemented to optimize the spooler's performance and durability. One crucial aspect was adjusting the clearances between gear axles and the frame to ensure smooth operation and prevent friction-related issues. Additionally, tolerance adjustments were made for the bolt securing the various components together, enhancing overall structural integrity and stability. These modifications were essential for fine-tuning the spooler mechanism, improving its functionality, and ensuring reliable performance in filament spooling operations. Figure 57 shows the spooling system fully assembled.

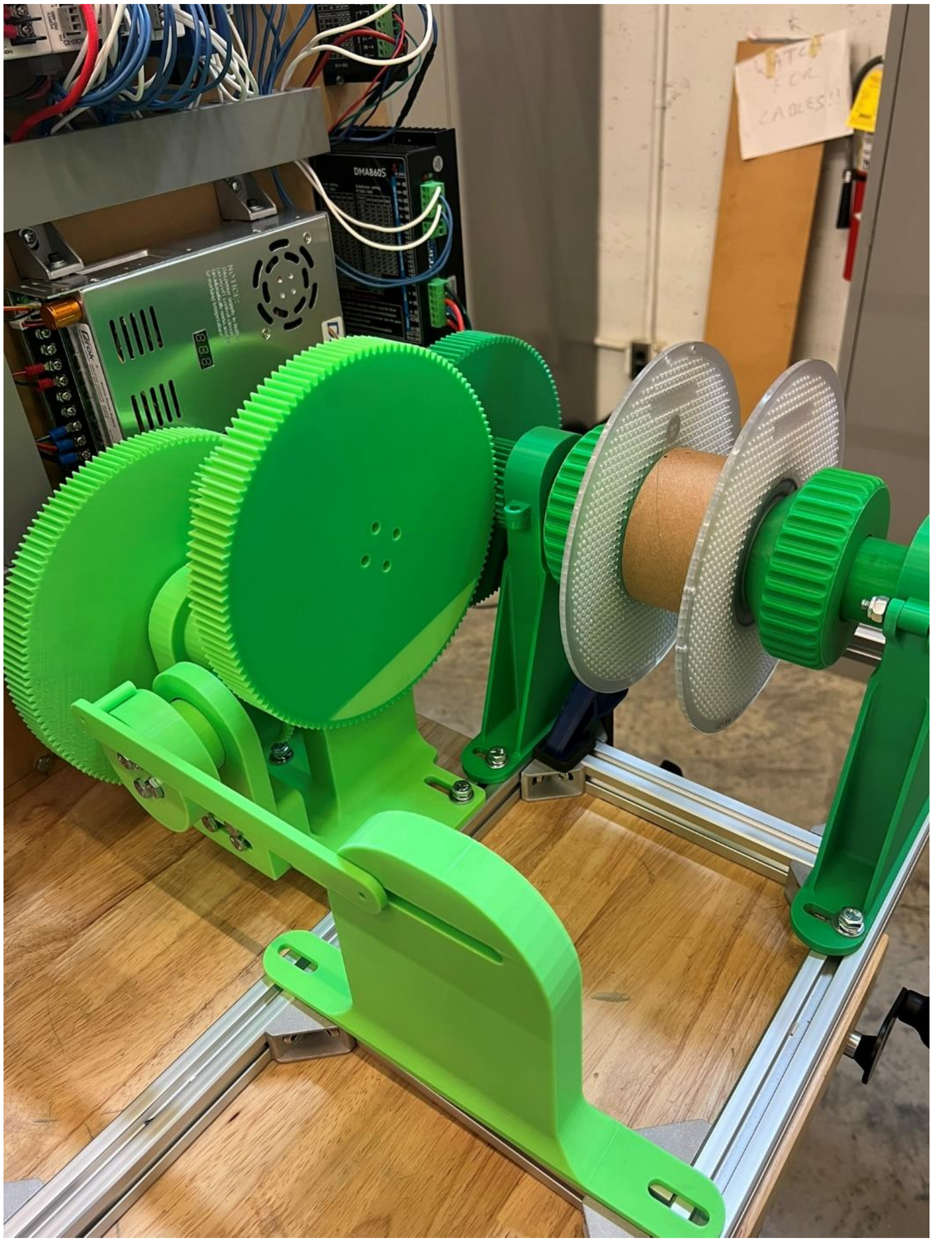

Figure 57: Final Spooling System

9.0 PLC AND ELECTRICAL

9.1 Determining a Suitable PLC

A PLC will be required for this project and will serve as the brain of the system. As such, the selection criteria for this decision are critical for success. Three alternatives were selected, Allen Bradley's Micro 870, Automation Direct Click PLC system, and Arduino's Opta. A decision matrix was created to identify the best solution. Each option was ranked in six weighted categories.

Cost is the category that is weighted the highest at 40% of the score because the budget of this project is limited. The PLCs were ranked from one to three with 3 being the cheapest. The Click PLC was the cheapest at only $92, while the Opta was $195, and the Micro 870 was $625.

The next most important category is availability as this project has a tight timeline. Waiting a significant amount of time for such an integral part of the system is not ideal. Again, the PLCs were ranked with the lowest shipping time being a 3. The Click PLC has guaranteed 2 business day shipping, the Micro 870 would arrive in 2-7 days, and the Opta would not arrive for 26 days.

Next the size of each PLC was ranked by volume in cubic inches. The Opta is the smallest at 7.65 in^3, and the Click was not far behind at 22.78 in^3, the largest option considered was the Micro 870 at 69.36 in^3.

Next the number of I/O was ranked. The Micro 870 ranked first with 24 points, the Click has 14 and the Opta has 12.

The last quality evaluated was the personal familiarity with the brand and software that the team members had. In ENGR 382 SCADA systems design, students had weekly labs requiring PLC programing using the Click PLC, and therefore it is the most familiar. The Opta can be programmed with multiple different programing languages and therefore would not be too difficult to learn to program. The Mirco 870 has proprietary programing software that would cost more to purchase and be more challenging to learn.

After grading each option, it was decided to go with Click PLC mainly because of the low cost and availability. Below is the decision matrix used.

Table 9. PLC Decision Matrix

Weighting	0.4	0.2	0.1	0.15	0.15	
Component	Cost	Availability	Familiarity	I/O Points	Size	
Click PLC	3	3	3	2	2	90%
Micro 870	1	2	1	3	1	50%
Arduino Opta	2	1	2	1	3	60%

9.2 Implementation of PLC and Control Systems

The PLC is responsible for controlling the entire machine and in conjunction with the human machine interface (HMI) must allow control of settings such as motor speeds for the grinder, extruder, and spooler, fan speed for cooling, and temperature are controlled through the PLC system. Each of the subsystems have a screen in the HMI and are color coded to match the physical machine. Furthermore, the numeric inputs and displays are color coded as well, values that the user can change are in green while values that are read only are in white. The HMI and control panel can be seen in Figure 58.

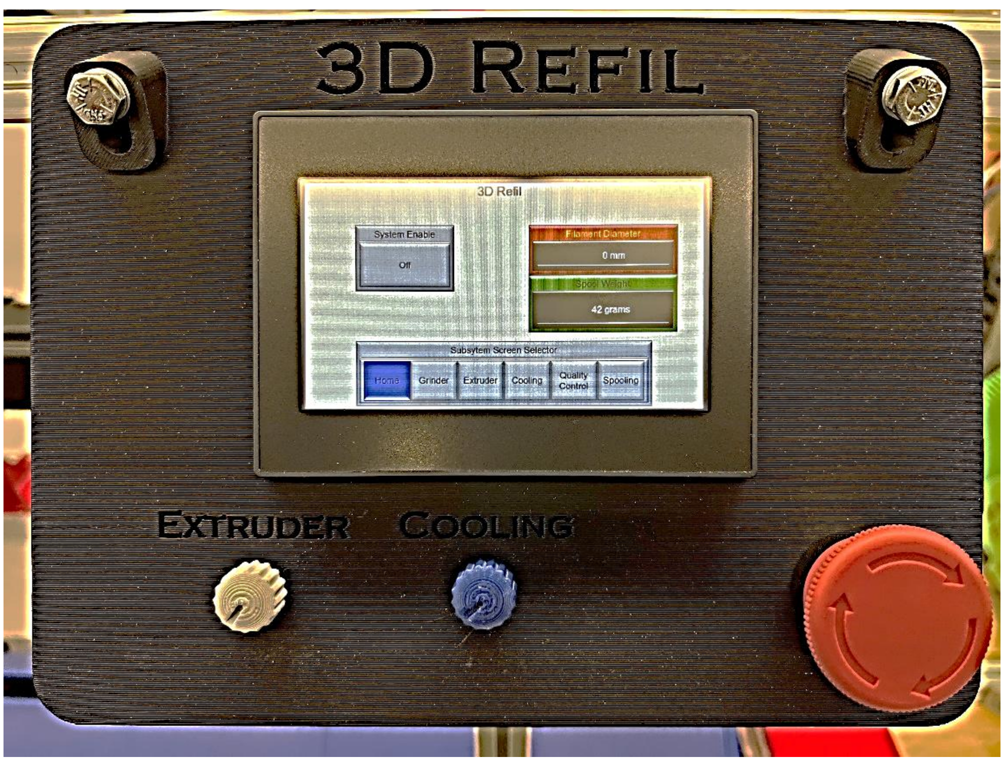

Figure 58: Control Panel and HMI

The power comes into the system from a main power switch that can be locked out for safety. From there it breaks out into terminal blocks for hot neutral and ground. The hot wire goes through a 15-amp circuit breaker that prevents the machine from drawing to much current. From there some of the components are isolated by a relay that acks as a switch the cuts power directly to the grinder and extruder when it either one of two estops are pressed. One emergency stop button is located on the control panel while the other one is located in between the grinder and extruder motor. Power then flow to various power supplies that convert the 120 volts to various DC voltages that are needed for the machine. A picture of the electrical and PLC and be seen in Figure 59.

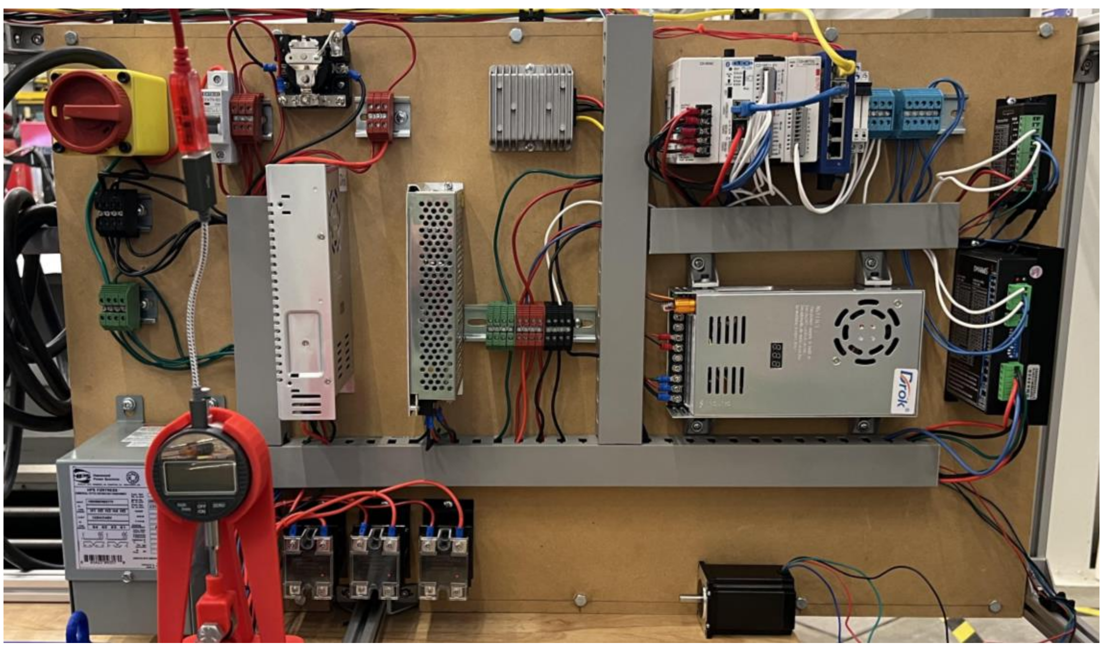

Figure 59:PLC and Electrical Layout

The grinder motor and spooler motor are controlled by the PLC by utilizing the high-speed outputs on the PLC. While the actual signals are separate the control philosophy is exactly the same for both motors. The ladder logic program takes an RPM value for the speed and calculates the necessary the pluses per second to send to the stepper motor drivers to make the output spin at the desired RPM. The ladder logic program also account for the gear reduction on the motor as well as the fact that the stepper motor driver was set up to micro step the motor for a soother rotation. Both the speed and the acceleration of the motors can be controlled on the HMI and the screen for the grinder control can be seen in Figure 60, and the spooler in Figure 61.

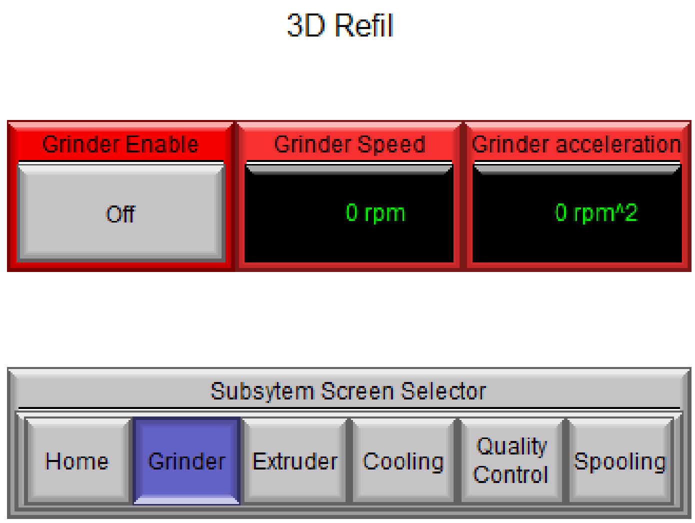

Figure 60: Grinder HMI Screen

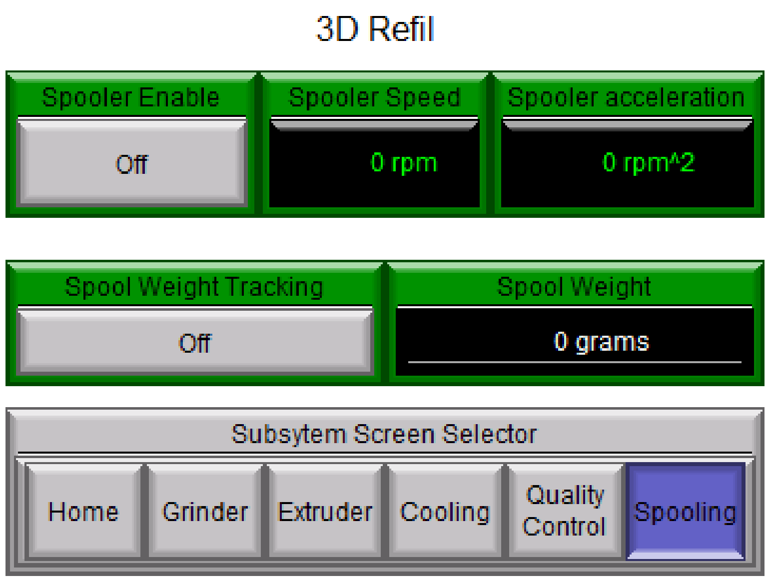

Figure 61: Spooler HMI Screen

The extruder kit was sold with a controller for the motor, three solid state relays for the heaters, and three temperature control modules. The motor controller serves as an AC variable frequency drive. Its control interface consisted of a dial potentiometer for adjusting speed and a power switch. To integrate this controller with the PLC the power switch was replaced with a digital relay switch that could be controlled by the PLC. The speed control was originally planned to be controlled by an analog output on the PLC but after the controller was taken apart it was discovered that there was AC current running through the potentiometer, and because the PLC operates with DC voltage a different solution was needed. The solution that the team determined was the best course of action was swapping the potentiometer for a dual level potentiometer. This allowed us to still pass the AC current through one layer to control the motor speed, and on the second layer send 5 volts and read the voltage drop to determine the speed of the motor. This was done by running the motor at various RPMs and recording the voltage drop of the 5-volt signal. These points were used to create an equation that would calculate the speed of the motor based on the voltage that the PLC was reading on the analog input.

The heating elements were tested once the extruder was mounted. The PLC was used to switch the high wattage relays that came with the extruder. The heater became the first issue with integrating the extruder into the project. The heating bands are 220 V, 450 W. A transformer was purchased to up step the 120 V wall outlet voltage to the required 220 V. These heating bands ran for a short amount of time before tripping the breaker in the circuit. During the analysis of this failure, the transformer eventually broke entirely. The team decided that instead of replacing the transformer, heating bands of 120 V, 150 W shall replace the ones that came with the extruder. This option was decided for the benefit of eliminating an electrical component from this system as well as lowering the total amperage draw for the extruder system. Also, the cost of new heating bands was lower than a new transformer. These 120 V heaters were implemented and functioned as needed.

The extruder also came with 3 sets of temperature controllers and thermocouples. To be able to integrate the reading of the temperature of the 3 zones into the PLC the temperature controller could not be used. Instead, small circuit boards were purchased that took in 5 volts for power and the signal from a K type thermocouple and output a voltage ranging from 0 to 5 volts. This voltage was then read by the PLC. The raw voltage signal needed to be calibrated to read a temperature. To do this each thermocouple was placed into ice water and boiling water, and the voltage output was recorded from the PLC. These temperature values and voltages were used to create an equation that calculates the temperature based on the voltage that the thermocouple amplifier boards output. One of the major problems that the team ran into with the thermocouples was getting the signal to be consistent. After some troubleshooting, we discovered that there was some potential build up on the extruder barrel, and because the thermocouples threaded directly into it the sensitive voltage signals, they were sending to the amplifier boards was being affected. The solution to this problem was to directly ground the extruder barrel giving a path for the build up to escape.

To control the temperature in the three extruder zones, PID loops were set up between the thermocouple and the heater. PID loops, or Proportional-Integral-Derivative loops, are a powerful control mechanism widely used in engineering and industrial applications. These loops are particularly useful for regulating systems where precise and stable control is necessary. The primary function of a PID loop is to maintain a desired setpoint by continuously adjusting control parameters based on feedback from the system. In the context of an extruder heater, the PID loop monitors the temperature of the extruder barrel and adjusts the power supplied to the heater to achieve and maintain the target temperature. The Proportional component of the PID loop provides a response to the current error between the measured temperature and the setpoint. A higher proportional gain results in a faster response to changes in temperature, but it can also lead to overshooting the setpoint or oscillations around the setpoint if set too high. The Integral component of the PID loop accounts for accumulated errors over time. It helps to eliminate steady-state error by continuously adjusting the control output based on the cumulative error. This component is particularly useful for correcting long-term deviations from the setpoint, ensuring that the system settles at the desired temperature without steady-state error. The Derivative component of the PID loop anticipates future changes in temperature based on the rate of change of the error. It helps to dampen oscillations and stabilize the system by reducing overshooting and improving response time. The programing software used for this project has a built-in PID loop utility which can be seen in Figure 62. The utility also has auto tuning functionality however, because of the slow reaction time of the system, the team was unable to use this feature. The PID values were tuned manually until the desired behavior was achieved when the set point was changed. The tuning menu can be seen in Figure 63.

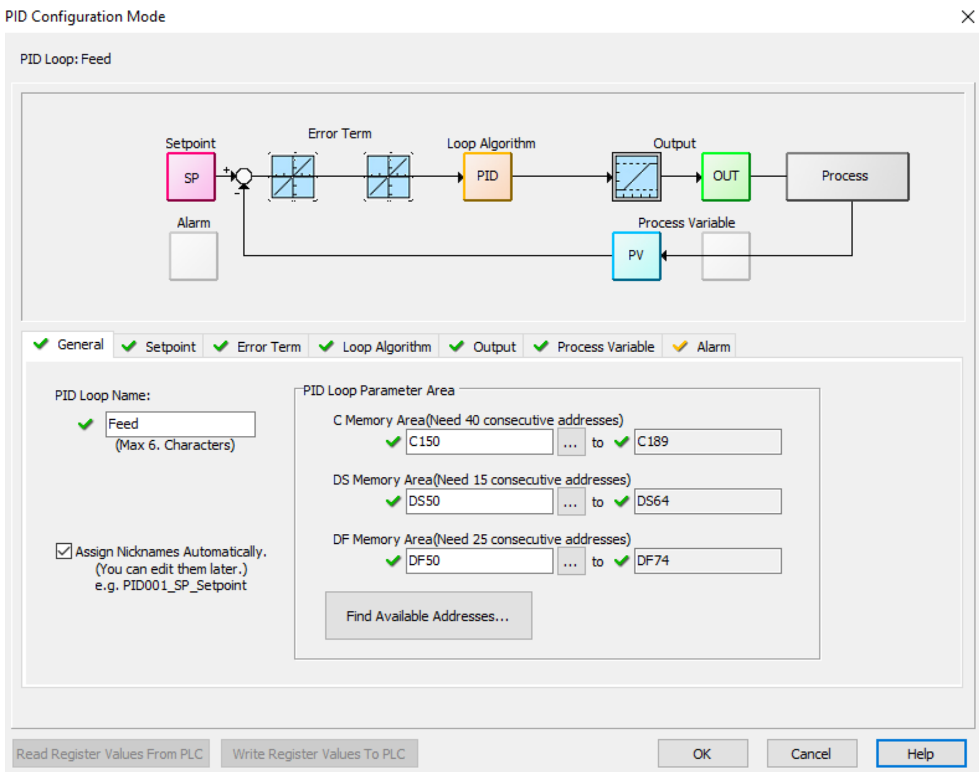

Figure 62: PID Configuration Menu

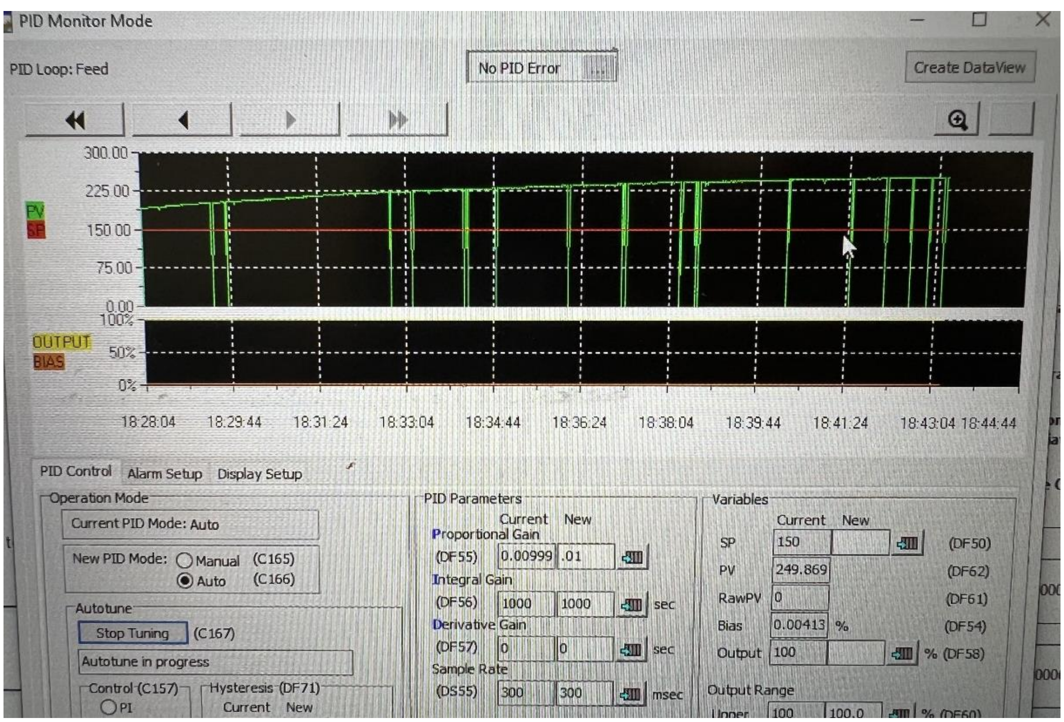

Figure 63: PID Tuning Menu

The user controls the temperature of each zone on the extruder screen. The set point as well as the actual temperature is displayed, and when the user changes the set point the heaters will automatically adjust to the new temperature. The HMI screen for the extruder can be seen in Figure 64. On this screen the user can also turn the extruder on and off. The speed of the extruder is also displayed on this screen.

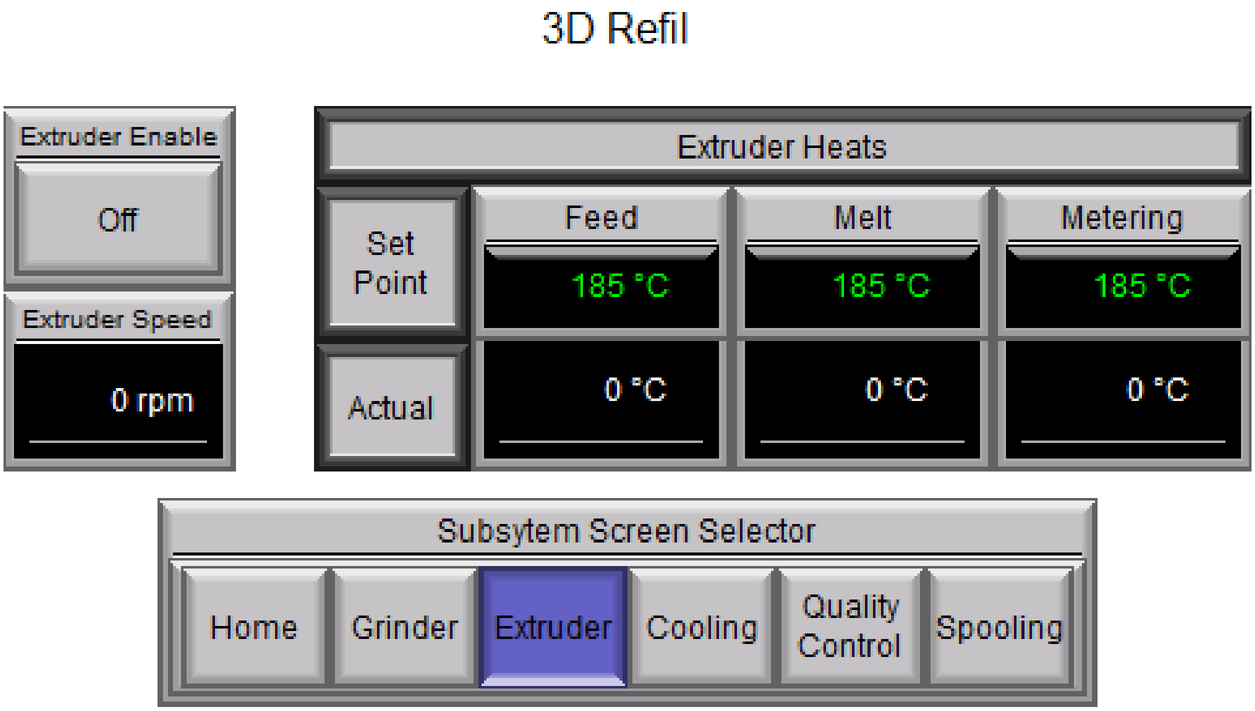

Figure 64: Extruder HMI Screen

The cooling system is controlled by a dial on the control panel. The dial directly controls an adjustable 0-to-24 volt DC power supply. In much the same way as the extruder motor a two-level potentiometer is used to allow the PLC to read the speed of the fans. A 5-volt signal is passed into the potentiometer and depending on where the dial is positioned a different voltage is output. The same calibration was performed to create an equation the correlates the voltage to the speed of the fans. The PLC also controls a digital relay that is responsible for allowing power to flow to the fans. This allows the user to turn the on and off without changing the position of the dial. The cooling screen has a direct user input to turn the system on and off and displays the speed as a percentage, show in Figure 65.

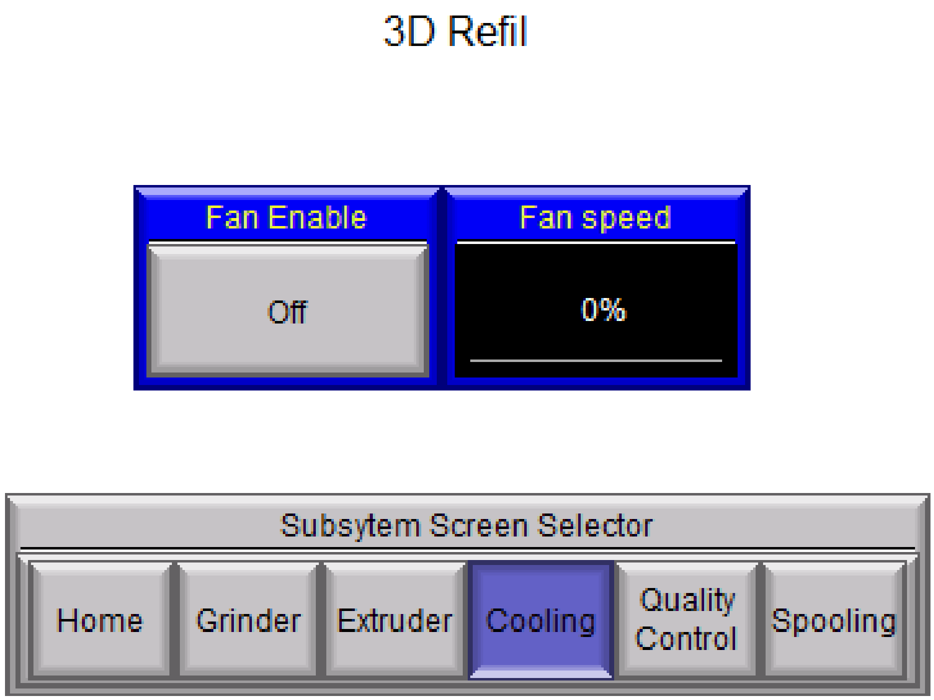

Figure 65: Cooling System HMI Screen

The quality assurance subsystem integrates with the PLC as well. The Hall effect sensor takes in 5 volts and based on the position of the magnet outputs a voltage in the 0-5 volt range. To calibrate the sensor drill bits of known diameters were inserted into the sensor and the voltage output was recorded. Again, an equation was created to correlate the diameter of the filament with the voltage output by the sensor. The data from the sensor is displayed on the quality control screen shown in Figure 66. The black line represents the desired filament diameter of 1.75mm and the green line is the diameter of the filament currently being produced.

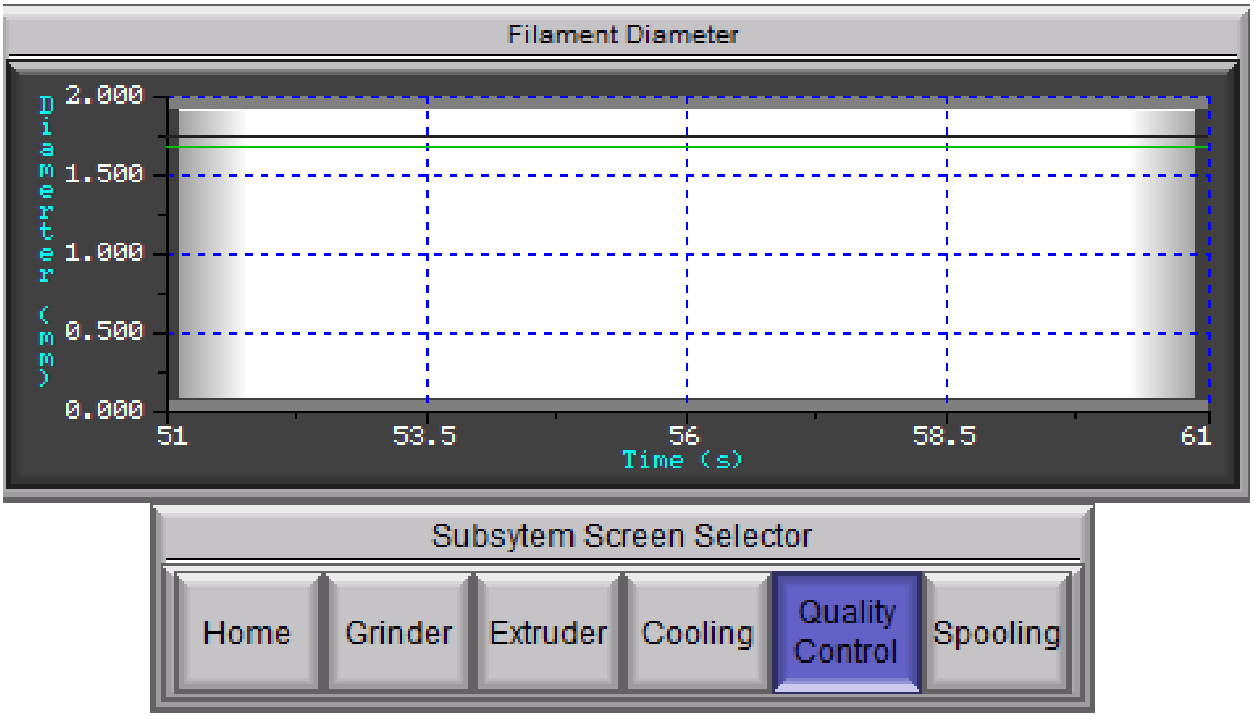

Figure 66: Quality Control HMI Screen

10.0 RESULTS

The quality of the filament that is produced is an important aspect in production. Making trash out of trash is not the objective. Poor quality filaments can lead to under-extrusion, over-extrusion, and poor surface texture. To ensure a good quality filament is made from recycled plastics, the microstructure will be analyzed.

10.1 Test Equipment

Utilizing USI's Strengths Lab, there are two pieces of equipment at disposal for analyzing microstructures.

The first one is a polishing wheel. Once 3D printer filament is produced, samples of it can be placed in an epoxy mold. This mold will be sanded to a fine grit quality of 1200 or higher. The sanding process starts at 180 and goes through 240, 320, 400, 600, and 1200. Once sanded, it will be polished so the test surface is clear and transparent. Each sanding grit takes 20 minutes or more of prep time. The polishing phase takes 30 minutes or more. Figure 59 shows the grinder machine used while Figure 60 shows the sanding pads, polishing pads, and other chemicals related to the preparation of these samples.

Figure 67. Grinding and Polishing Machine

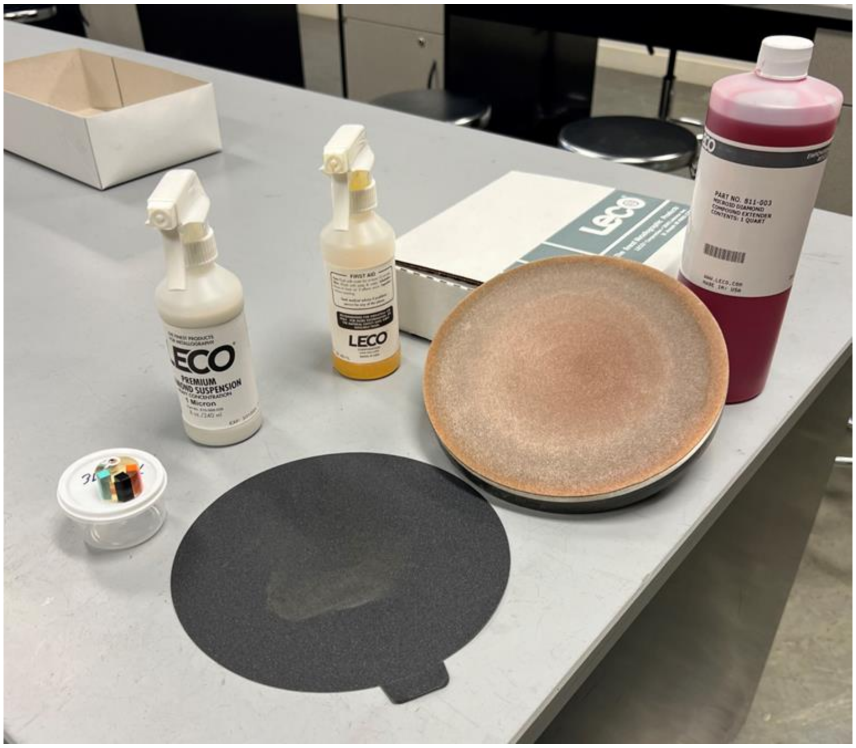

Figure 68. Grinding and Polishing Pads with Chemicals

The second piece of equipment is a high-powered microscope. Once the samples are polished, they are placed on this microscope's test plate to be analyzed. This microscope has the capability to do a 1000X zoom on the sample. Pictures can be taken directly from the scope and have an image quality of 4K. This microscope is shown in Figure 61

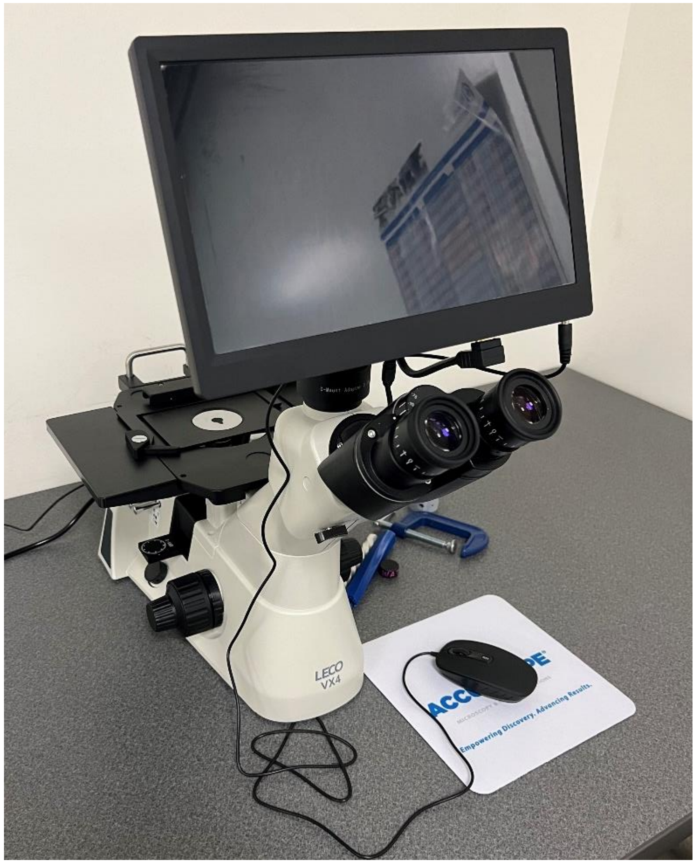

Figure 69. High-Powered Microscope

10.2 Filament Microstructure

Figure 70 is an image taken with this microscope of a high-quality filament that was purchased. Figure 71 is an image taken with this microscope of a cheap, low-quality filament that was purchased. These pictures are of the circular cross section.

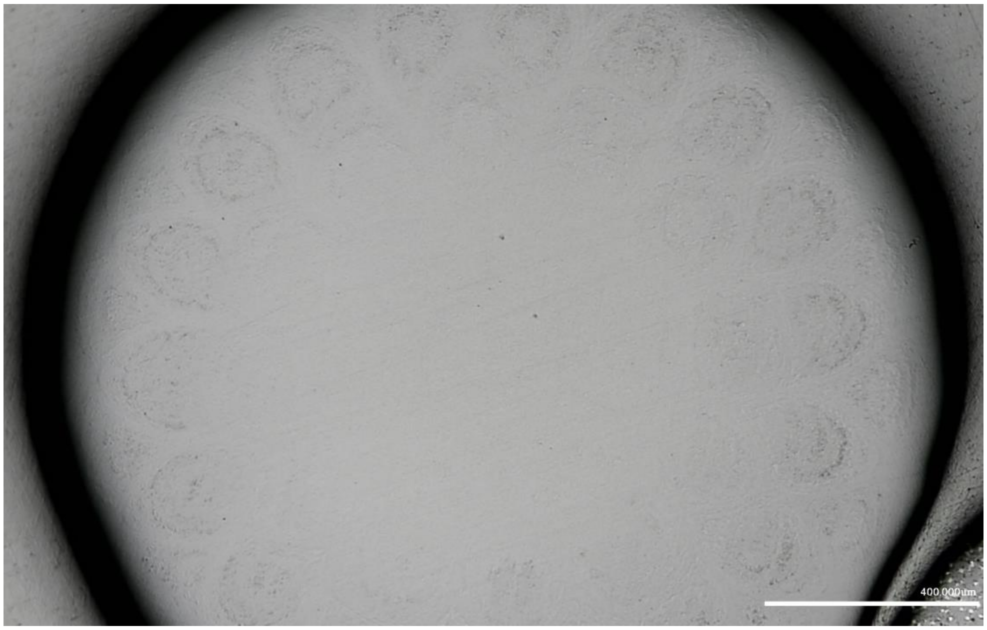

Figure 70. High Quality Filament Microstructure

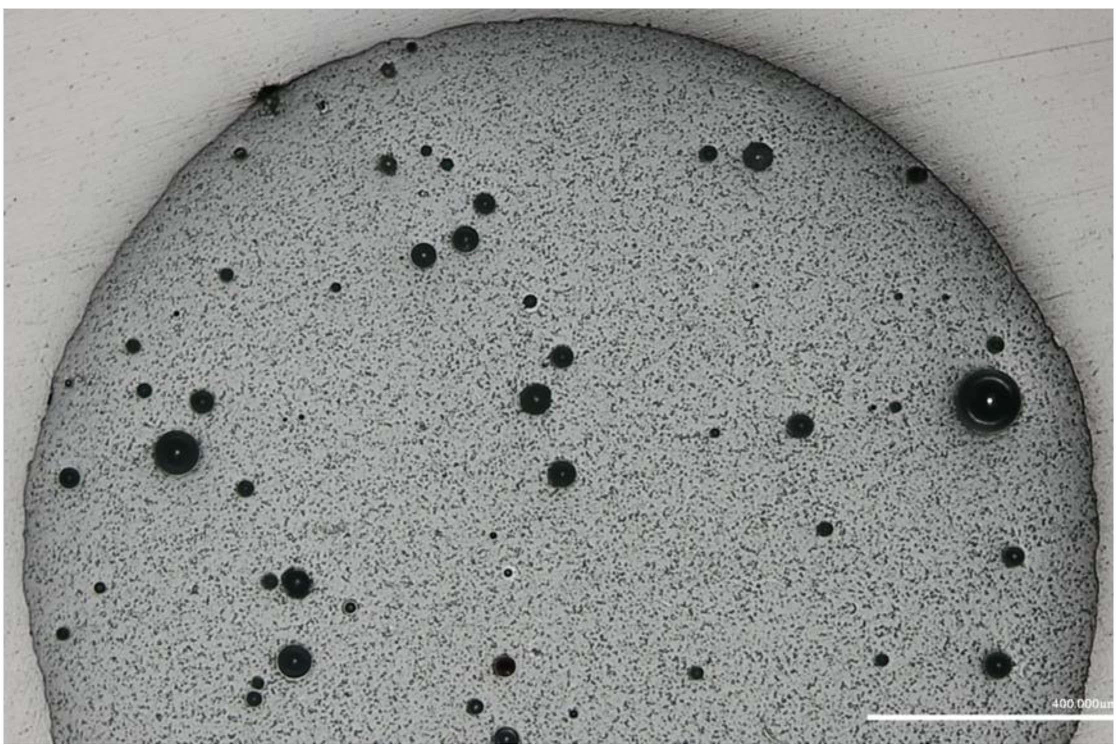

Figure 71. Low Quality Filament Microstructure

The low-quality filament has several dark spots across the cross-sectional area. All these spots are some forms of dirt, debris, water, or air pockets that is embedded in the plastic filament. These impurities will decrease the quality of whatever is being printed with it. The high-quality filament does not have as many of these spots and will have better printing results than the other. Using a computer software program, the percentage of the cross-sectional area that is dirt or debris is calculated. The high-quality filament had a defect area of 0.0845%. The low-quality filament had a defect area of 2.747%. It may seem that not even 3% of the low-quality filament being defective would be a major issue, but 3D printers are very sensitive, and this type of filament will lead to extrusion issues.

We analyzed our filament by preparing samples the same way as the store-bought filaments. We compared our samples to a store-bought filament that was made of recycled plastic. Using a computer software program, the percentage of the cross-sectional area that is dirt or debris is calculated. Figure 64 shows the microstructure of the store-bought recycled filament. It had a percent defect area of 1.83%. Figure 65 shows the microstructure of our filament. It had a percent defect area of 0.595%.

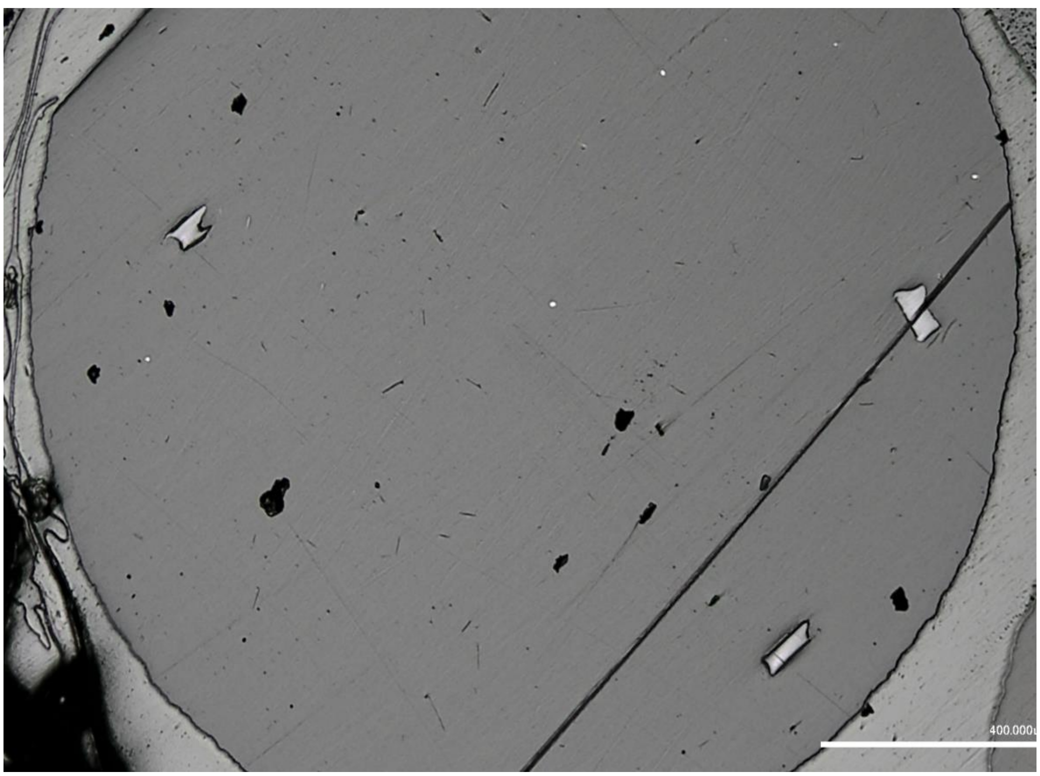

Figure 72. Store-Bought Recycled Filament Microstructure

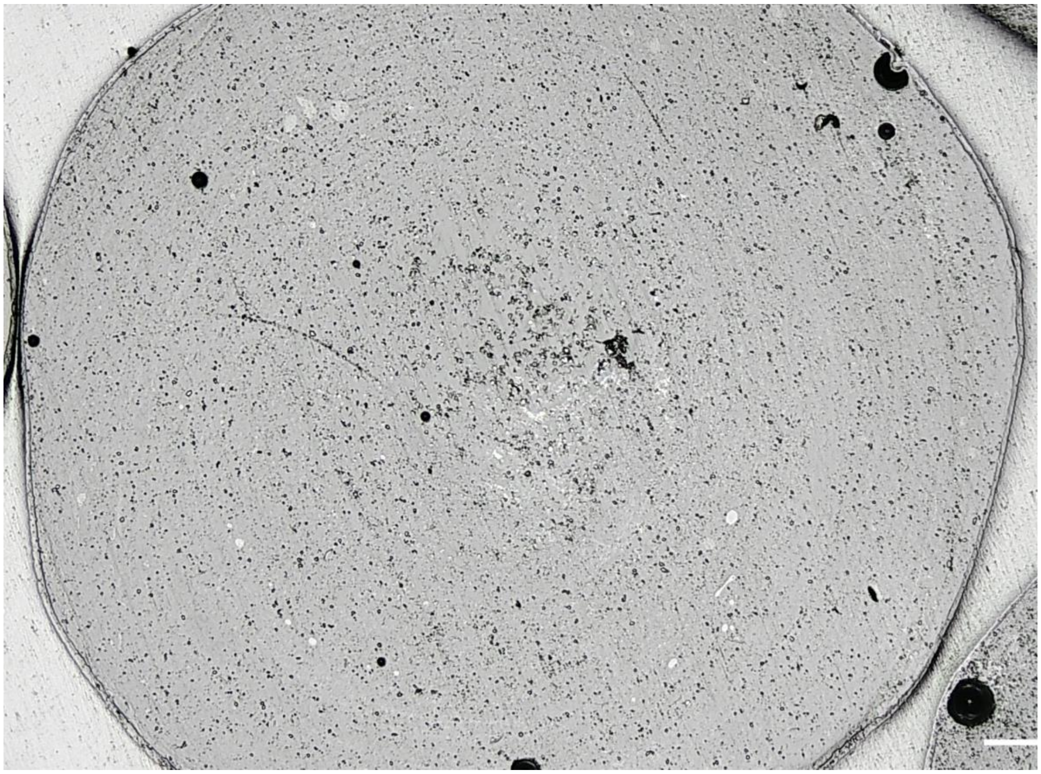

Figure 73. 3D ReFil Filament Microstructure

The Benchy is the name of a print to measure all the types of 3D printing in a print. It is short for benchmark and measures how well a printer can print. Benchys were printed with store-bought filament as well as the filament our project produced. Shown in Figure 66 is a Benchy made from purchased filament. Shown in Figure 67 is a Benchy made from our filament.

Figure 74. Benchy Made from Store-Bought Filament

Figure 75. Benchy Made from 3D ReFil Filament

Our filament made a lower quality Benchy than what was expected. More print lines are visible than desired, and there are some rough edges where the plastic did not lay flat. With more trial and error on the machine’s extrusion rate, cooling rate, and spooling speed, a higher quality filament can be made. As discussed in the next section, the plastic used for recycling is somewhat old and has acquired moisture throughout its life. More suggestions on improving the quality will be discussed as well.

11.0 SUGGESTIONS FOR FUTURE WORK

Moving forward, our project team envisions several enhancements to further optimize the plastic recycling process and elevate the quality of the filament produced. One key area of improvement lies in enhancing the print quality by implementing measures to dry out the filament. Moisture content in the filament can adversely affect print quality, causing issues such as bubbling, inconsistent layer adhesion, and stringing. By integrating a filament drying step into the process those issues can be mitigated in the future and ensures the system produces the best quality possible.

Additionally, we propose the incorporation of rollers into the cooling system to facilitate smoother filament travel. Presently, the filament passes over a static cooling system, which may result in uneven cooling and potential deformities in the filament. By introducing rollers, we anticipate achieving more uniform cooling and minimizing filament irregularities, ultimately enhancing the overall filament quality.

Moreover, our team suggests that the machine settings need to be fine-tuned to achieve a tighter diameter tolerance of ±0.03mm across an entire spool of filament. Consistency in filament diameter is crucial for seamless 3D printing, as deviations can lead to print failures and compromised part quality. Through meticulous calibration and adjustment of machine parameters, we aim to achieve enhanced precision in filament diameter, thereby ensuring optimal printing performance.

Furthermore, as part of our future project work, we suggest that comprehensive work instructions for the operation and maintenance of the recycling system. Clear and detailed instructions will streamline system operation, facilitate troubleshooting, and promote efficient maintenance practices, ultimately maximizing system uptime, longevity, and usability.

In addition to these enhancements, our team envisions the implementation of advanced analytical tools to further refine the recycling process. Specifically, we propose the creation of a Process Failure Mode Analysis (PFMA) chart to systematically identify and address potential failure modes in the filament production process. By analyzing filament defects and correlating them with specific machine settings, we can pinpoint areas for improvement and refine the process parameters accordingly.

Furthermore, we aim to leverage the programmable logic controller (PLC) to automate certain aspects of the filament production process. One such enhancement involves automatically adjusting the speed of the spooler in response to changes in filament diameter. By dynamically controlling the spooler speed, we can maintain consistent tension and winding density, ensuring uniform filament distribution on the spool.

Lastly, possible future endeavors include experimentation and calibration for producing different types of plastics, such as ABS and PETG. By expanding our material repertoire, we can cater to a broader range of user needs and applications, thereby enhancing the versatility and utility of our recycling system.

11.0 References

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APPENDICES

APPENDIX A – BILL OF MATERIAL

Sub Section	Part	Cost	Quantity	Total
Frame				$ 412.83
	76 in T-Slotted Rail	5	$ 18.24	$ 91.20
	20 in T-Slotted Rail	12	$ 4.80	$ 57.60
	74 in T-Slotted Rail	1	$ 17.76	$ 17.76
	11.25 in T-Slotted Rail	4	$ 2.88	$ 11.52
	8.375 in T-Slotted Rail	6	$ 2.16	$ 12.96
	6 in T-Slotted Rail	7	$ 1.44	$ 10.08
	7.75 in T-Slotted Rail	5	$ 1.92	$ 9.60
	7.in T-Slotted Rail	4	$ 1.68	$ 6.72
	Extruded Aluminum Slide Nuts	13	$ 3.29	$ 42.77
	Extruded Aluminum Mounting Brackets	4	$ 30.93	$ 123.72
	Extruded Aluminum Internal Brackets	1	$ 28.90	$ 28.90
Grinder				$ 411.69
	1-1/4" Pillow Block Bearing	1	$ 20.45	$ 20.45
	Hex Bar 1-1/2" Shaft	1	$ 30.79	$ 30.79
	Nema 34 Stepper Motor 6.0A 36V	1	$ 78.00	$ 78.00
	Planatery Gearbox 50:1 Nema 34	1	$ 182.00	$ 182.00
	Power Supply for Grinder	1	$ 48.46	$ 48.46
	Difital Stepper Motor Driver	1	$ 35.00	$ 35.00
	Scale	1	$ 16.99	$ 16.99
Extruder				$ 817.41
	Extruder Kit	1	$ 545.00	$ 545.00
	Thermocoupler Amplifier	3	$ 25.38	$ 76.14
	Power Supple for Heater	1	$ 189.00	$ 189.00
	Spray Paint	1	$ 7.27	$ 7.27
Cooling				$ 180.67
	Blue PLA	3	$ 24.99	$ 74.97
	120mm Noctua Fans	4	$ 14.94	$ 59.76
	24 Volt Adjustable Power Supply	1	$ 39.99	$ 39.99
	Fan Splitter	1	$ 5.95	$ 5.95
QA				$ 116.71
	Red PLA	2	$ 24.99	$ 49.98
	Clockwise Dial Indicator	1	$ 31.88	$ 31.88
	Micro USB to USB Cable	1	$ 9.85	$ 9.85
	Hall Effect Senor	1	$ 25.00	$ 25.00
Spooler				$ 207.91
	Nema 23 Stepper Motor	1	$ 25.99	$ 25.99
	Nema 23 Stepper Motor Driver	1	$ 9.99	$ 9.99

	Green PLA	6	$ 24.99	$ 149.94
	Power Supply for Spooler 24 V	1	$ 21.99	$ 21.99
PLC/Electical				$ 983.46
	12 Volt DC Relay	1	$ 12.50	$ 12.50
	Emergency Stop Buttons	2	$ 7.79	$ 15.58
	PLC CPU Model (C2-03CPU)	1	$ 205.00	$ 205.00
	Wiring	4	$ 24.99	$ 99.96
	Grey PLA	1	$ 24.99	$ 24.99
	24 Volt relay	2	$ 8.00	$ 16.00
	20k Dual Potentiometer	1	$ 7.49	$ 7.49
	24V to 5V Buck Converter	1	$ 18.99	$ 18.99
	15Ft Power Cable	1	$ 25.09	$ 25.09
	20 Amp Breaker	1	$ 7.99	$ 7.99
	Recycled PLA	1	$ 19.99	$ 19.99
	PLC Power supply (C0-00AC)	1	$ 51.00	$ 51.00
	Power switch (ML1-025-E-H03R)	1	$ 33.00	$ 33.00
	PLC Internal I/O modual (C2-08D1-6V)	1	$ 90.00	$ 90.00
	PLC add-on I/O modual (C0-08TD2)	1	$ 50.00	$ 50.00
	DIN Mounting Rail	1	$ 14.00	$ 14.00
	Multicolor zip ties	1	$ 8.99	$ 8.99
	Resistor kit	1	$ 9.99	$ 9.99
	Wago connectors	1	$ 42.00	$ 42.00
	MDF Board 3' x 8'	1	$ 58.44	$ 58.44
	Red terminal Block	1	$ 9.00	$ 9.00
	Black terminal Block	1	$ 9.00	$ 9.00
	Green terminal Block	1	$ 9.00	$ 9.00
	Fixed Bridge Jumper	1	$ 17.48	$ 17.48
	12 Gauge Wire	1	$ 35.00	$ 35.00
	Usb to Micro Usb	1	$ 7.99	$ 7.99
	Rj 12 Cable to usb	1	$ 19.99	$ 19.99
	Cable Housing	2	$ 24.00	$ 48.00
	Power Relay	1	$ 17.00	$ 17.00
Final Cost				$ 3,130.68

APPENDIX B – SPOOLER SHAFT DEFLECTION MATLAB CODE

Contents

Shaft Deflection Driver

```
clc
clear
```

checking xy plane deflections/slopes

```
%Forces
F=[0.00980665,0]; %magnitudes of forces are applied
Floc=[0.1807464, 0.3615182]; %location of where forces are applied
d=1*[.008,.0381,.008]; %diameters of the shaft
dloc=[0,.04419,0.3172714]; %locations of start of diameter change
Rloc=[.0035,.3580182]; %locations of bearings
L=0.3615182; %length of the shaft

[x1,y1,dydx1, M1, MdEI1, Ry, diam1, EI1]=ShaftDeflectionMetric(F,Floc,d,dloc,Rloc,L);
```

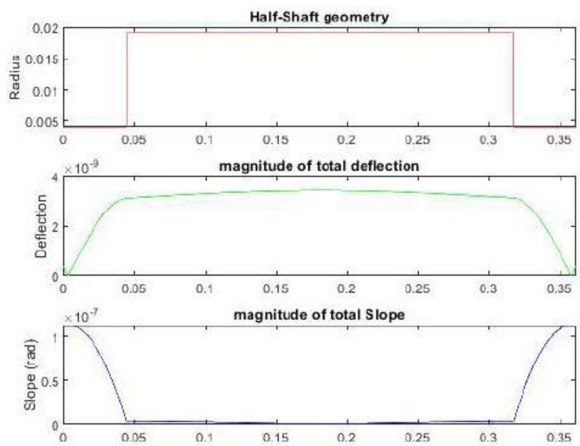
checking xz plane deflections/slopes

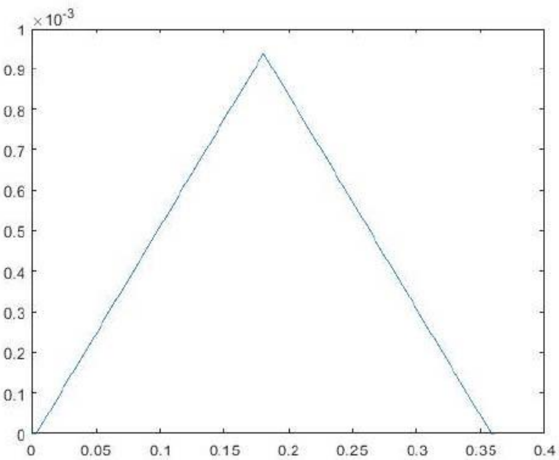
```
%Forces
F=[.004,0];
Floc=[0.1807464, 0.3615182];

[x2,y2,dydx2, M2, MdEI2, Rz, diam2, EI2]=ShaftDeflectionMetric(F,Floc,d,dloc,Rloc,L);
```

vector summing to find total slopes and deflections

```
x=x1; %should be same x value for both dimensions
y=sqrt(y1.^2+y2.^2);
dydx=sqrt(dydx1.^2+dydx2.^2);
M=sqrt(M1.^2+M2.^2);

figure
subplot(3,1,1)
plot(x,diam1/2,'r')
title('Half-Shaft geometry')
xlim([0,L])
ylabel('Radius')

subplot(3,1,2)
plot(x,y,'g')
xlim([0,L])
title('magnitude of total deflection')
ylabel('Deflection')
```

```
subplot(3,1,3)
plot(x,dydx,'b')
xlim([0,L])
title('magnitude of total Slope')
ylabel('Slope (rad)')


figure
plot(x,M)
```





APPENDIX C – SPOOLER FATIGUE CALCULATIONS

Shaft Design

For rotating shafts with an alternating moment load, constant torque load

Instructions: Provide numbers for values in green, and either (1) input a diameter, (2) use solver for values in red to solve for a diameter

diameter	0.314961	in	Smaller diameter
r	0.1574805	in	
I	0.000483055	in^4	Solid Shaft
J	0.000966111	in^4	Solid Shaft
Ma	0.0019	in-lb	Alternating
Tm	7.081	in-lb	Mean
nom bend stress	6.19E-04	ksi	
nom shear stress	1.15E+00	ksi	
Kt bending	1.4		
q	0.4		
Kf	1.16		
Kts	1.6		
qs	0.3		
Kfs	1.18		
max bend stress	7.19E-04	ksi	
max shear stress	1.36E+00	ksi	
static vm stress (yield)	2.00E+00	ksi	ductile assumed
vm alt stress	7.19E-04	ksi	
vm mean stress	2.36E+00	ksi	
Sut	8.542723	ksi	
Sy	6.077081	ksi	
Se'	4.2713615	ksi	
Finish	As-forged		

k factors			
ka	2.4984		
	a	12.7	*Reads ka sheet*
	b	-0.758	*Reads ka sheet*
kb	0.994661709	*Calculates kb based on size of rotating diameter*	
kc	1	kc=1 when VM equivalent stresses used	
kd	1	temperature	
ke	0.814	reliability	
kf	1		

Se	8.640E+00 ksi	
Goodman FS	3.620	
Gerber FS	3.621	Can set target value with SOLVER
Static Yield FS	3.040	

*Note, if Gerber FS is undefined in this spreadsheet, it is equal to the Goodman FS

APPENDIX D – SPOOLER GEAR RATION CALCULATIONS

Gear Stress Calculations

Variable	Pinion	Gear
ϕ, pressure angle	20	
N, # of teeth	10	120
P = (N/d), Diametral Pitch	16	
n, angular speed (rpm)	100	8.33333333
H, power (hp)	3.0213E-07	
F, face width of gear	1	
Hardness (Brinell)		
Qv, quality rating	5	5
N, Life	1.00E+06	83333.3333
Reliability, R	99%	99%
Temperature	-	
Material	PLA	
Loading	Smooth	
Crowned or uncrowned	Uncrowned	
Mounting	Canteliver	
gear ratio, m_G	12	
d = (N/P), Pitch Diameter	0.625	7.5
V, pitch line velocity (ft/min)	196.3495408	
W_t, Tangential Force (lb)	26.55375	

picked 1 Mil Cyl

S_F Bending safety factor	3.33	4.16
S_H Contact safety factor	3.22	2.80
S_H^2 Contact safety factor squared	10.385	7.862

Variable	Pinion	Gear
K_o, Overload Factor	1.75	
K_v, Dynamic Factor	1.000	1.000
B	0.91483	0.91483
A	54.7697	54.7697
Ks, Size Factor	1	1
Y		
Km, Load Distribution	1.2428988	
Cmc	0.8	
Cpf	0.05	
Cpm	0.8	
Cma	0.2636235	
Ce	1	
K_B, Rim Factor	1	1
J, Geometry Factor	0.21	0.3
σ = Bending Stress (psi)	4400.48	3080.34
S_t, tensile strength (ksi)	6.08	6.08
Y_N	2.04916	1.79273
K_T	1	
K_R	0.85	0.85
Allowable Bending Stress (psi)	14657.5	12823.3
Cp Elastic Coefficient	3500	
C_f, Surface Condition Factor	1	1
I, Surface Strength Geometry	0.32137398	
σ = Contact Stress (psi)	59350.2	59350.2
S_c	75000	75000
Z_N	2.16767	1.88607
C_H, Hardness Factor	1	1
A' or B'	N/A	
Allowable Contact Stress (psi)	191265	166418