Spring 2020

Zips Precious Plastics: Plastic Extruder

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ZIPS Precious Plastics Extruder

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Honors Research Project

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Project Title: Zips Precious Plastics - Plastic Extruder

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I. Introduction:

At the University of Akron, Mechanical Engineering students are required to complete Senior Design I and Senior Design II to meet the Accredited Board of Engineering and Technology (ABET) accreditation. The students that comprise this project group completed Senior Design I in Fall 2019 and completed Senior Design II in Spring 2020. The project selected for both classes was presented by the University of Akron's chapter of Engineers for a Sustainable World (ESW) which provided the opportunity and funding to development machinery used for their Zips Precious Plastic (ZPP) project.

ZPP follows a worldwide recycling project called Precious Plastics which was formed by Dave Hakkens in 2013. Mr. Hakkens created the Precious Plastics project as an open source format to collaborate with people around the world passionate about reducing, reusing, and recycling humans single use plastic. The open source format allows for new groups to easily build equipment essential to start a recycling workstation, while giving the same group the flexibility to revise the equipment to their own project requirements. In 2018, students at the University of Akron followed the Precious Plastics template and formed Zips Precious Plastics as a student run design group focused on bringing a sustainable focus to the Akron area by creating a small scale on campus plastic recycling workstation. The workstation will have a process of collecting, sorting, and cleaning the plastic before eventually recycling it. The workstation will have machinery that will transform single use plastic (i.e. water bottles, milk jugs etc.) into innovative and reusable products. The new products will educate the Akron community about the importance of recycling while also making them aware of the plastic pollution in the community. The machinery in the workstation consists of a plastic shredder, a compression machine, an injection molding machine, an extrusion machine, plus additional machinery and equipment necessary to educate students on and off campus about the importance of reducing, reusing, and recycling single use plastic. The engineering students in this design group chose to design and develop a plastic extrusion machine with a specific focus on recycling 3D print filament. The team used the Precious Plastics tutorial of an extruder as a basic understanding before conducting further research to create an extruder focused on 3D prints.

The overabundance of failed 3D prints and unused 3D print filament spools are a growing problem in the Akron area schools and at the University of Akron, now that 3D printing technology is growing increasingly popular. As students and instructors learn to operate the new equipment, they make mistakes with their prints. In some cases the printers can also malfunction which results in a failed print. Student design groups at the University of Akron utilize 3D printing technology to create prototypes and actual components for their projects. Teachers in the Akron area discard 3D print filament spools in the waste bin which will end up building in a landfill. These three examples of end life of 3D print filament accompany many others that build up plastic pollution. The 3D prints are thrown in a landfill due to a number of factors, but mainly because of the lack of recycling centers in the Akron area that will collect the plastic to reuse and recycle. Zips Precious Plastics and the plastic extrusion machine senior design group created the extrusion machine to provide a means of collecting and recycling the plastic.

A. Background

The design and creation of the plastic extrusion machine allowed the project group to utilize the engineering skills they gained in the classroom and apply them to the project. The team followed engineering design methodology taught in the Concepts of Design curriculum and outlined in the textbook Engineering Design by Dieter and Schmidt. Generally, the team started with a preliminary design brief followed by the conceptual design, embodiment design, and concluded with a detail design. During the conceptual design phase, the team researched extrusion machines and brainstormed numerous designs. The embodiment design process is where the team structured the selected design that is selected from the conceptual design. Finally, the detailed design process is where the part drawings, bill of materials, and a cost estimate are made in preparation for manufacturing the design.

B. Preliminary Design Brief

There is a need for a plastic extrusion machine that will heat particles of single-use plastic to its melting temperature and create a string of plastic. The plastic to consider is thermoplastics that are similar to those recycled in small scale plastic recycling workstations.

II. Conceptual Design

A. Expanded Design Brief

The plastic extruder is desired to be mobile and light enough to place on a tabletop if possible. The extrusion screw must transfer material down the barrel and melt it by the time it exits out of the nozzle. The electronics of the machine must be able to be powered from any residential power source (120V). The power of the machine must not make the extruder prone to any jams. If any part of the machine is able to be constructed from recycled parts, every attempt should be made to do so.

B. Function Structure Diagram

A functional decomposition diagram is useful for breaking down a complex project into smaller, simpler components. Having simpler components allows for more creativity in the design of the project because different designs can account for each component. During the first steps in the conceptual design phase, the group made use of resources on campus and within the greater Akron community to gain insight into the extrusion process, thermoplastics, and how the group could take advantage of the growing 3D printing community to create more sustainable solutions. The team met with Jeff Smith from Bounce Innovation Center located in downtown Akron to discuss how they are using 3D printers in their new makerspace. The group toured the facility and talked about the project scope and goals. Jeff has many years of experience working with and building 3D printers. He was able to provide useful information to consider when dealing with thermoplastics and the various materials used in the 3D printing process. The group then met with Dr. Todd Lewis in the National Polymer Innovation Center at The University of Akron to learn about the main components in industrial extruders and to see how they worked first hand. Dr. Lewis took the group on a tour of different facilities and showed multiple types of extruders ranging in size and abilities. The information Jeff Smith and Dr. Todd Lewis provided through their own experiences working with 3D printers, thermoplastics, and the extrusion process helped the group to hone in on how the team would proceed. The function structure diagram depicts how material is transferred and how energy affects the system.

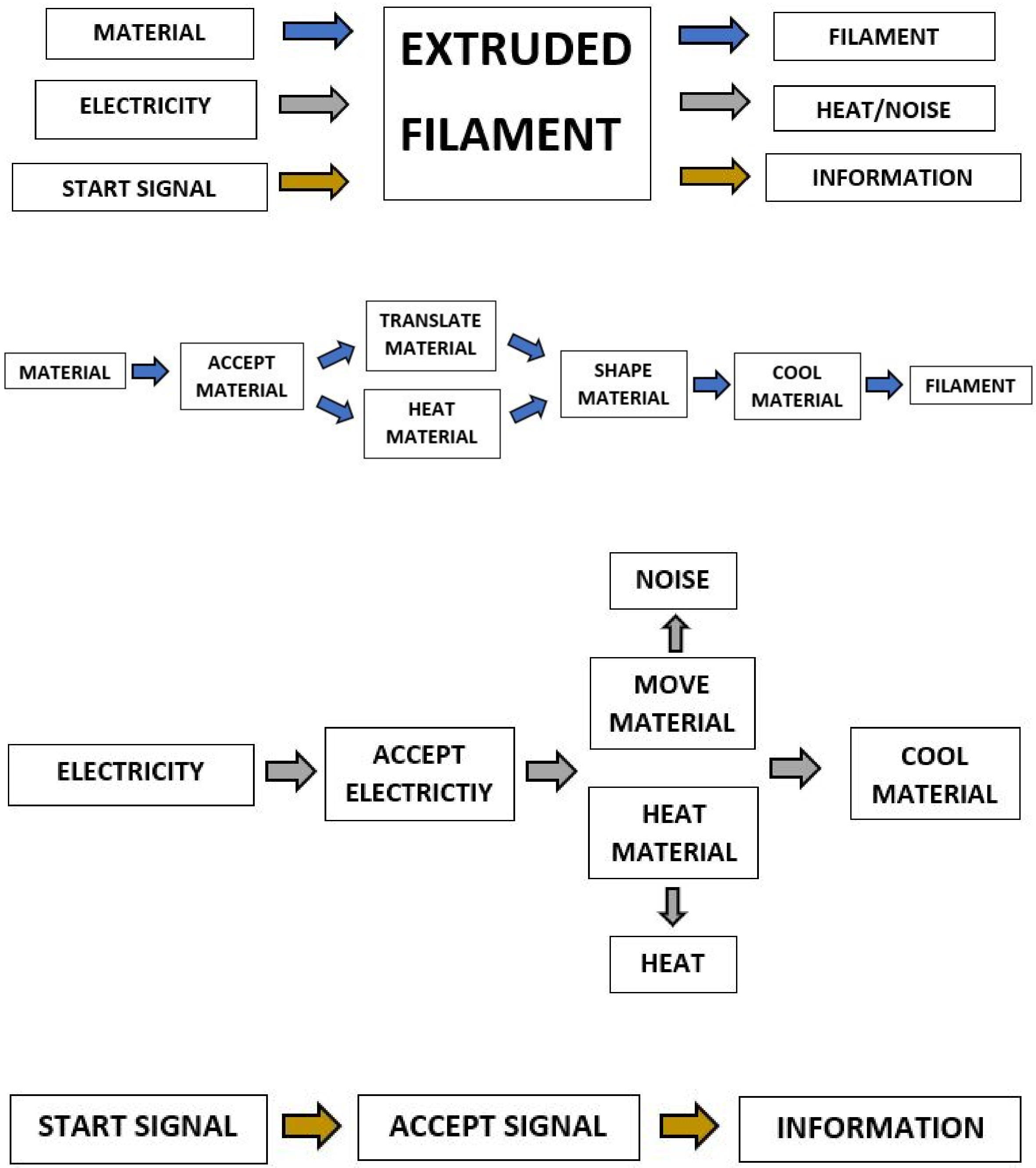

Figure 1. Function Structure Diagram

C. Morphological Chart

Creating a morphological chart allowed the exploration of several new ways the multidimensional problem could be solved. The design problem was divided up into several sub-problems such as frame material, hopper design, cooling system, heating system, collection method, motor selection, and plastic transportation method. These sub functions were refined based on information gathered from the meetings the group had had with Jeff Smith and Dr. Todd Lewis. One of the main goals was to simplify the design in a way that would be easy to assemble, operate, and maintain over time. Research on the internet was conducted throughout the design process to better understand how others were able to achieve similar results and to gain further insight to the extrusion process. Multiple meetings and brainstorming sessions took place to further discuss design ideas in depth. Solution screening was performed to eliminate ideas that were unfeasible based on available resources and project goals. Multiple solution concepts to these sub-problems were formulated and placed in various combinations together to be evaluated , shown in Figure 2.

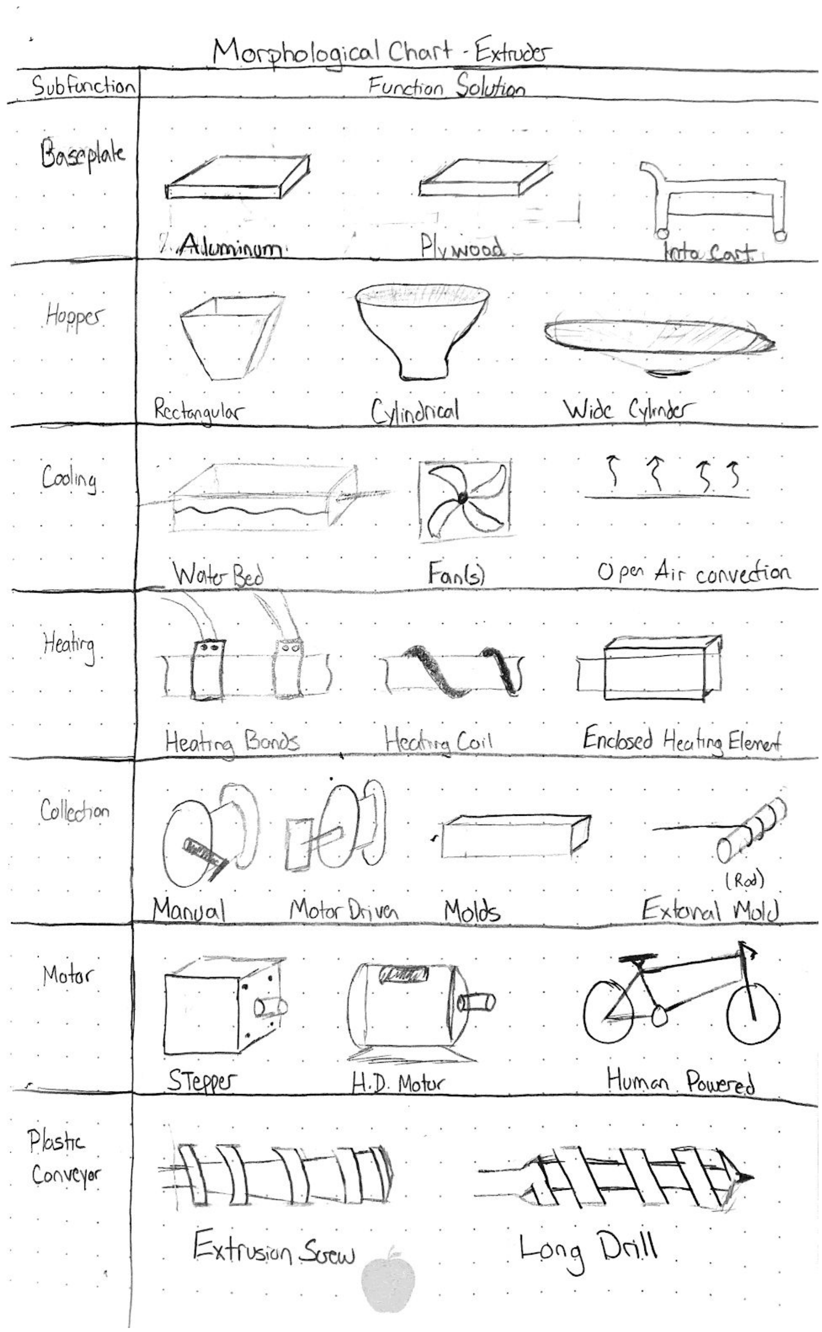

Figure 2. Morphological chart of the extruder

D. Concept Sketches

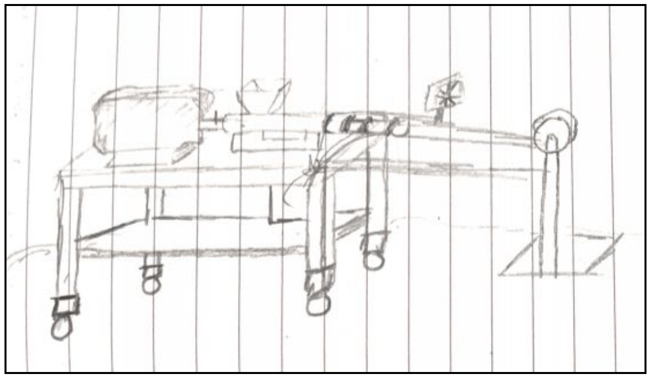

Figure 3a. Concept sketch reusing a cart with spooling subsystem separate from extruder

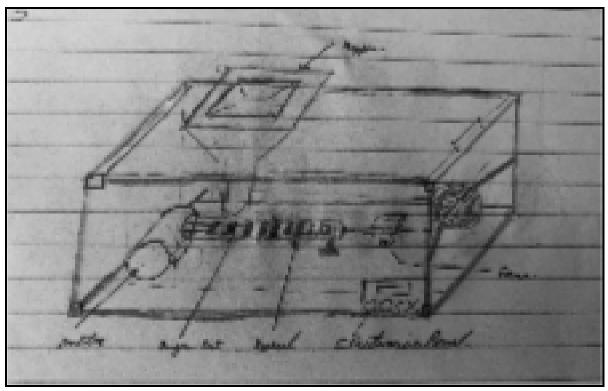

Figure 3b. Concept sketch of compact extruder

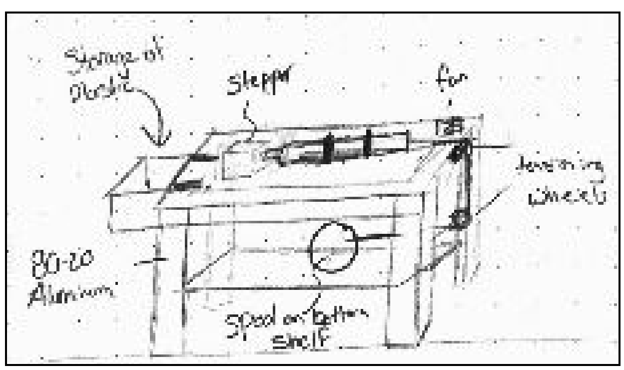

Figure 3c. Concept sketch using stepper motor and 2 pulleys for spooling

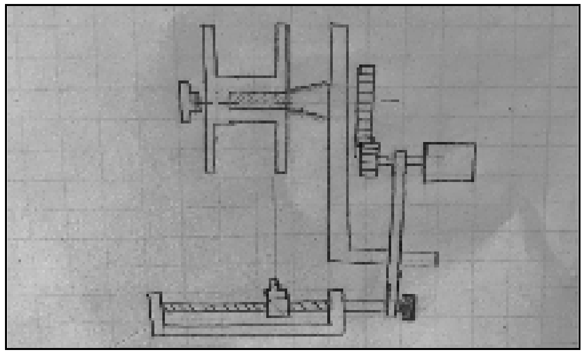

Figure 3d. Top down concept sketch of spooler with guiding mechanism

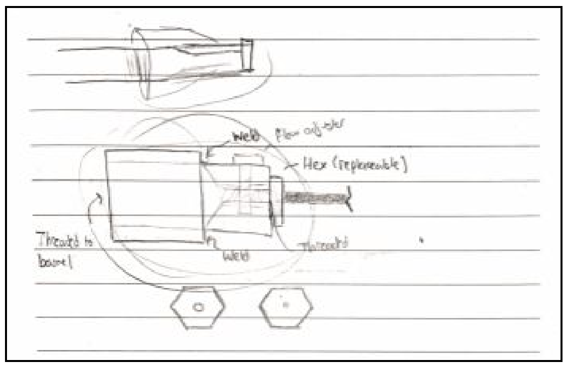

Figure 3e. Concept sketch of nozzle with different bolt configurations

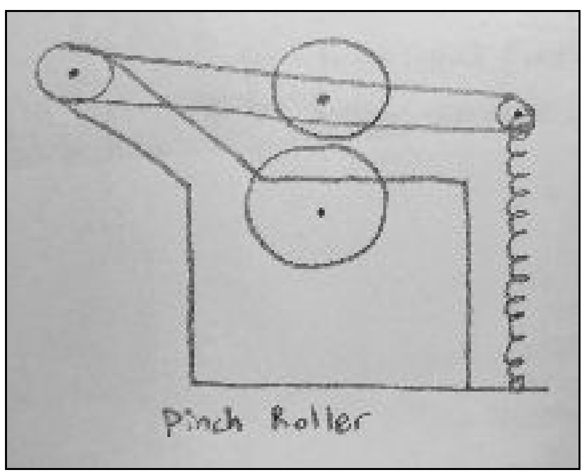

Figure 3f. Concept sketch of pinch roller to control filament diameter

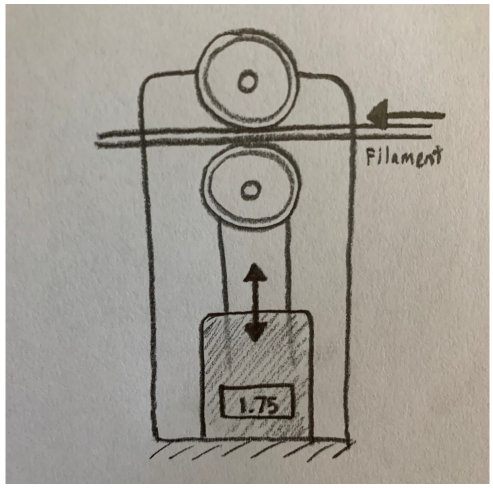

Figure 3g. Concept sketch of filament diameter sensor

E. Objective Tree

To determine weighting factors, a hierarchical tree called an objective tree was constructed. The different levels of the criteria will assist in properly ranking the importance of each criteria. From the objective tree, it was found that the quality of the process was important along with the safety. The low cost of the machinery will also be an important factor due to the project being student funded. During the design process, the objective tree will help aid the team with critical decisions.

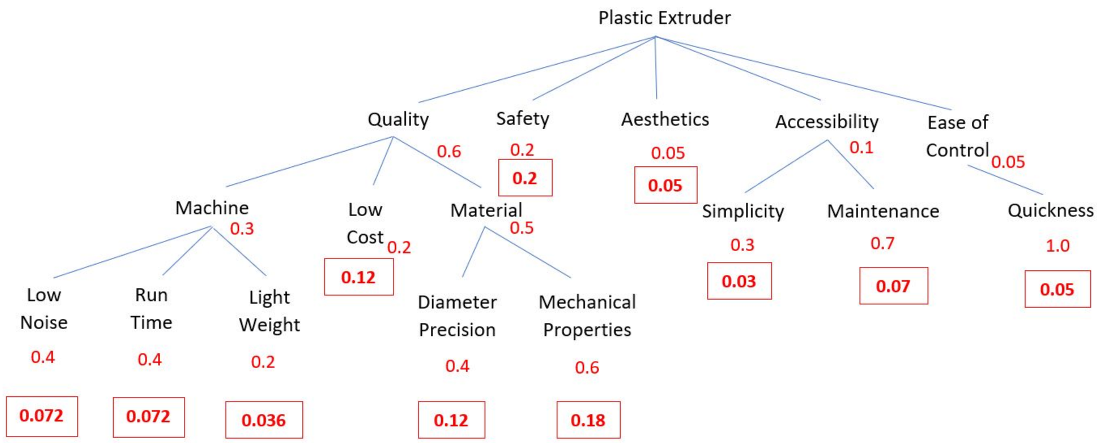

Figure 4. Objective Tree

F. Weighted Decision Matrix

From the weighing factors determined in the objective tree, the weighted decision matrix is a method employed to rank to what degree a certain design concept meets the criteria. The weighted decision matrix showing the procedure for the selected design is shown in Figure 5. The design columns have two separate columns with the left being a scale from 1-5 evaluating the design according to the evaluation criteria. The right column takes the product of the weighting factor and the evaluation criteria. The right column is summed and compared with other designs. The selected design has the largest sum due to the selection of a stepper motor that drives the screw rather than a 120V motor and the selection of a drill bit rather than an extrusion screw. The choices were made due to the cost of both the 120V motor and extrusion screw which would exceed the allocated budget for the extruder. The team was able to salvage a NEMA 34 stepper motor from another design team that was not in use. Motor specifications can be seen in the appendix. Early on in the conceptual design phase the team understood the importance and advantages of using a compression screw for extrusion applications. Because of this the team spent time researching and selecting designs that would be best for the project's design goals. A general purpose extrusion screw consisting of three main zones was selected. Calculations for compression ratio, length to diameter ratio, pitch, channel depth, and flight thickness were all conducted. Once these calculations were performed, a model was designed in SolidWorks. Unfortunately the university machine shop did not have the capabilities to make the part. The team then tried to source the part out to multiple compression screw manufactures but the prices were all well beyond available resources. Because of this, a general purpose drill bit that met diameter specifications was purchased. The stepper motor and drill bit will allow for the extruder to perform the task, provide an excellent educational opportunity for students in the Akron area that interact with the machine, and allow for experimenting with different motor speeds.

Evaluation Criteria	Weighting Factor	Design A	
Machine Quality	0.072	4	0.288
	0.072	3	0.216
	0.036	5	0.18
Low Cost	0.12	4	0.48
Material Quality	0.12	5	0.60
	0.18	5	0.90
Safety	0.20	5	1.00
Aesthetics	0.05	4	0.20
Simplicity	0.03	3	0.09
Maintenance	0.07	4	0.28
Quickness	0.05	3	0.15
Sum	1.00	4.384	

Figure 5. Weighted Decision Matrix

III. Embodiment Design:

A. Schematic Diagram

Final decisions produced from the conceptual design served as the starting point to creating a model of the filament extruder. A methodical approach was taken when designing the sub-assemblies and components to ensure the extruder would be structurally supported and could be assembled efficiently. Important considerations such as how physical components would be machined, fastened together, and supported were made throughout the designing process. The schematic shown below in Figure 6 represents the architecture of the product design. It shows the layout of all the subassemblies that are able to fit in an area of 36”x18”x12”.

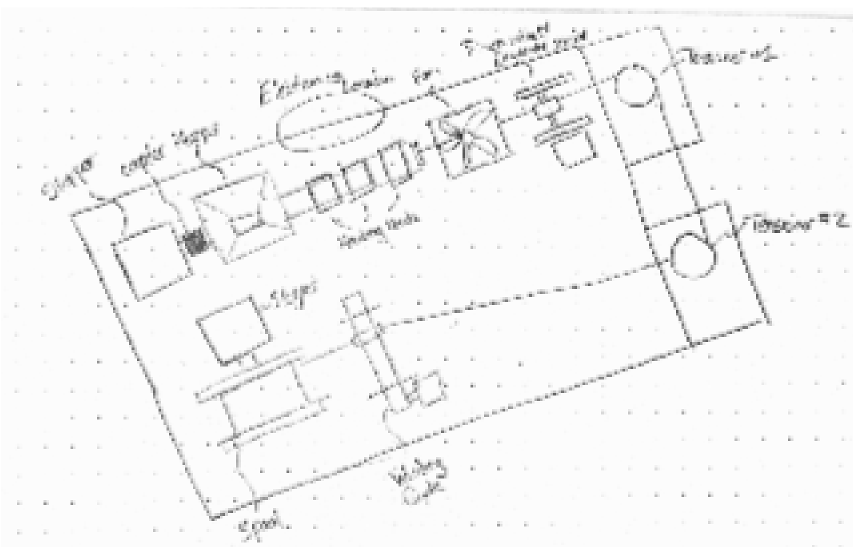

Figure 6. Extruder Assembly Schematic Diagram

B. Configuration Design

Within the extruder assembly a variety of connections were used as shown in Figure 7. Welding connections were used in the construction or the support for the barrel and hopper. These two components are expected to not move or be easily tampered with, thus the selection of a more permanent connection method. Many of the other mounts of subassemblies such as the motor, fan, pinch rollers, diameter sensors, spool winder, and winder guide used bolt connections into the base board. With a more temporary connection method these components are modular and able to be adapted to address new updates for added capabilities of the extruder.

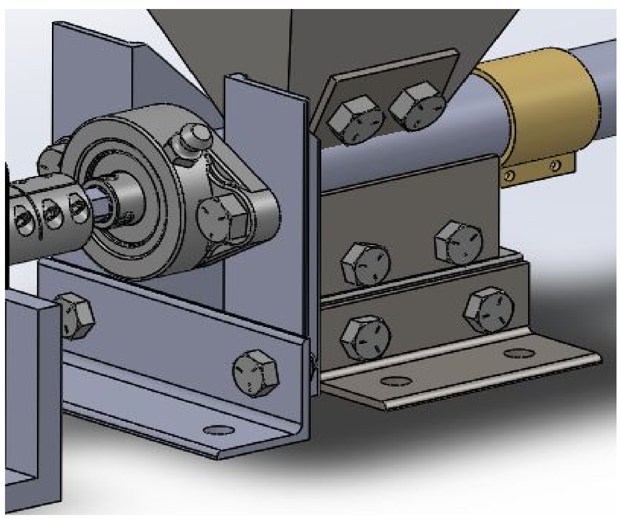

Figure 7. Extruder Assembly Connections

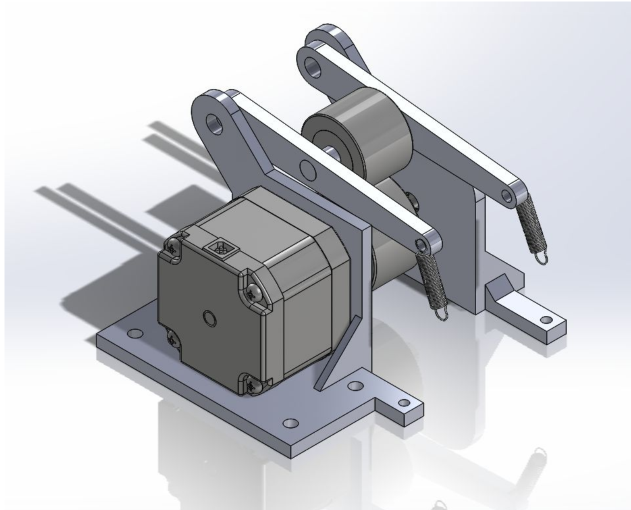

Figure 8. Pinch Roller Assembly Embodiment

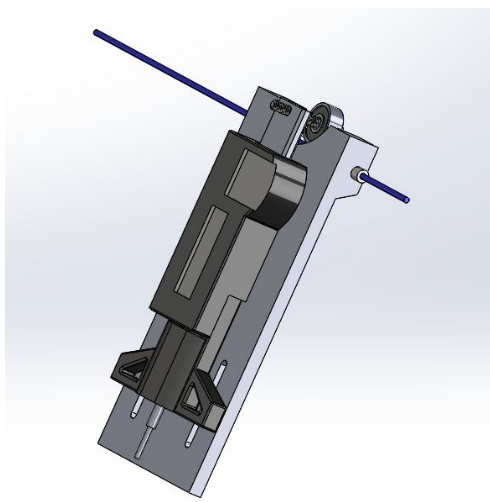

Figure 9. Filament Diameter Sensor Embodiment

C. Embodiment Rules and Principles

During the embodiment design phase there are three basic guidelines to follow; clarity, simplicity, and safety. These allow the technical functions to be fulfilled while keeping the cost economically feasible, and maintaining safety to the user along with the environment.

Clarity: The idea of clarity is to keep seperate functions from interacting in undesired ways. The extruder has five main functions; loading, heating, moving, cooling, and spooling the material. While all of these functions need to be done at the same time, they are kept separate so they can be adjusted as needed. Loading of the material is done by hand. The material is loaded into the hopper where it awaits the screw to move it along the barrel. The heating bands are connected separately and heat the barrel and material. The motor turns the screw, moving the material through the barrel. The motor only controls the screw and rotates it with no transverse movement. The cooling system consists of a fan that cools the material once it leaves the barrel. Finally the material is pinch-rolled and spooled.

Simplicity: The goal is to keep the design simple by reducing the number and complexity of the components. The extruder design accomplishes this by having no redundant components. Each function is necessary to fulfill the final outcome of taking plastic and turning it into usable 3D printing filament.

Safety: It is crucial to keep the design safe for the user along with the environment. There were many factors to consider when designing the extruder and components. The barrel will have insulation to protect the user from being exposed to too much heat. The barrel is mounted with 3/16" steel angle and tubing that will hold the barrel in place and it will not experience excessive deflection when being used. The hopper will have a grate large enough for the material to fit through while keeping foreign objects from reaching the rotating screw. The extruder will be used under a ventilation hood in order to protect the user from being exposed to any fumes that may come from the plastic melting. The machine itself is helping the environment by taking plastic that would end up in a landfill and turning it into a usable product. More safety features are discussed in the Failure Mode and Effect Analysis portion.

D. Failure Mode and Effects Analysis

At the junction between the motor shaft and screw shaft a clamping shaft coupling was chosen to protect the motor from a potential jamming torque. The clamping coupling also provides more holding torque than its alternative, set-screw couplings. Near the base of the screw shaft, a ball bearing flange is mounted by two-bolts to support the screw. This element of the system protects against radial loads. A concentric alignment between the screw and the barrel is important to maintain a consistent clearance inside of the barrel.

Precautions are also required for the operation of heating up the barrel. First, operators should not place anything flammable or any items that can be burned near the heating bands and barrel. Operators of the machine should not touch the barrel while the machine is running or before the machine has time to cool down. The assembly of the extruder will have insulation on the barrel to cover the band heaters so failure or injury does not occur. Due to multiple components that require a draw of electricity it is important to take precautions so a circuit overload does not occur for the system. Since one of the design goals is for educational purposes, it is expected to run in residential sources of electricity. The design team limited the number of band heaters needed for the extruder to 3 and individually wired each to a circuit breaker. The limit to 3 band heaters is to cap the current that will be required to run the system. The circuit breakers are an extra precaution taken to trip excess current before damage occurs on the system or source of electricity. A circuit box will be placed on the assembly that will house the circuit breaker.

To ensure the machine works correctly, only approved materials shall be placed in the extruder. If materials other than approved plastic or cleaning supplies are placed in the extruder, components such as the screw, die, motor etc. may be damaged. Additionally, while operating the machine, it is recommended to make a homogenous melt of materials. Meaning, when extruding PLA, only PLA should be put in the extruder.

E. Material and Manufacturing Process

Once a final model of the extruder assembly was created in SolidWorks, drawings for each of the components were made. These drawings were necessary and required in order to make the physical components in the university's machine shops. The students utilized the university machine shops to fabricate and machine necessary components. By working in the machine shop the team was able to apply classroom concepts directly to hands-on applications. The full time machinists served as an excellent resource throughout the machining process and provided insight that helped the team to work in a safe and effective manner. The team gained exposure to working with mills, lathes, vertical and horizontal band saws, grinders, drill presses, and sheet metal bending. Each of the parts were deburred when machining processes were completed so they would be safe to handle. Once each of the parts were cut and deburred, the angle and flat bar used to support the bearing and barrel were sandblasted to provide a smooth surface finish. Measuring devices such as rulers, compasses, and vernier calipers were used throughout the machining and fabricating process to ensure that the parts were made according to the specified drawings. Components that were machined included the barrel, extrusion nozzle, barrel support assembly, the hopper, and the bearing supports. When selecting material the group wanted to use lightweight solutions when possible without compromising structural or thermal integrity. For the supports of the extruder, the team looked for more sturdy options to ensure the bearing that supports the screw is supported properly, so low carbon steel was used for the supports. The hopper is made out of 1/16” sheet metal to allow for proper connections while remaining sturdy for operation. The barrel is a schedule 40 steel pipe to provide good machinability and good thermal conductivity. The baseplate was selected to be made out of plywood for its inexpensiveness and ease of mounting sub components. The extrusion nozzle was designed on SolidWorks and machined out of steel round bar provided by the machine shop. The nozzle consists of two female threads and a tapered section in the center to direct material towards the front of the nozzle. One end fastens onto the end of the barrel and the other end houses a ½” diameter bolt. A 2 mm hole was drilled in the bolt for the material to be extruded through. This die can be easily altered during the future testing phase if the hole diameter is not suitable to keep the filament within certain specifications.

For the majority of parts on the bill of materials, McMaster-Carr was the main supplier for ordering components used to build the extruder assembly. This distributor was chosen based on group members' past experiences throughout coop and on other projects. McMaster-Carr has a user-friendly website that consists of CAD models and has an excellent reputation for turnaround time. After purchasing the materials from each of the vendors the parts were machined by the engineering team in the University of Akron machine shop. Figures 10a-e below show team members in the university machine shop working on parts for the design.

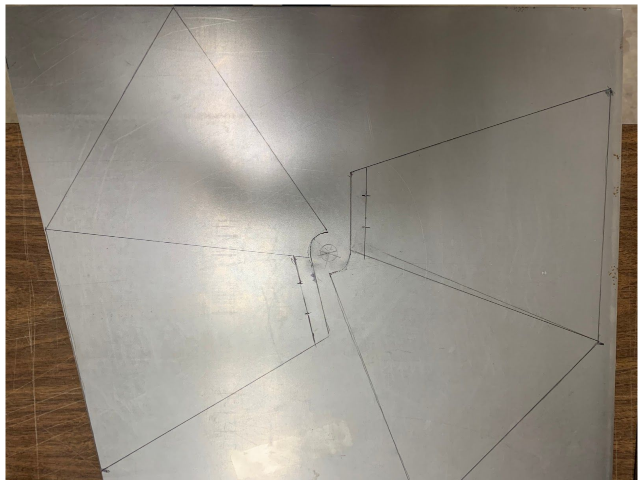

Figure 10a. Sketching the hopper on sheet metal

Figure 10b. Cutting sheet metal for hopper

Figure 10c. Drilling sheet metal for hopper

Figure 10d. Machining the nozzle

Figure 10e. Machining the barrel

F. Numerical Calculations

Compression Screw Design:

As previously mentioned, one of the most important components of the extruder is the screw used to translate material down the barrel. To better understand screw design, the group researched different designs used in industry today. Operating speeds, material type, and size all play a factor when selecting a proper design. After talking with Dr. Todd Lewis, various compression screw manufacturers, and researching designs on the internet it was determined that a general purpose compression screw made of a 4140 Steel Alloy with a Nitride or Chrome finish would be the best option for the design. General Purpose compression screws consist of three main zones throughout the usable length: the feed zone, the transition zone, and the metering zone. The feed zone consists of the smallest root diameter and carries material from the hopper down the screw. The root diameter remains constant until reaching the transition zone. The second zone is the transition zone which consists of an increasing taper root diameter. The increasing diameter in the transition zone causes an increase in pressure exerted on the material. This pressure results in shear forces on the material, aiding in the melting process. The metering zone is located near the discharge end and consists of a constant root diameter. The zone profiles also vary in length and typically follow a 50:25:25 ratio. Where the feed zone is twice as long as the transition and metering zones (Reiloy 2015).

Information regarding each of the main design criteria for a compression screw are discussed below.

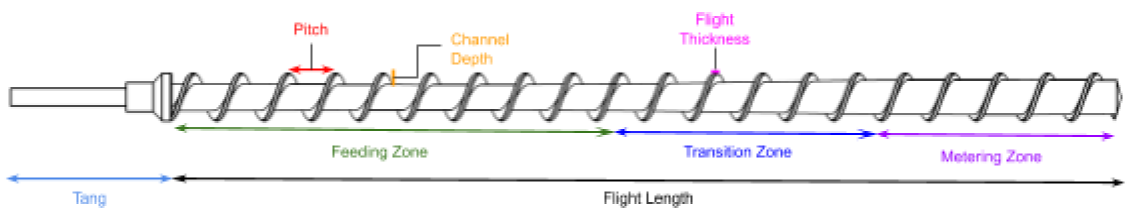

Figure 11. Compression Screw Terminology

L/D Ratio: The length to depth ratio is the relationship in the flighted length of the screw to the outside diameter of the screw. These ratios typically range from 20:1 to 28:1 (Dynisco 2020). However the ratios can increase based on different applications. Because one of the main goals is to create a table top design the group opted for the smallest length to depth ratio possible without compromising performance. A 20:1 L/D ratio was selected for the screw design as it was the smallest recommended ratio.

Compression Ratio: Compression ratio is a parameter used in screw design to designate how much pressure will be exerted on the material as it travels from the feed zone through the transition zone, and into the metering zone. The compression ratio is calculated by dividing the feed zone flight height by the metering zone flight height. General Purpose compression ratios typically range between 2.2:1 to 2.8:1. The higher the compression ratio the more shear heat is produced. Amorphous materials tend to use lower compression ratios and crystalline materials tend to use a higher compression ratio (Concor 2020). Because of the different types of materials planned to be put through the extruder, the group decided on a conservative 2.5:1 compression ratio.

Channel Depth: Channel depth or flight height is also a key design factor. Flight height in the metering section is critical to optimum processing. The outer diameter of the screw never changes however the root diameter along the screw does vary which results in a different channel depth from the feed section to the metering section. Once metering flight height is determined, the flight height in the feed section can be calculated using the compression ratio (Reiloy 2015). The feeding zone flight height of 0.29” transitions to a metering zone flight height of 0.116”.

Pitch: The pitch of the screw refers to the distance from the front of one flight to the same location on the next flight. Although it can be altered, the pitch is typically the same length as the diameter and is referred to as a square pitch. The helix angle for a square pitch is 17.6568° (Reiloy 2015).

Flight Thickness: From resources maintaining a flight thickness that is 0.1 X the outer diameter of the screw flights will provide a balance between heat development and backward leakage (Concor 2020). With this calculation the group arrived at 0.082”

Based on the information and dimensions discussed above, a CAD model was created in SolidWorks for the part.

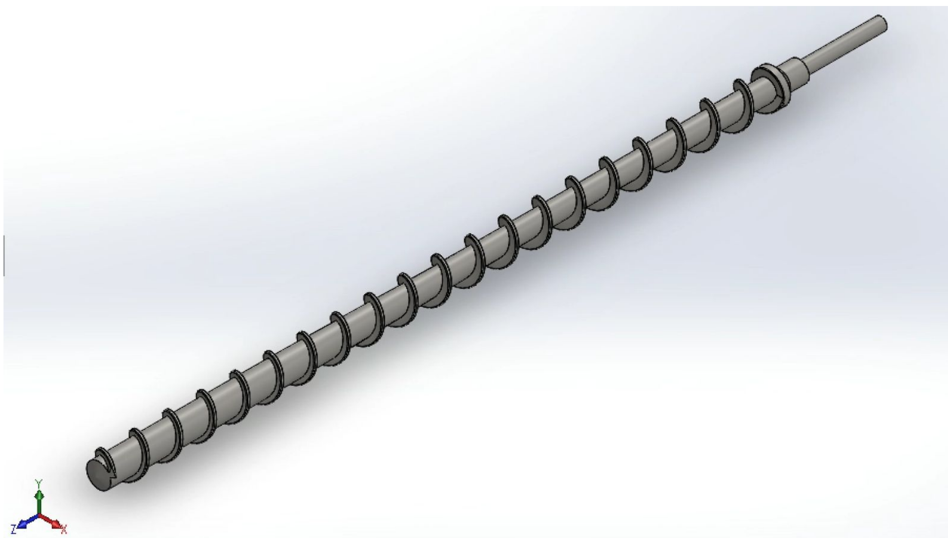

Figure 12. Zips Precious Plastics Compression Screw Design

Multiple conversations between group members and the on campus machinists took place to discuss how to machine the part. The group originally planned to have the compression screw manufactured in the University’s machine shop, but due to the complicated geometry, it was beyond on campus capabilities. Vendors located in Northeast Ohio and across the country were contacted to request quotes for the compression screw design. Unfortunately, all of the quotes to manufacture the design were beyond available resources. The solution to the problem was to purchase a drill bit that would meet specified dimensions. Although it will not provide the shear force that a compression screw would, the group was confident that it would successfully transfer material down the barrel. Further research online was done to compare similar designs and it was found that others were successful with this approach. Because of this, and the fact that the rest of the assembly was dependent on this decision, the group went ahead and purchased a drill bit. Figure 13 shows a detailed drawing of the compression screw design created for the filament extruder.

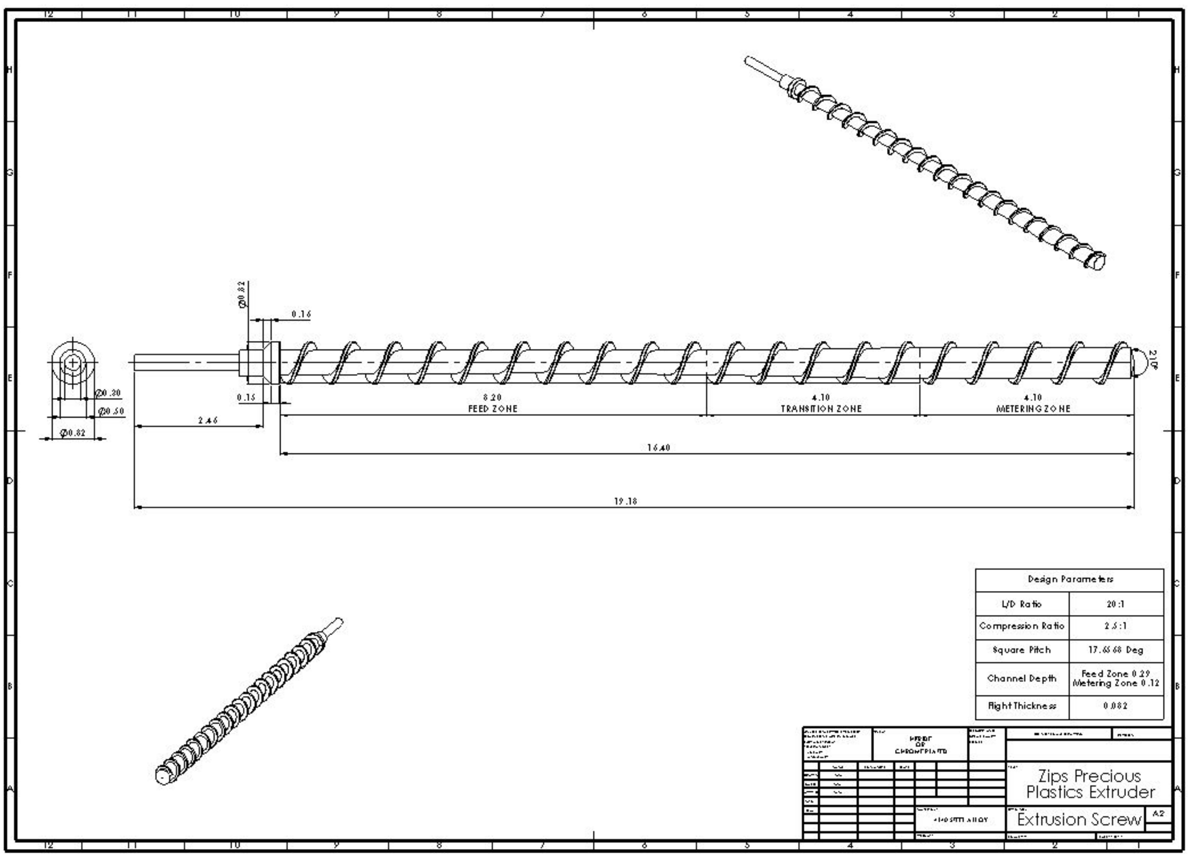

Figure 13. Detailed Design of ZPP Compression Screw Design.

Within the flights of the rotating screw the plastic particles are fed in at the start of the feeding zone by the hopper. A frictional force between the barrel and solid conveys the material while friction between the solids and the screw opposes this motion. The particles move forward due to drag flow, also known as Couette flow. During this movement the particles increase in temperature and pressure and form a solid bed which is visualized in Figure 14. Eventually this solid bed is melted due to friction and the heated barrel bands. The transfer of this heat through the barrel was investigated further. (Cavicchi 2019)

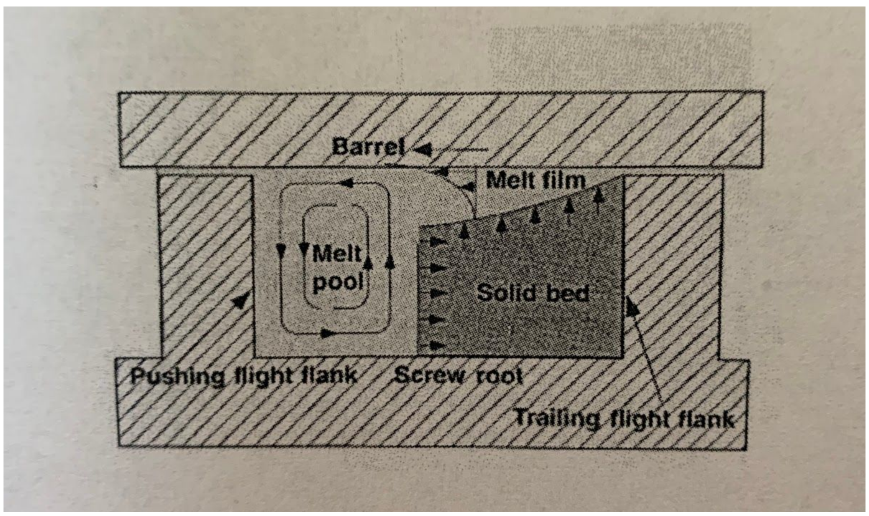

Figure 14. Extruder Melt Dynamics (Cavicchi, 2019)

Heat Transfer through Barrel Wall:

To better understand how heat is transferred through the barrel, concepts from page 69 in the Introduction to Heat Transfer textbook by Incropera, DeWitt, Bergma, and Lavine can be referenced. The group was planning to apply Fourier's Law of conduction once the system was up and running. These numerical calculations were to be compared to COMSOL simulations based on surface temperatures produced by the heating bands in the assembly.

The following assumptions were made for the problem. It is assumed that the heat transfer is one dimensional, steady state, and the path is over a constant cross sectional area. A schematic of the cross section of the barrel can be seen below.

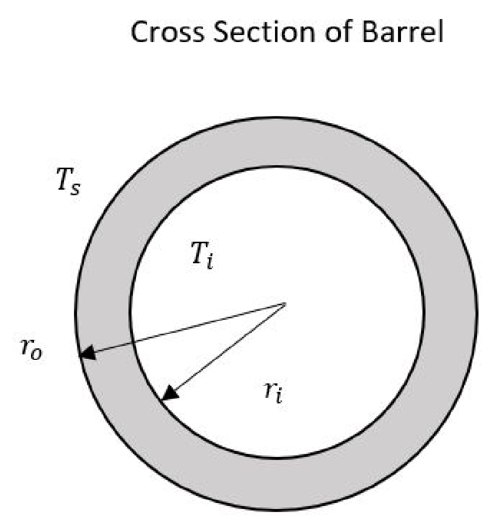

Figure 15: Cross section of Barrel for Heat Transfer Analysis

The governing differential equation for Fourier's Law of conduction can be seen below

$$q = -kA\frac{dT}{dr} \tag{1}$$

In this equation q represents the heat transfer, k is the thermal conductivity of steel, A is the surface area of a cylinder, dT is the change in temperature, and dr is the change in radius of the cylinder. The equation for the surface area of a cylinder is used to calculate the heat transfer of the system and can be seen below.

$$A = 2\pi rL \tag{2}$$

This equation will be inserted into the governing differential equation to solve for the heat transfer through the barrel.

Parameters

Constant Inside Surface Temperature $T_i = 473.15K$ (Polylactic Acid Melting Temp)

Constant Outside Surface Temperature (Recorded by Thermistor, when operational)

Thermal Conductivity of Plain Carbon Steel $k = 52.4\frac{W}{m\cdot K}$

Length of Barrel $L = 34.37cm$

Outside Radius of Barrel $r_o = 1.67cm$

Inside Radius of Barrel $r_i = 1.33cm$

The following steps show how the governing equation is manipulated to solve for the heat transfer with the given parameters.

$$\frac{q}{A}dr = -kdT \quad (3)$$

$$\frac{q}{2\pi L}\int_{ri}^{ro}\frac{1}{r}dr = -k\int_{T_i}^{T_o}dT \quad (4)$$

$$\frac{q}{2\pi L}ln\left(\frac{r_o}{r_i}\right) = -k(T_o - T_i) \quad (5)$$

$$q = \frac{2\pi Lk(T_o - T_i)}{ln\left(\frac{ro}{r_i}\right)} \quad (6)$$

Flow Rate:

It is important that the plastic exiting through the nozzle of the extruder is a fully molten string of plastic. Because of this, the rate of flow in the barrel as it is being conveyed via the screw must be controlled. Because the extruder is a unique design, it has its own equation for volumetric flow rate that depends on the geometry and speed of the screw. Equation 7. is for volumetric flow rate for extruders with an extruder screw where Q is the volumetric flow rate, D is the screw diameter, H is the channel depth of the screw, and N is the screw rotational velocity. The selected design for the project has a long drill bit that does not compress the material along the barrel, and thus the pressure flow is significantly less, so the selection of a stepper motor that controls the speed of the screw is selected to have that flexibility. Experimentation following the assembly of the extruder is required to optimize the screw speed and volumetric flow rate. Table 1. shows calculated values of volumetric flow rate by using values of a drill bit used in the design team's extruder. Figure A2 in the appendix shows the hand calculations and assignment of values for initially evaluating expected flow rate.

$$Q = \frac{\pi^2}{2} D^2 H N sin\theta cos\theta \tag{7}$$

Constants					Volumetric Flow Rate Table	
Variable	Value	Units	Value	Units	Screw Speed [RPM]	Q [ft^3/min]
Theta	32	deg	0.559	rad	5	0.0613
Screw Diameter	1	in			10	0.1226
Channel Depth	0.5	in			12	0.1471
					14	0.1716
					16	0.1961
					18	0.2206
					20	0.2451
					22	0.2696
					24	0.2941
					26	0.3186
					28	0.3432
					30	0.3677

Table 1. Values of flow rate according to flow rate equation. Optimization to be performed through validation in testing.

Constants					Volumetric Flow Rate Table	
Variable	Value	Units	Value	Units	Screw Speed [RPM]	Q [ft^3/min]
Theta	17.65	deg	0.308	rad	5	0.0064
Screw Diameter	0.82	in	2.083	cm	10	0.0127
Channel Depth	0.12	in	0.305	cm	12	0.0153
					14	0.0178
					16	0.0203
					18	0.0229
					20	0.0254
					22	0.0280
					24	0.0305
					26	0.0331
					28	0.0356
					30	0.0381

Table 2. Flow rate calculations using designed compression screw parameters

G. Layout Drawings

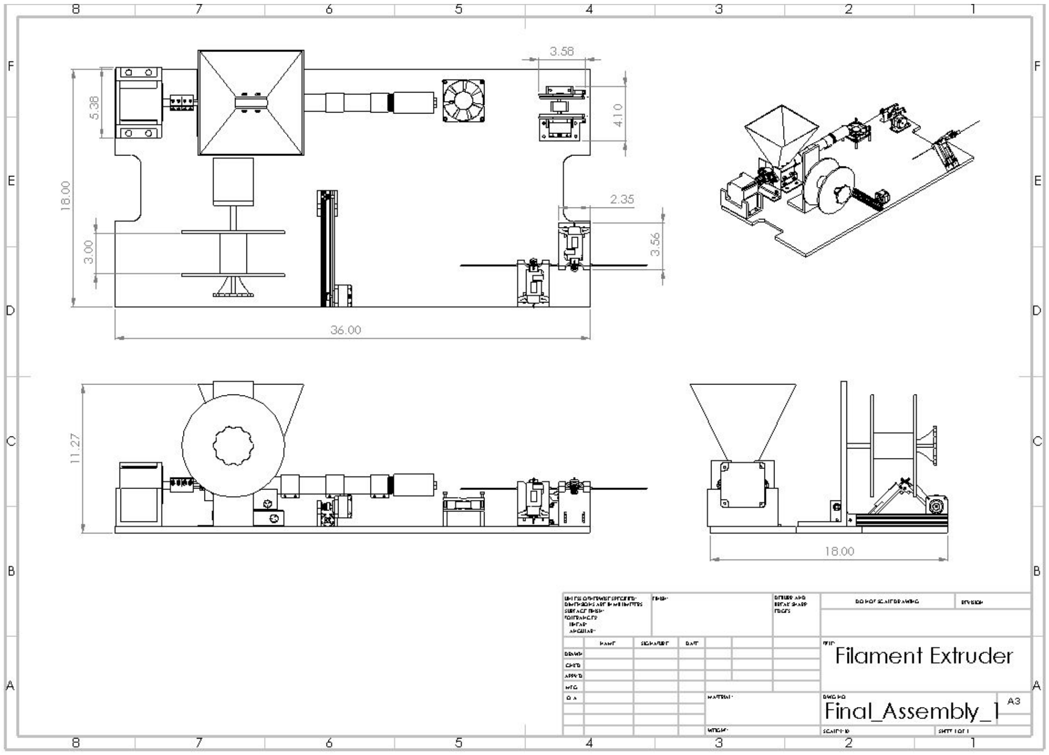

Figure 16: Layout drawing of filament extruder

IV. Detail Design:

A. Part Drawings

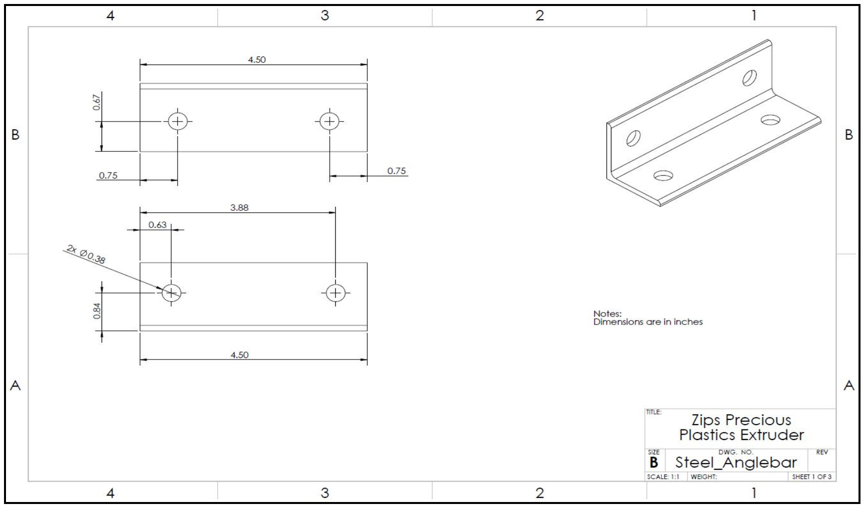

Figure 17a. Horizontal angle iron for bearing part drawing

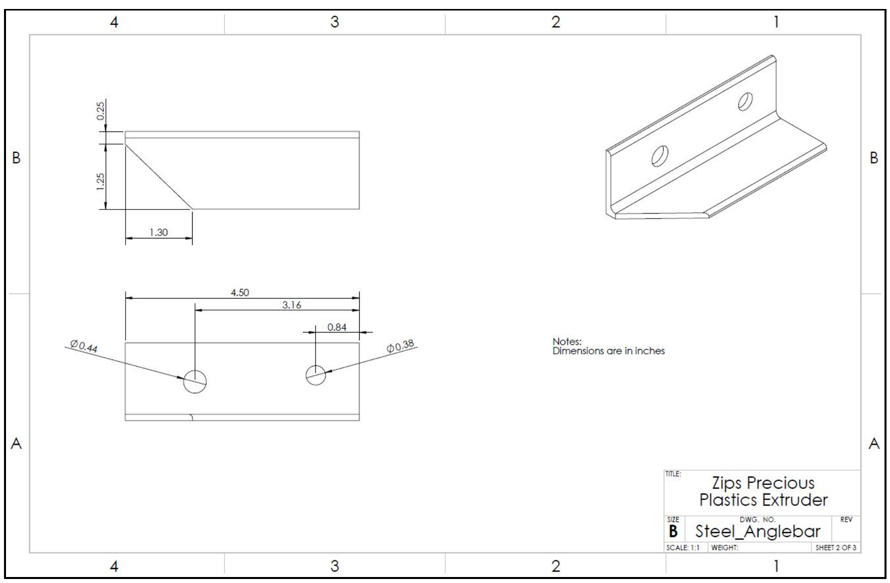

Figure 17b. Vertical angle iron for bearing (1) part drawing

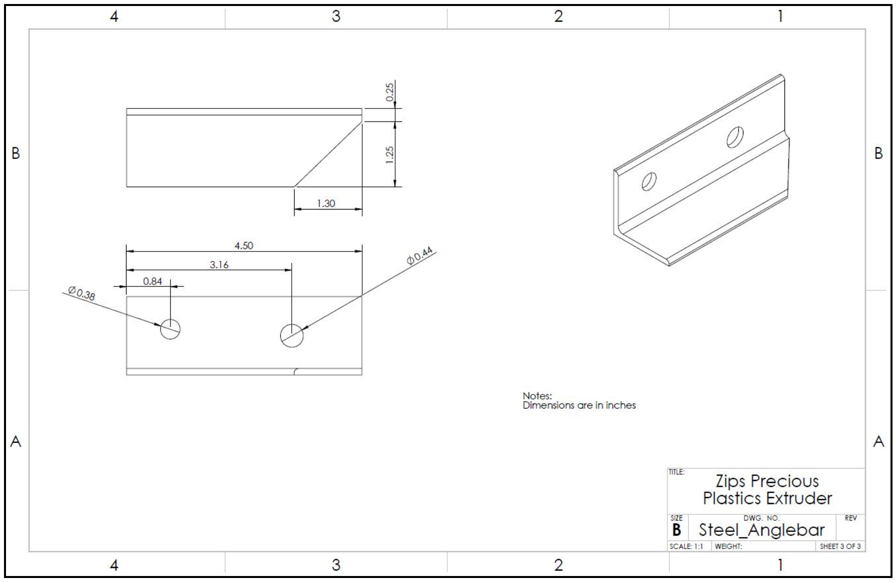

Figure 17c. Vertical angle iron for bearing (2) part drawing

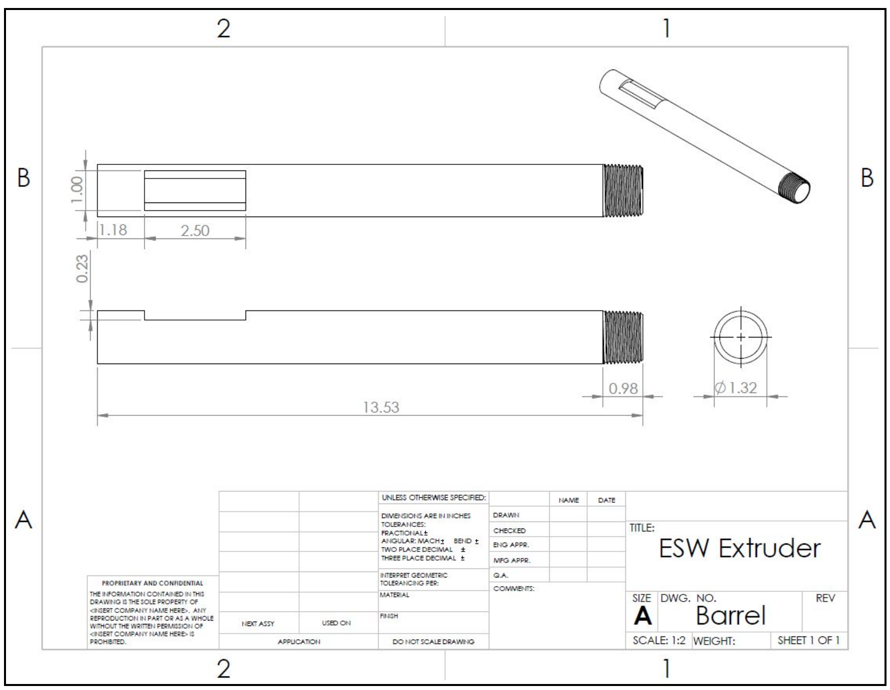

Figure 17d. Barrel part drawing

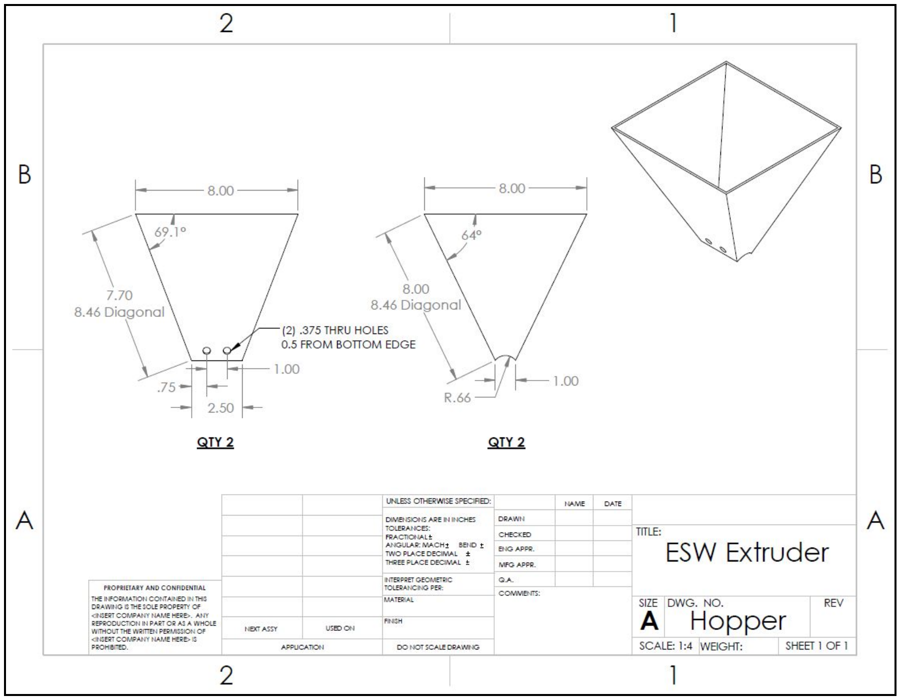

Figure 17e. Hopper part drawing

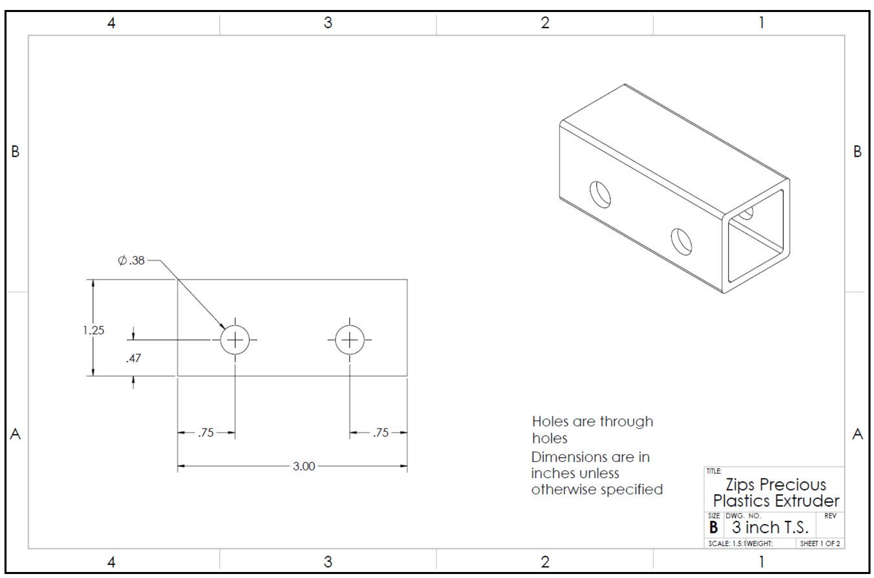

Figure 17f. 3” tube steel support part drawing

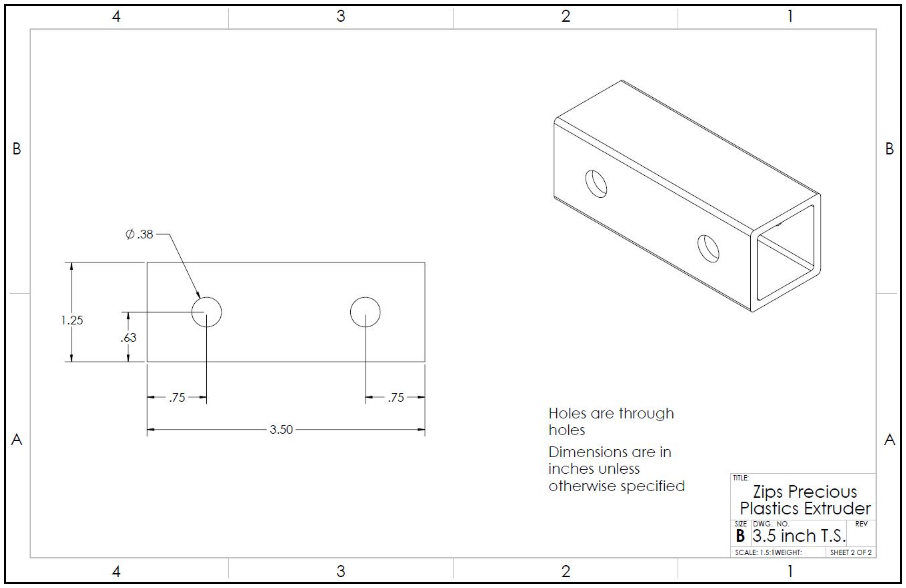

Figure 17g. 3.5" tube steel support part drawing

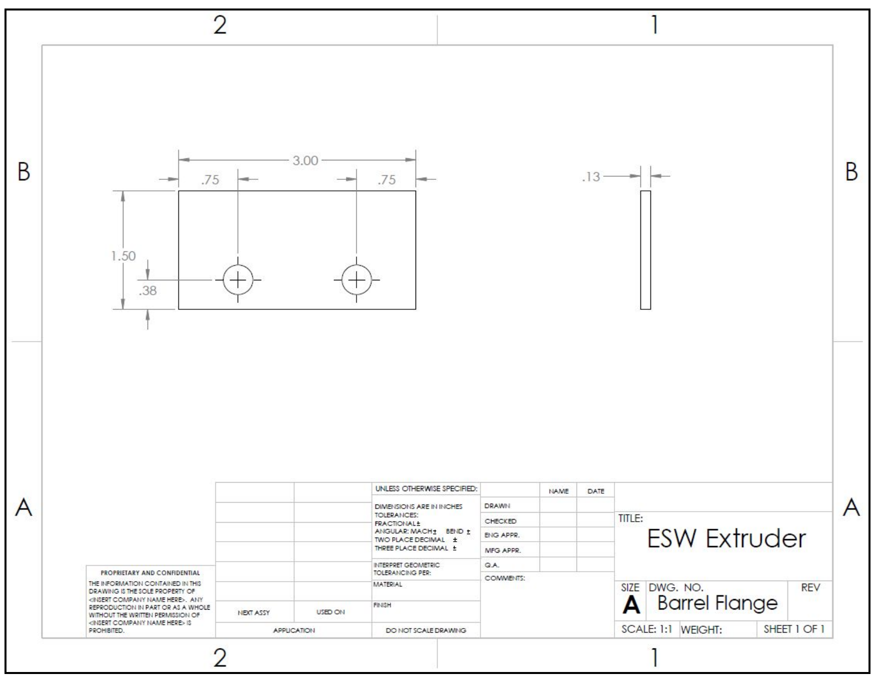

Figure 17h. Barrel flange part drawing

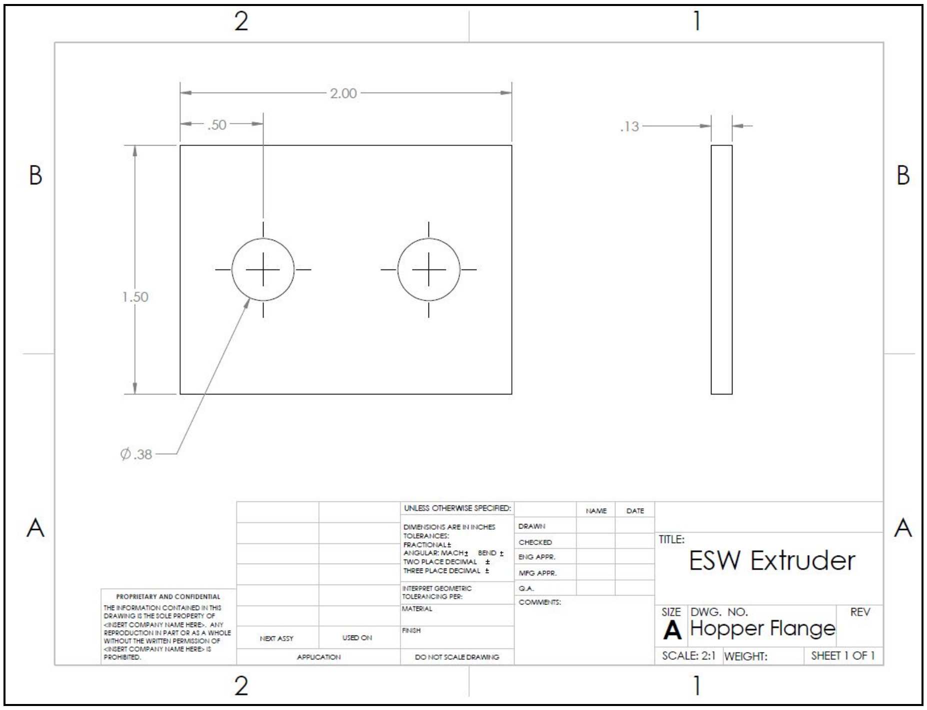

Figure 17i. Hopper flange part drawing

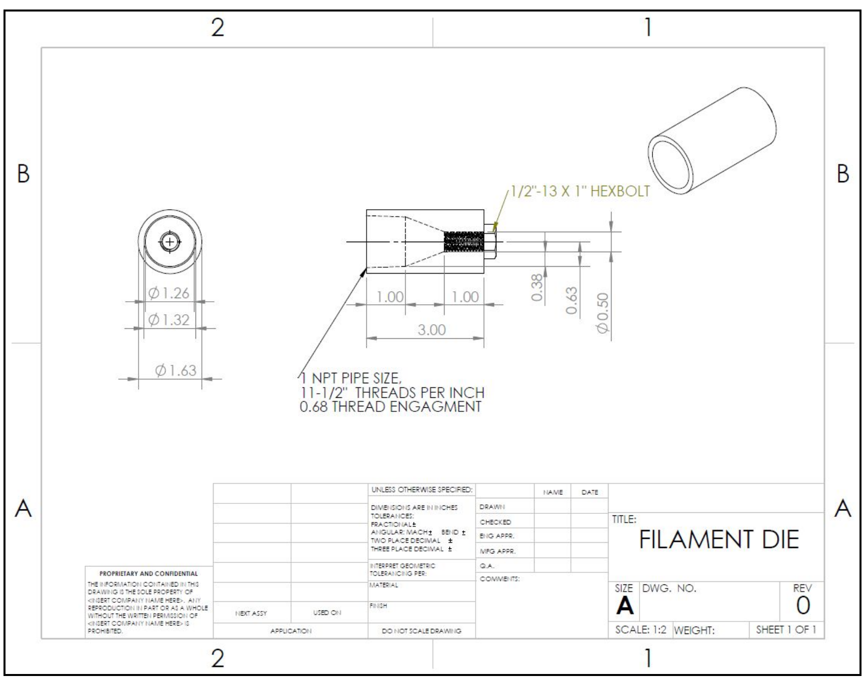

Figure 17j. Filament die part drawing

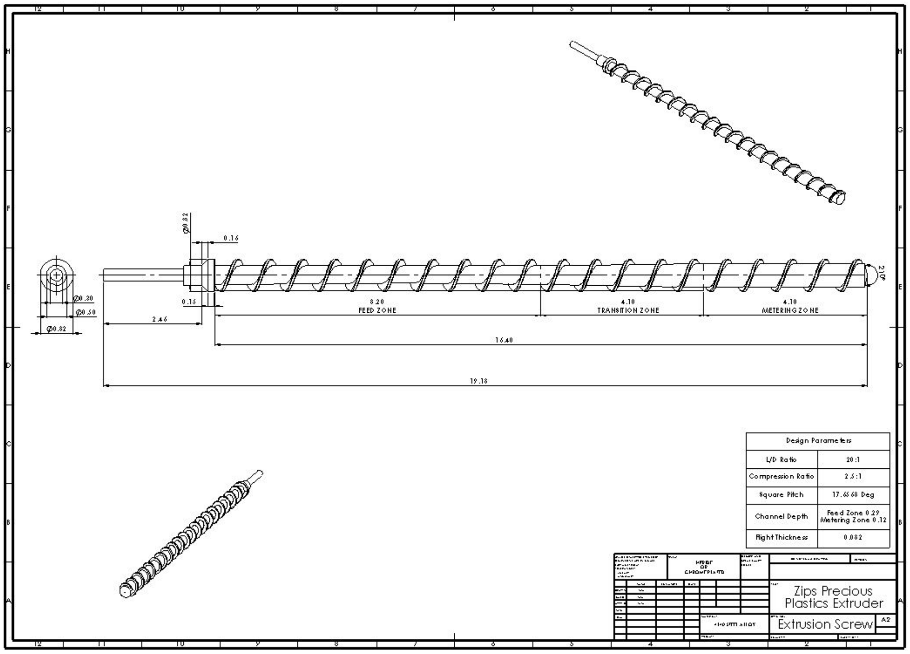

Figure 17k. Compression screw

B. Assembly Drawings

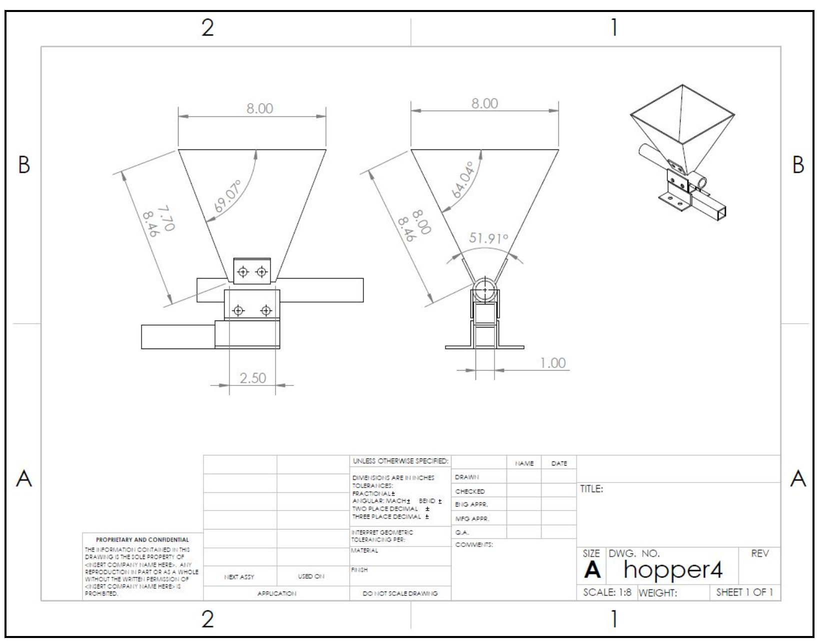

Figure 18a. Hopper assembly drawing

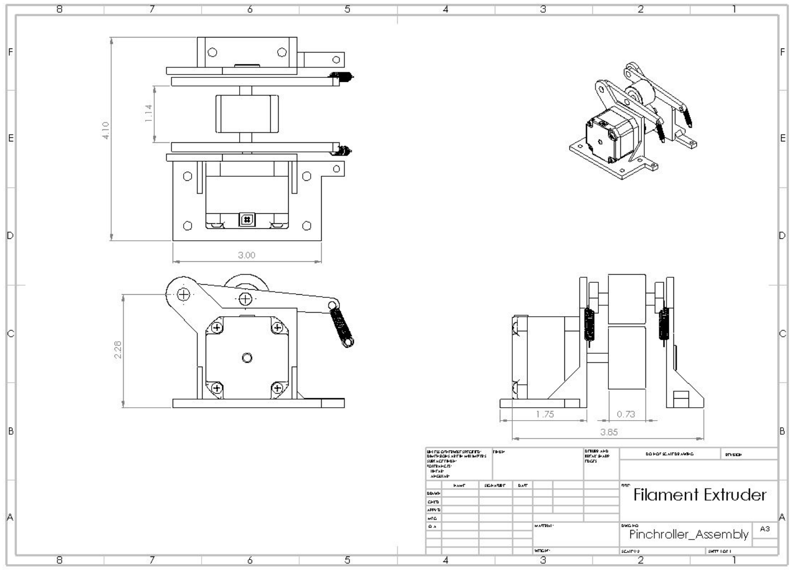

Figure 18b. Pinch roller drawing

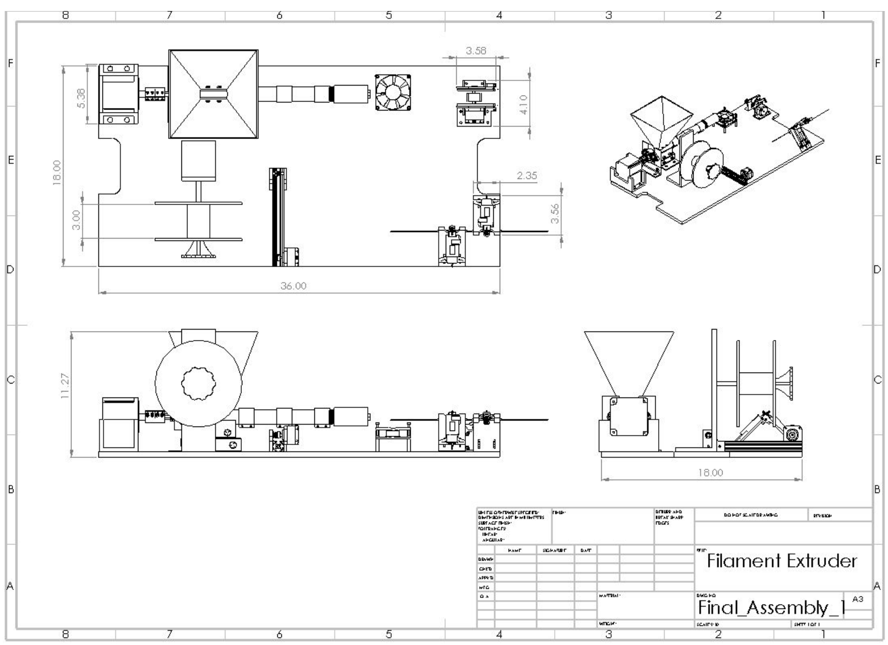

Figure 18c. Extruder assembly drawing

C. Bill of Materials

Category	Brief Description	Item Description	Supplier	Quantity	Price	Link	Ordered	Delievered
Motor	Stepper Motor	Nema 34 CNC Stepper Motor 4.5Nm (637oz.in) 5.5A 86x86x80mm Key Way Shaft	Stepper Online	1	$0.00	https://www.omc-stepperonline.com/n	x/xx	x/xx
	Driver	Y Series Digital Stepper Driver 2.4-7.2A AC18V-80V / DC 36V-110V for Nema 34 Motor	Stepper Online	1	$56.48	https://www.omc-stepperonline.com/di	3/4	3/9
	Microcontroller	Arduino Uno Rev3	Arduino	1	$22.79	https://store.arduino.cc/usa/	2/11	2/14
	Power Supply	SUPERNIGHT 12V 30A Switching Power Supply, 110-240 Volt AC to DC 360W Universa	Amazon	1	$20.59	https://www.amazon.com/SUPERNIGI	3/4	3/5
Barrel & Screw	Auger	1 in. x 18 in. High Speed Steel Long Auger Drill Bit	Lowes	1	$53.40	https://www.lowes.com/pd/IDEAL-Nail	2/12	2/14
	Barrel	Standard-Wall Steel Pipe Nipple - Threaded on One End, 1 NPT, 36" Long	McMaster Carr	1	$29.88	https://www.mcmaster.com/7750k393	2/11	2/11
	Bearing	1/2" Diamater Shaft (2) 7/16 Bolt Holes (3" spacing between bolt holes)	McMaster Carr	1	43.64	https://www.mcmaster.com/5968k71	x/xx	x/xx
	angle		McMaster Carr	3ft	$10.17	https://www.mcmaster.com/angles	2/11	2/11
	coupler	Clamping Shaft Coupling	McMaster Carr	1	31.19	https://www.mcmaster.com/61005k33	x/xx	x/xx
Frame	Cart	AV Cart	Surplus	1	$0.00	N/A	x/xx	x/xx
	Barrel Support	.12" thick 1 1/4" x 36" steel tube	McMaster Carr	1	$20.41	6527K45	x/xx	x/xx
	Flange	3/16" thick 1 1/4" x 24"	McMaster Carr	1	$28.68	9517K398	x/xx	x/xx
Heating	Band	2 of Nxtop 110V 380W Injected Mould Heating Element Band Heater 35x35mm (2-PCS)	Amazon	2	$39.38	https://www.amazon.com/dp/B07DGV	2/11	2/14
Hopper	Sheet Metal	1/16" thick 24"x48"	Grainger	1	$78.73	https://www.grainger.com/product/GR/	x/xx	x/xx
Electronics	Power Cord	12 AWG 3 Conductor 3-Prong Power Cord with Open Wiring, 20 Amp Max, 6ft Replacem	Amazon	1	$16.99	https://www.amazon.com/Conductor-3	3/4	3/5
	Breaker	Square D by Schneider Electric One Source QO120CP 20-Amp 1-Pole Plug Circuit Brea	Amazon	1	$8.62	https://www.amazon.com/Square-Sch	3/4	3/5
	Breaker Box	Square D by Schneider Electric QO2L30SCP QO 30 Amp 2-Space 2-Circuit Indoor Main	Amazon	1	$14.37	https://www.amazon.com/Square-Sch	3/4	3/5
	PID Bundle	PID Temperature Controller Meter Indicator, Jaybva Digital Programmable Universal The	Amazon	2	$67.98	https://www.amazon.com/Temperature	3/4	3/5
	Power Switch	Heavy Duty Rocker Toggle Switch 15A 250V 20A 125V SPST 2 Pin ON/Off Switch Metal	Amazon	1	$9.59	https://www.amazon.com/Heavy-Rock	3/4	3/5
	LED Indicator	Amotor 10 pcs/Lot LED Indicator Light Lamp Pilot Dash Directional Car Truck Boat Blue	Amazon	1	$9.99	https://www.amazon.com/Indicator-Lig	3/4	3/6
Die	Die	Aaron in machine shop has stock and will machine	ME Lab	1	0			
Hardware	3/8" Bolt			1	$10.17	https://www.mcmaster.com/91309A619		
	3/8" Washer			1	$6.33	https://www.mcmaster.com/90473A031		
Cooling	Axial Fan	Newark Axial Fan, 5 V, DC, 40 mm, 10 mm, 6 cu.ft/min	Newark	1	$9.35	https://www.newark.com/nmb-technol	x	
Pinch Roller/Tensionor	Stepper Motor	Nema 17, Bipolar 0.9deg 46Ncm (65.1oz.in) 2A 2.9V 42x42x48mm 4 Wires, USA	Stepperonline	2	$17.07	https://www.omc-stepperonline.com/n	x	
	Springs	Steel extensional springs with Loop Ends, 1.25" Long, 0.313" OD, Pack of 12	McMaster Carr	1	$9.58	https://www.mcmaster.com/9654k117		
Diameter Sensor	Tire Guage	Audew Digital Tire Tread Depth Gauge, Metric Inch Conversion 0-25.4mm	Amazon	2	$9.99	https://www.amazon.com/Audew-Digit	x	
	Ball Bearing	XiKe **10 Pcs** 624-2RS Double Rubber Seal Bearings 4x13x5mm	Amazon	1	$12.99	https://www.amazon.com/XiKe-Pre-Lu	x	
Winder Guide	80/20	Extruded Aluminum, Double Six Slot Rail, Silver, 2" High x 1" Wide, Solid (1 ft)	Mcmaster Carr	1	$8.22	https://www.mcmaster.com/47065t107	x	
	Timing Belt Pulley	10 tooth pinion pulley, 0.25" ID	Servo City	2	$6.99	https://www.servocity.com/10-tooth-pir	x	
	Timing Belt	3/8" Wide XL Timing Belts, 25" long	Servo City	1	$6.15	https://www.servocity.com/0-375-3-8-w	x	
	Limit Switches	Snap-Action Switch with 16.3mm Roller Lever, 3 Pin, 5A	Pololu	2	$1.35	https://www.pololu.com/product/1404		
	Shaft (non motor side)	5" x 1/4" Precision D Shaft	Servo City	1	$2.69	https://www.servocity.com/0-250-1-4-s	x	
	Set Crew Coupling	1/4" to 5mm, Part # 625120	Servo City	1	$4.99	https://www.servocity.com/set-screw-s	x	
	Bearings(non motor sid	1/4" ID x 1/2" OD Flanged Ball Bearing (2 pack)	Servo City	1	$2.89	https://www.servocity.com/0-250-id-x-(	x	
	PTFE tubing	2mm ID tube, 5ft but really only need 1 ft	Amazon	1	$6.99	https://www.amazon.com/Teflon-tubing	x	

Figure 19. Extruder Bill of Material

The bill of materials outlines the parts that were purchased or obtained for the extruder. The green rows are materials that were purchased with the date obtained on the right column. The yellow rows are the materials for the subsystems of the extruder that are yet to be purchased.

D. Cost

During the initial stages of the conceptual design phase, it was estimated that the cost of the extruder would approximately be $1,357.49. After making the decisions via the decision making tools, the price of the extruder was reduced to approximately $794.61.

V. Future Details:

When the Covid-19 outbreak caused the University to close, the group was on schedule to complete the table-top extruder as planned. The Zips Precious Plastics group will have the responsibility of completing the plastic extruder once the University of Akron reopens from its indefinite closure. Students in Zips Precious Plastics will have access to part and assembly drawings and models via the Zips Precious Plastics google drives. Members receive access by requesting the Zips Precious Plastics lead design engineer or Engineers for a Sustainable World president. **The team may contact alumni and former Zips Precious Plastic lead engineer Brenton Wilmoth (330-696-7882) who worked on the project with any questions during the assembly process.** Every part for the machine is staged in the new Zips Precious Plastics headquarters in ASEC 226B. Fasteners for the machined components and plyboard are still needed to be purchased through the University of Akron source office. The senior design group finished machining each component of the extruder assembly in the university's machine shop. Figure 20 shows some of the machined components the senior design team completed prior to the university's closure.

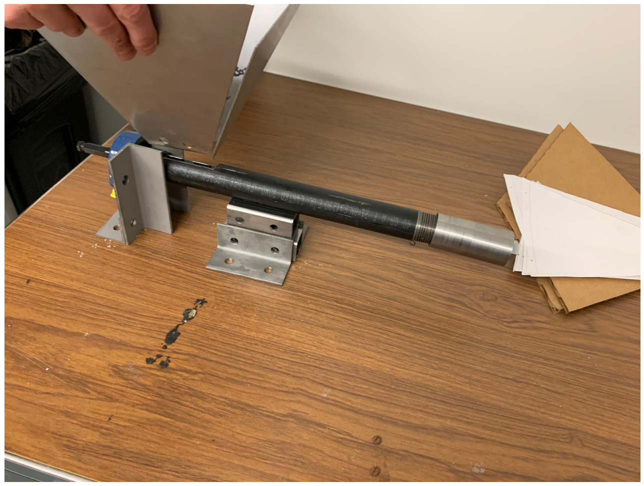

Figure 20. Components machined held together

During the machining process one of the lessons learned was that using a tapered pipe thread as opposed to conventional straight thread actually made it harder to machine the nozzle. The tapered thread was purchased because a male thread was already present on one end of the pipe. However, this small detail was overlooked and actually complicated the tapping process when machining the nozzle. Moving forward, it is recommended that students who continue this project get hands on experience in the machine shop. Working in the machine shop introduces new challenges and skills are gained that cannot be taught in the classroom. With that being said, it is strongly advised that any components redesigned or added to the existing design are first discussed with the university machinists before machining. Each of the university machinists are very knowledgeable and are a great resource. The next step in the assembly process was to weld some of the permanent connections. Welding must be performed on the hopper to connect the two pieces together. The two tube pieces that support the barrel of the extruder must be welded together, with the longer 3.5" piece on the bottom. The machined plate that mechanically fastened to the hopper is to be welded to the barrel. The baseplate will need holes drilled into the board to allow for connections with the extruder assembly. The ⅜" fasteners will connect the support structures to the plyboard baseplate. Then to supply power to the machine, the stepper motor needs to be programmed and wired up to the arduino, power supply, and driver. The power supply energizes the motor while the arduino controller commands the motion of the stepper, and the corrects the power coil to move the stepper motor. The heating bands also need to be fastened to the barrel while also being wired to the PID temperature controller. A thermocouple that is wired to the PID will have the sensor in place between the heating band and the barrel. There are two PID controllers purchased that will help control temperature of the plastic as it moves through the barrel of the extruder. The power supplied to the heating bands will also be connected to a breaker that will cut off current before it damages the components of the extruder or the electric grid where power is being drawn from. Electrical engineering students in Zips Precious Plastics will assist students in the wiring process. A power cord will bring electricity to the extruder which can also be controlled with an on/off switch. The majority of components used in the cooling subsystem can be easily 3D printed and assembled with the other sourced components found in our bill of materials.

Once the assembly was operational, the group was planning to run material through the extruder to test its performance. Varying motor speeds and temperatures for the heating elements were to be tested until a desired output was reached. This information was then to be recorded as a reference so future students working with the extruder assembly would understand how to use it. Another goal for the team was to find solutions to properly clean and maintain the barrel and screw assembly. Once the extruder is up and operating properly, the group was planning to take the extruded filament and compare it to off the shelf filament. One of the methods to compare the filaments was going to be conducted through tensile testing. By analyzing how tensile properties compare between off the shelf filament and the recycled filament would provide insight to the performance of recycled filament. Ultimately, the goal for this project is to improve this process until recycled filament could be reused in a 3D printer. This would create sustainable solutions and save costs among groups on campus and in the Akron community.

VI. Conclusion:

Zips Precious Plastics is creating its on-campus collaborative workshop to bring sustainability to the Akron area. Plastic consumption has only grown with 3D printers growing in popularity, which has led to more plastic deposited in landfills. The plastic extruder project is providing a solution to highlight our over reliance on plastic, while providing a means for members in the community to learn about plastic recycling with hands-on experiences. Throughout the process of designing a plastic extruder, the group conducted an extensive amount of research into the extrusion process and sub-assemblies associated with it. All of this was done to produce an optimal product given the design goals and limited resources. Personal connections were made with experts on campus and in industry to better understand thermoplastics and the extrusion process. The design team was able to pair this knowledge with engineering design fundamentals to create conceptual, embodiment, and detail designs of the extruder which led to the final design. Due to the COVID-19 pandemic, the University of Akron campus closed which led to a halt in assembling. Unfortunately, the machine performance of optimizing screw speed, heating band temperatures, operation limits were unable to be performed. Additionally, the comparison through testing was unable to be performed on the filament the extruder produced. The remaining time was spent carrying out calculations based on known variables and report writing. The team also worked to organize and layout information and research so that the progress accomplished could be carried on with future senior design groups and members of the Zips Precious Plastics. Although the team was unable to complete the initial goal, the project received a first place award during the design day presentations in the “Student Initiated Self Projects” category. This was very rewarding and gave the group a sense of pride for all of the work done over the past two semesters.

VII. References:

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VIII. Appendix

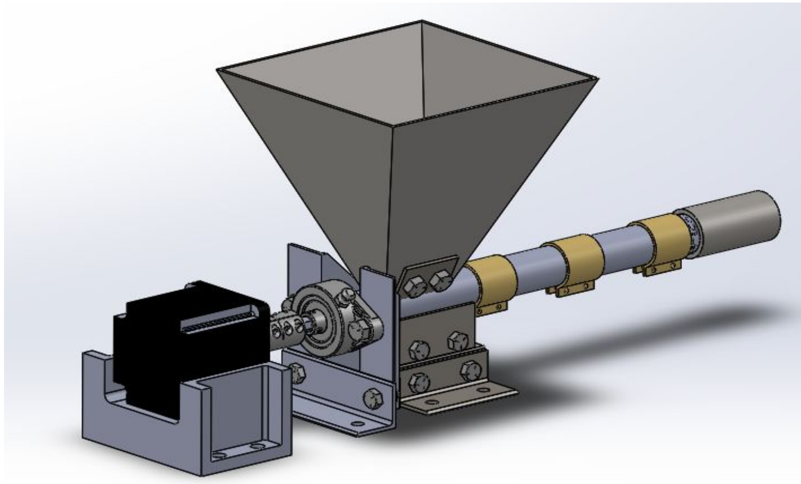


Figure A1a. SolidWorks model of extruder

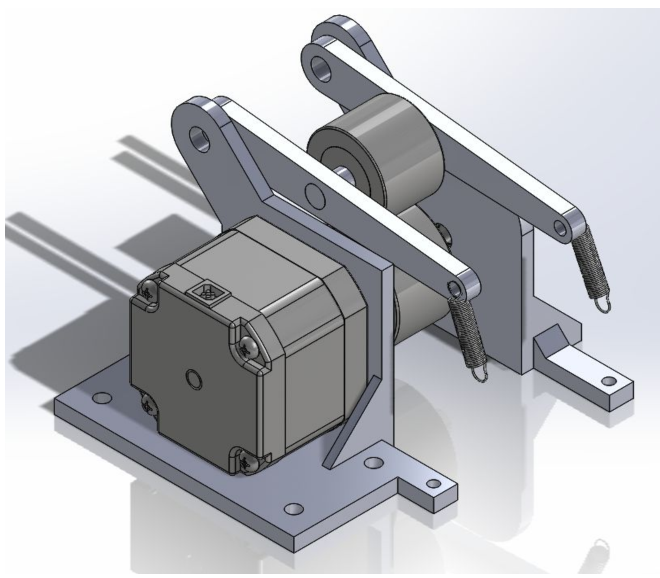


Figure A1b. SolidWorks model of pinch roller

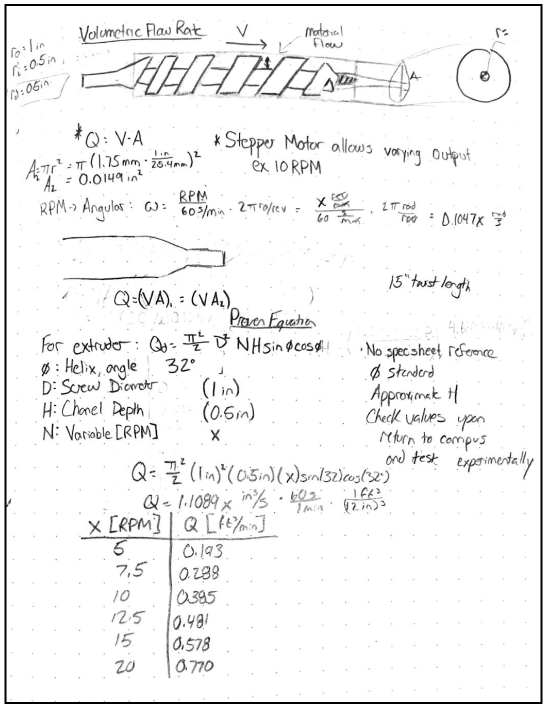
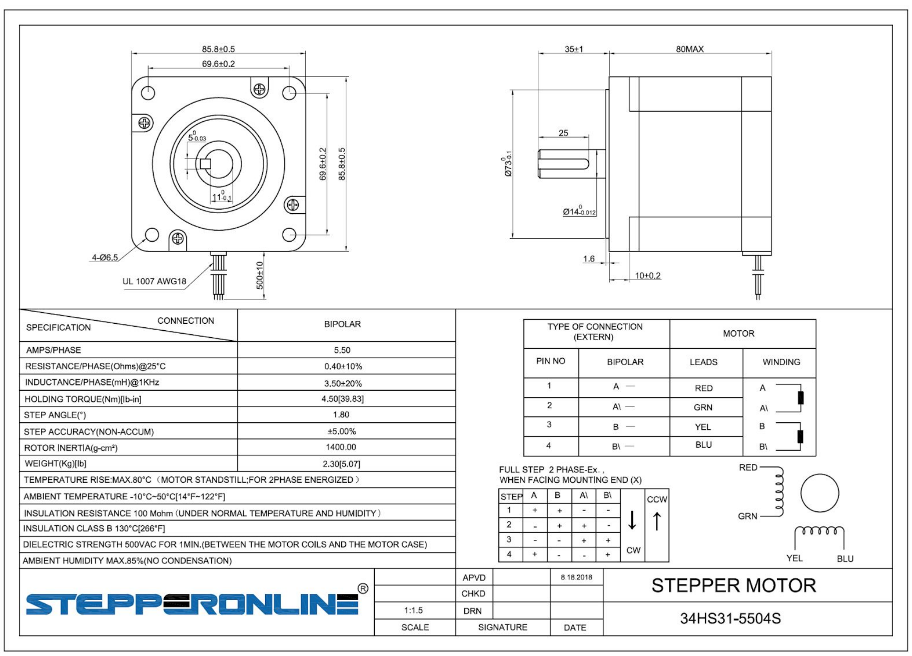


Figure A2. Flow rate work



SPECIFICATION \ CONNECTION	BIPOLAR
AMPS/PHASE	5.50
RESISTANCE/PHASE(Ohms)@25°C	0.40±10%
INDUCTANCE/PHASE(mH)@1KHz	3.50±20%
HOLDING TORQUE(Nm)[lb-in]	4.50[39.83]
STEP ANGLE(°)	1.80
STEP ACCURACY(NON-ACCUM)	±5.00%
ROTOR INERTIA(g-cm²)	1400.00
WEIGHT(Kg)[lb]	2.30[5.07]
TEMPERATURE RISE:MAX.80°C（MOTOR STANDSTILL;FOR 2PHASE ENERGIZED）	
AMBIENT TEMPERATURE -10°C~50°C[14°F~122°F]	
INSULATION RESISTANCE 100 Mohm（UNDER NORMAL TEMPERATURE AND HUMIDITY）	
INSULATION CLASS B 130°C[266°F]	
DIELECTRIC STRENGTH 500VAC FOR 1MIN.(BETWEEN THE MOTOR COILS AND THE MOTOR CASE)	
AMBIENT HUMIDITY MAX.85%(NO CONDENSATION)	

TYPE OF CONNECTION (EXTERN)		MOTOR	
PIN NO	BIPOLAR	LEADS	WINDING
1	A	RED	A
2	A\	GRN	A\
3	B	YEL	B
4	B\	BLU	B\

FULL STEP 2 PHASE-Ex.,
WHEN FACING MOUNTING END (X)

STEP	A	B	A\	B\	CW	CCW
1	+	+	-	-	↓	↑
2	-	+	+	-		
3	-	-	+	+		
4	+	-	-	+		

STEPPERONLINE®

	APVD		8.18.2018	STEPPER MOTOR
	CHKD			
1:1.5	DRN			34HS31-5504S
SCALE	SIGNATURE		DATE	

Figure A3. Stepper Motor Specifications