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# Conveyor Belt 3D Printer MQP

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# Conveyor Belt 3D Printer

A Major Qualifying Project Report

Submitted to the Faculty

of the

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by

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# Abstract

Our MQP problem was to design a 3D printer that had continuous printing capabilities, whether to create longer parts or to rapidly produce multiple parts. The goal was to create a 3D printer that could achieve these specifications while maintaining a less expensive price point than the current market options. We designed and created our own 3D printed parts where we could so that we could save on money while not sacrificing the performance of the printer. We machined custom parts to accommodate our pipe system used in our conveyor design. We also used a 5:1 planetary-gear stepper motor to ensure that sufficient torque existed for the conveyor system.  Our printer is designed to be significantly more economical than market alternatives while providing comparable performances.

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# 1. Introduction

The birth of 3D printing can be traced back to 1984, when Charles Hull developed stereo lithography, a printing process that allows a tangible 3D object to be created from digital data [1]. Since then the technology has grown into a widely used resource to prototype different products for various engineering applications, including biomedical, aeronautical, automotive and other various engineering fields. As prices of the printers have decreased to a reasonable range, 3D printing has started to gain a consumer following. Hobbyists often use the technology for their own personal projects.

3D printing is not likely to replace traditional manufacturing methods soon. Instead the technology is typically used in the fabrication of a testable prototype prior to the final manufacturing of a part. The speed of additive manufacturing is one of the main factors that make it ideal for prototyping applications. Additive manufacturing is a single step manufacturing process, so once a CAD design is uploaded to a printer it can be printed with no additional operations, whereas traditional manufacturing methods can often require multiple different processes to achieve the desired shape. This means an intricate design can be taken from a CAD model to a physical prototype in a few hours. This allows for design concepts to be tested and iterated at a faster rate, thus speeding up the entire design process. Additive manufacturing can also afford the designer freedom over possible restrictions imposed by traditional manufacturing, such as draft angles, undercuts and tool access. The additive manufacturing process also offers more sustainability compared to subtractive manufacturing. While subtractive manufacturing generates a significant amount of waste, additive manufacturing mostly only uses the material needed to create a part, with a small percentage of material waste coming from the support material. [2]

Despite being created over 30 years ago; the 3D printing industry has experienced most of its growth in the last decade. As of 2018, the industry is projected to grow to $11 billion by 2022, with a projected growth rate of 27% each year during that span. [3] Despite all this growth there are still some limitations on the technology, as nearly all 3D printers in the market print using a top down method, where the first layer is printed on a flat surface and then subsequent layers are added until the prototype is completed. This method possesses some significant limitations as print size is limited by the size of the printer. Large objects cannot be printed without the use of a printer that is larger than the desired object. Additionally, parts often must be manually removed from the prints, which limits the user to one print at a time and risks damaging the parts during removal.

With the technology growing rapidly in recent years, it is likely that there will be several innovations to 3D printing soon. Our goal was to be at the forefront of those innovations. We developed a 3D printer which prints at a 45-degree angle onto a moving conveyor belt. By printing onto a conveyor belt, provided enough print material, there are no longer any limitations on the length of the prints along the axis parallel to the belt. This can be applied to prototypes for airplane wings, prosthetics and other parts that are longer than a typical 3D printer. Our design also has a mechanism to peel parts off the belt at the end, allowing automatic removal of the parts, meaning that multiple prints can be queued up and carried out without any user intervention. By printing at a 45-degree angle, the layers of the part are angled at 45 degrees, which allows for a reduced need for support material in many cases.

# 2. Background Information on 3D Printing

3D printing is a process of additive manufacturing where thin layers of material are melted and stacked on one another to form a design. The designs for printing come from computer-aided design (CAD) software, such as SolidWorks or FreeCAD. The model can be taken from the CAD software and exported in a file type, such as OBJ or STL since these are the types of files that are generally compatible with 3D printers [4]. Once the files are exported to the printer, the operator, depending on the configuration of the printer, must undertake some preparations. There are printers that come with an automatic bed leveling mechanism and some do not, therefore what printer the operator uses influences aspects of manual preparation for printing [5]. After the operator exports the file and undertakes the necessary, if any, calibration of the printer itself, the printing occurs.

## 2.1. General Components of a 3D Printer

Every 3D printer contains a similar list of components. There are, obviously, some printers that come with more features than are standard, however, Chapter 2.1 will summarize the basic components found in most commercial 3D Printers.

### 2.1.1. Frame

The overall structure of the printer is heavily dependent upon how the frame is constructed. Many 3D printers can be constructed out of 3D printed materials; according to a popular 3D printing community, RepRap, many of their 3D printers can be constructed out of materials, such as PLA, ABS, HDPE, etc. which are all possible thermoplastic filaments usable by their printers [6]. There are also possibilities in producing the frame through machined metals, such as 8020 T-slot Aluminum, shown in Figure 1, which is particularly useful for components of 3D printers as the T-slots allow for simple connections between the bars.

Figure 1: 8020 Aluminum Framing *[7]*.

In addition to these methods of construction, simple machined aluminum or steel is a realistic option. Mass-manufacturing would favor the option of using machined metals, as the 3D printed material cannot be produced at nearly the same rate. 8020 T-slot Aluminum, while qualified as a machined metal, could potentially require more assembly than a metal with a less intricate design.

### 2.1.2. Extruder

The extruder is the mechanism responsible for passing filament, or the printed material, into the hot end, which melts the filament. The extruder is referenced as the “cold end” as it holds and feeds the filament to the hot end using either a hobbed gear or hobbed bolt [8]. The hobbed gear in Prusa’s i3 MK2 extruder, for example, is driven by an extruder motor [9]. A hobbed gear can be seen in Figure 2, while the motor and hobbed gear assembly can be seen in Figure 3. The filament rests between the hobbed mechanism, gear or bolt, and the extruder idler. The idler serves the function of a static, rigid body that ensures the filament is secured against the hobbed mechanism so that, when the extruder motor drives the mechanism, the filament will be fed through the extruder at the rate set for extruder motor.

Figure 2: Hobbed Gear *[8]*.

The preparation for inserting filament prior to prints is dependent upon the type of printer and the type of extruder used. The group has access to one of Prusa’s printers that ejects the filament at the end of every print and needs to be manually reinserted prior to each print, and with that the operator can feel the gear grip the filament and, after the gear has time to completely grip it, it will feed filament through to the hot end. Some printers, however, might not necessarily need to remove the filament after each print and some have multiple hobbed mechanisms to feed filament to the hot end for prints with different colors or different materials.

Figure 3: Hobbed Gear and Motor Assembly *[9]*.

After filament is fed through the hobbed mechanism, it is fed to the hot end, the other large component of the extruder. The hot end is the heating element that melts the filament to be printed. Most extruders will also have a print fan fixed close to the nozzle of the hot end to cool the print as quick as possible. The tip of the hot end will be a metal, like brass, to allow heat to hit the filament as it transitions to the open air. The shape of the tip also facilitates the way the plastic leaves the hot end, as most nozzles are cylindrical in shape and come to a point where the plastic leaves the extruder.

### 2.1.3. Stepper Motors

Stepper motors are commonly used in 3D printers. A stepper motor is a motor that completes its rotation in specified increments, or steps, in which the motor rotates a specified step angle. One of the most important traits of a stepper motor is that it can be used without a feedback loop. Since the motor moves in distinct steps, all that is needed to position the motor correctly is to count the number of steps. This is ideal for 3D printing applications that require the extruder to be in very precise locations to correctly print parts. The motor has high torque relative to a comparable DC motor and has no need for mechanical braking, which also makes it ideal for applications where a motor must hold its position firmly [10].

There are three types of stepper motors, Permanent Magnet, Variable Reluctance and Hybrid. The Permanent Magnet uses current flow through a magnetized rotor to achieve the steps of the motor. Variable Reluctance uses a nonmagnetic geared rotor for its steps. Hybrid combines elements of the Permanent Magnet and Variable Reluctance.

One advantage of the Permanent Magnet Motor is that its resolution can be increased by increasing the number of stators, which are soft iron components wrapped in multiple windings that are energized by a voltage source to produce a polarity. Rotation in a direction is accomplished by applying voltage to the individual phases which control each step in a sequence. The stepper motor can be reversed by simply applying these voltages in an opposite sequence [10].

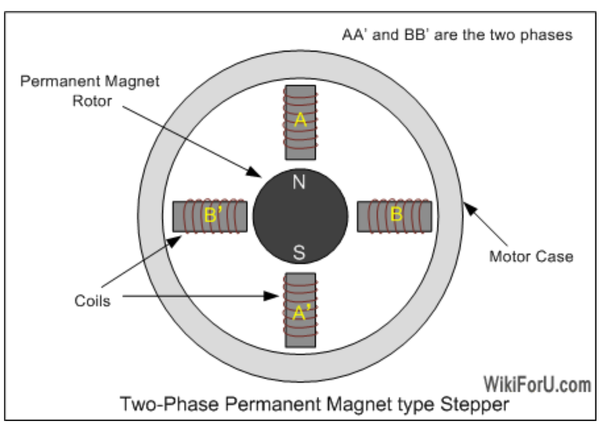


Figure 4: A Permanent Magnet Stepper Motor *[10]*.

In a Variable Reluctance Motor, the rotor has teeth that are offset from the stator poles, which is what rotates the motor. Like the Permanent Magnet Motor each winding is energized one at a time to cause a polarity which forces the part to rotate [10].

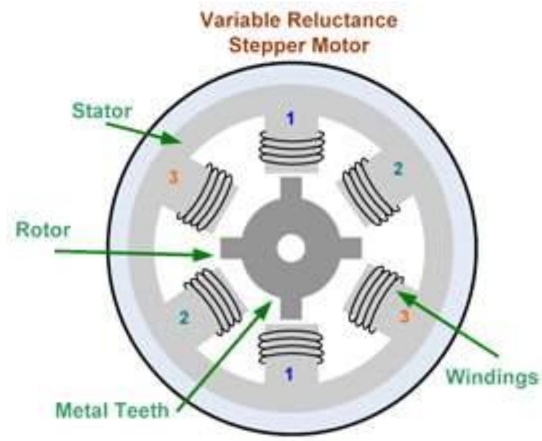


Figure 5: A Variable Reluctance Stepper Motor *[11]*.

A Hybrid Motor combines elements of the Permanent Magnet and Variable Reluctance type motors with a rotor that is magnetized and has teeth. The rotor is broken into two sections that have opposite polarity and have teeth that are offset. Variable Reluctance and Hybrid Motors are more expensive due to manufacturing cost, but they are also able to achieve higher resolutions in their steps compared to Permanent Magnet Motors. Permanent Magnet and Hybrid Motors can support micro stepping algorithms, while Variable Reluctance motors are limited to full steps [10].

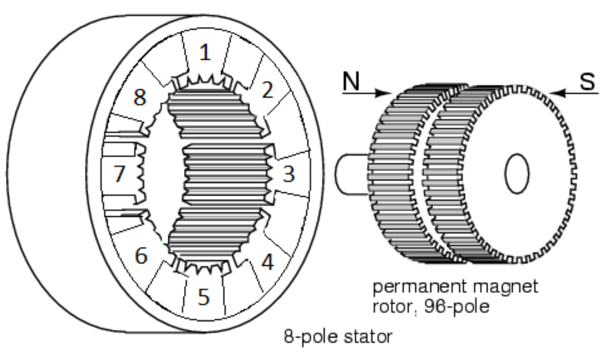


Figure 6: A Hybrid Stepper Motor *[12]*.

Unipolar and Bipolar motors are both sub variations of Permanent Magnet and Hybrid Motors. A Bipolar configuration has a winding where each lead is brought out separately, allowing each stator to be magnetized to North or South. A Unipolar configuration only allows flow through half a winding at a time and thus only supports single direction flow. Bipolar Motors generate more torque and require more complex circuitry, while Unipolar Motors have thinner wiring and therefore need more wire, which increases the windings resistance [10].

### 2.1.4. Controls and Power

A standard Fused Deposition printer, such as the PrintrBot and Up! Printers has a build volume of 384 $in^3$ to 641 $in^3$ and does not consume a large amount of power, maxing out around 170 watts, with an average power of 105 needed for a print. Breaking down where this power usage comes from, when the printer is idle it has a power requirement of 15.7 watts, on par with a laptop in sleep mode. The power needed for the stepper motors to maintain a holding torque is 5 watts. The power needed by the stepper motors to move along each axis were as follows, 0.3 watts for the x-axis, 0.4 watts for the y-axis and 2 watts for the z-axis. Using a Buddaschnozzle hotend and heating to a temperature of around 200°C required 28.3 watts. The major power hog of the printer was the PCB Heated Bed, requiring 129.5 watts of power to reach a temperature of 90°C [13].

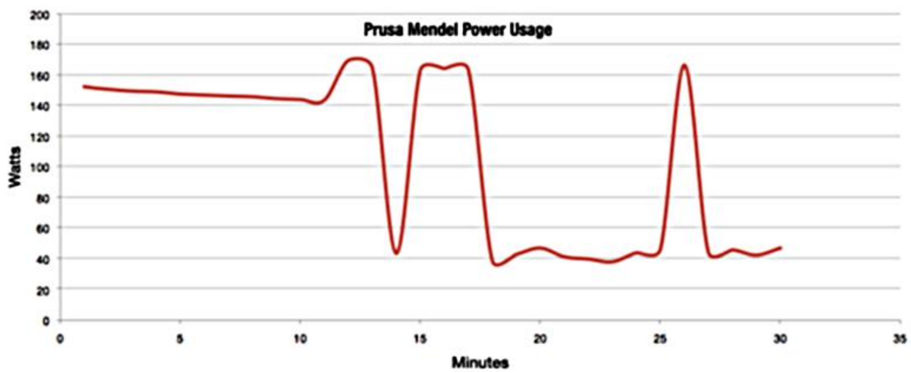


Figure 7: Power Fluctuation During a Typical Print *[13]*.

Figure 7 shows the power fluctuation printing a 40 x 60 x 20 mm box. As seen the power starts off high at the start of the print. This is to get the heated bed and hotend to their appropriate temperatures. The subsequent spikes occur when the heated bed is turned on to maintain the bed temperature.

Stepper motors are typically used to control the extruder and bed of the printer, due to their ability to stop at a precise location. The motors are each powered by a driver, and the drivers are centralized on a motherboard [14]. On most printers there is a manual interface that can be used to adjust the stepper motors. There are also numerous software programs available to control the stepper motors, provided the printer is compatible with a computer.

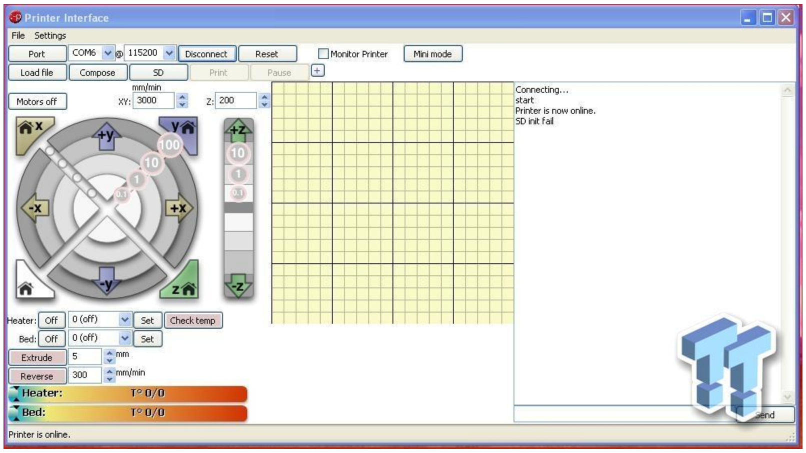

Figure 8: A Print Control Software called Printrun *[15]*.

### 2.1.5. CAD and Slicing Software

A major component in 3D printing is Computer-Aided Design, or CAD, software. CAD software is what allows a creator to make a 3-dimensional object digitally, as it can be saved as a file for convenient exporting. Most software will consist of functions that can create basic shapes from sketches and the ability to modify the sketches to more complex designs. For example, SolidWorks has basic sketch tools that act as the building blocks for modeling in their software. There are many types of sketches: circles, arcs, 3-point arcs, slots, corner rectangles, simple lines, etc. and these applications allow the designer to extrude shapes based on their sketches. Multiple methods of achieving the same design are possible, as extruding a simple sketch and then using an extruded cut can yield the same result as extruding a more complex sketch and not using a cut tool at all. In addition to shape creation, the designer can use chamfers or fillets to smooth out sharper edges, a hole wizard to fit a hole to a specific size and thread, or simulation software to find out theoretical strengths and weaknesses of design based on a variety of characteristics. There are many applications of 3D modeling software that allows for much creativity, but it is important to note that not all designs made in CAD software are printable as certain geometries are difficult to 3D print.

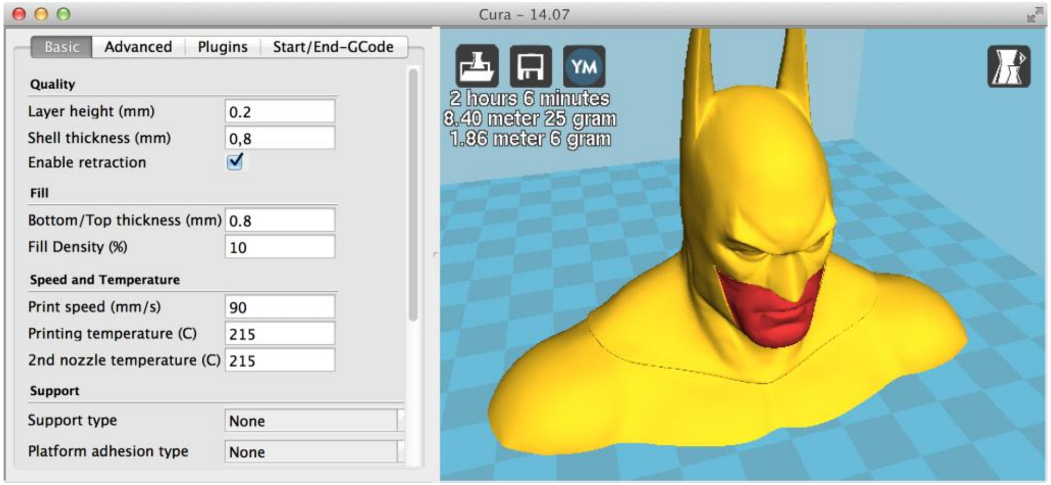


Figure 9: Slicing software CURA interface *[16]*.

Printers may come with control software directly associated with the printer that can accept popular file types from CAD software or change the file into a readable format for the software. There are, however, plenty of open source and premium software that are available to creators for converting a 3D model file into a code that the printer can interpret. This type of software is called slicing software. Figure 9 shows a slicing software, CURA, interface with the 3D model in a dynamic view as well as the controls for the print. From this software, a designer can control the layer height, the print speed, the print temperature, potential support material, etc. This software is what will control how the printer is supposed to move, how fast, how much material to fill the object with, etc. The programs will have a method to convert the print values into a readable format, such as g-code, so that the printer will know how to create the part.

## 2.2. Applications and Materials

In general, 3D printing has many important uses for design in just about any industry. 3D printing allows for companies designing just about any product to rapidly prototype the design instead of manufacturing. In addition to this the medical industry has similar uses of the efficiency of 3D printing. There are also a wide range of materials to print, which further augments the potential applications for 3D printing from rapid prototyping to simple recreational intrigue.

### 2.2.1. Rapid Prototyping

The biggest advantage that 3D printing has over standard manufacturing is that any part a company wishes to test as a prototype can be produced as a CAD model and rapidly produced in a 3D printer [17]. Rapid prototyping reduces the product to its general mechanical design and allows for a design team to work out how certain electrical components will fit into the design, how mechanical items, such as gears, will work together, and general sizing applications. The limiting factor on rapid prototyping is that generally it is much more difficult to print the product in the specific material that the design team wishes to incorporate. 3D printers can print metals but these types of printers that can handle metal filament are generally more expensive [18]. For a startup company a smaller, more economical 3D printer that can rapid prototype in plastic should work just fine for almost any prototyping need.

The prototypes created by plastic filament are most likely not the material desired in the final design of a product, however the requirements for a true to form prototype in terms of finding the proper materials and assembly are more time consuming. The purpose of rapid prototyping is to see if a general design can work, and then eliminate features that hinder design progression. For getting a general prototype for quick testing, 3D printing is the most efficient process. Generally, the company would want to test the physical properties of the actual material in a final design for quality assurance and consumer safety, but from a design perspective, rapid prototyping with a 3D printer is an invaluable asset for getting a product to the manufacturing stage swiftly.

### 2.2.2. Medical Industry

3D printing may have a comparatively profound impact on the medical industry. According to a 2014 estimate, 3D printing is a “$700 million industry, with only $11 million (1.6%) invested in medical applications.” [19]. According to the same source, 3D printing is projected within 10 years “to grow into an $8.9 billion industry, with $1.9 billion (21%) projected to be spent on medical applications.” [19]. The numbers indicate that 3D printing is an asset that the medical industry wants to expand upon. The potential uses of 3D printing in the medical field include customization of surgical implants, less expensive manufacturing standard prosthetics, quickly producing the necessary part, and opening collaboration amongst medical researchers, and potentially driving down costs for the consumer [19].

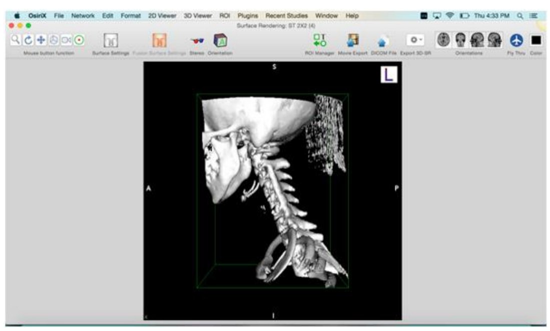

Figure 10: MRI/CT scans converted to STL files *[20]*.

The image shown in Figure 10 is an example of the potential of advancing 3D printing in the medical industry. The ability to convert x-rays, MRIs, CT scans from a radiographic image to an STL file opens the potential for geometries specific on a patient-by-patient basis [19]. More specifically, if a patient needs a type of prosthetic to walk, the STL file of the x-ray can provide relevant geometry of the patient’s leg which greatly improves the design process of the prosthetic by getting exact dimensions accurately. Prosthetics are obviously much larger than, for example, dental implants. Dental work is much more specific to the patient and there are smaller tolerances to work with. Orthodontists, for example, take dental impressions using alginate in a tray to record the specific dental structure of the patient [21]. Not only could advancements in 3D printing accuracy obtain the correct dental information from the patient, but it would remove the process of taking the dental impressions which are generally considered to be an uncomfortable experience.

These STL conversions still offer close readings to the actual patient information and are therefore accurate enough for uses in the medical industry as of 2017. For the dental industry, the specifics are very important, so 3D printing may not be accurate enough yet, however for production of surgical implants in other locations on the body, the process is close enough where the printed part can be changed slightly to accommodate for the small discrepancies. A similar process would be when a dental surgeon fills a cavity, generally the material used to fill the cavity will amass during application, which causes discomfort in the patient's jaw. The dental surgeon will use a drill to chip away at the excess material until the filling takes a form close enough to the patient's tooth structure to remove complications. A 3D printed implant may not perfectly fit the patient; however, the part can be adjusted during surgery in a similar fashion to a filling, to remove complications that would arise from having an improperly sized component in any place on the body.

### 2.2.3. Printed Materials

A wide variety of materials ranging from plastics, metals, and ceramics are used in 3D printing. Plastics are the most common filament used in printing for recreational use, rapid prototyping, and in the medical industry. Plastic filaments are generally less expensive than the more advanced alternatives, which makes 3D printing appealing to the consumer. The cost factor appeals to design teams for rapid prototyping as well. 3D printing more economical filaments in an environment where constant iteration is necessary will generally help a design team save on costs.

Figure 11: Steelfill Filament from Prusa Research *[22]*.

There are filaments that are comprised largely of plastic but contain up to 30 – 40% metal that add rigidity to the plastic filament but are considered less useful for structural properties and more useful for the aesthetic qualities. Steelfill PLA filament from Prusa's store displays artistic designs; one such depicted in Figure *11*, displays how the steel infused in the PLA can influence how the printed object looks. The bust of Marvel's Ironman looks close to a machined metal, yet the filament for printing is over 50% PLA [22]. We can determine that the concentration present in the Steelfill PLA is roughly 30% by taking the equation: $\rho_C = x * \rho_P + (1 - x) * \rho_M$, where x is equal to the concentration of the plastic and the different densities are determined by the material; C for composite, P for plastic, and M for metal. Using a steel density of 8.05 $g/cm^3$, a PLA density of 1.25 $g/cm^3$, and given the density of the composite from Prusa as 3.13 $g/cm^3$, we can determine the amount of PLA present is about 72.4%, making the metal about 27.6% of the composition [22] [23] [24]. This shows that the material can mimic a metallic finish without making completely metal filament.

In addition to the thermoplastics and metal infused thermoplastics, pure metal filaments exist. The benefit of having a titanium, stainless steel, or gold filament is generally the strength that is characteristic with the material [25]. Generally, these metal filaments will be much more durable than the thermoplastic filaments and some, like titanium, can even be exceptionally detailed [25]. One major caveat with metal filaments is the cost. The exceptional quality of the material properties will account for the rise in cost, but a design team would choose a thermoplastic filament over a metal filament for rapid prototyping except, potentially, for the final prototype.

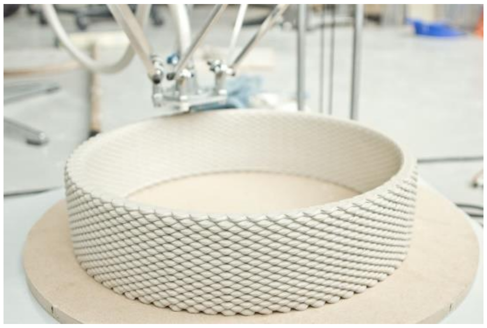

Figure 12: 3D printed ceramic design *[26]*.

Ceramics are also a possibility with 3D printing. The benefits of 3D printed ceramics are like that of normal ceramics, where the product is rigid but also fragile. A practical application can be seen in Figure 12, where a designer, Olivier van Herpt, uses a delta-coordinate 3D printer to print intricate ceramic designs [26]. Herpt's website is full of his and other designers' works, which are printed ceramics that are used for detailed pottery designs and can function the same as a processed ceramic [26].

### 2.3. Limitations, Difficulties, and Feasibility

Despite its wide range of applications and convenience to the Manufacturing and Medical industries there are still some limitations to the technology. The size, speed of production and accuracy of the printed part compared to its CAD model are all limitations that face even the best 3D printers. Many printers also have trouble creating geometries that are very detailed and especially geometries that feature overhangs.

#### 2.3.1. Size

In a conventional top down 3D printer, maximum build volume of a given part is limited by the geometry of the device and more specifically its build space. Each printer has a build platform which is where the material is built upon until eventually forming the desired shape of the part. This platform is typically square or rectangular. A 3D printed part cannot have dimensions that exceed the dimensions of the platform it is built upon. The part is limited in the x and y directions by the dimensions of the build platform. The part's height in the z direction is also limited based on the difference between the height of the bed and the height of the extruder at its max height. 3D printers come in many different sizes as shown in Figure 13 so there is no standard build volume.

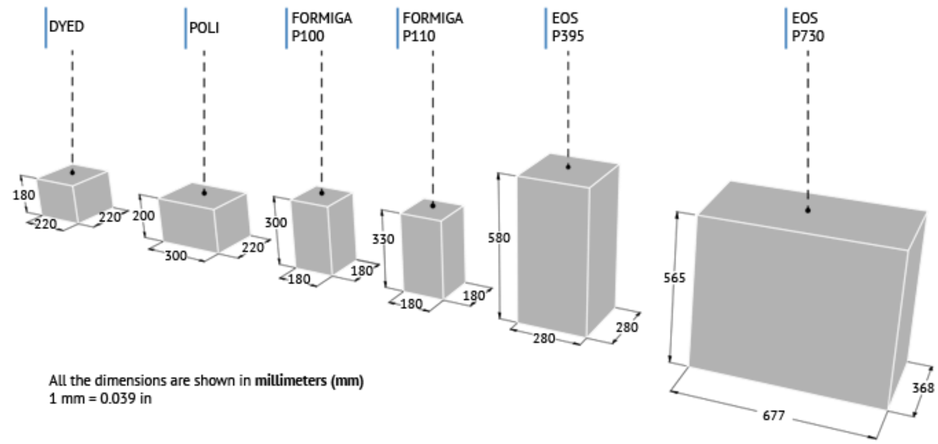


Figure 13: Build Volumes of Various 3D Printers *[27]*.

For most standard commercial 3D printers, the build volume will not exceed one foot in any given dimension. The two printers in Figure 13 that exceed these dimensions are Industrial 3D printers used in the manufacturing industry whose total dimensions are much larger than their build volume.

### 2.3.2. Production Speed

A major factor limiting the applications of 3D printing is the speed at which the object is printed. 3D printing even a simple part such as the boat in Figure 14, which is 6 cm long, 4.8 cm high and 3.1 cm wide, can take around 2 hours to print under standard speeds [28]. There are two major factors that limit the print speed, the extruder flow rate and the motion system peak speed. However typical stepper motors can exceed the extrusion speed of an average printer, so in virtually all modern 3D printers the extruder flow rate is the limiting factor to print speed. A typical 3D printer can support print speeds anywhere from 40-150mm/s, however when the print speed is increased the parts will be lower quality. The infill of a part can also be adjusted to cut down on print speeds, as for most parts an infill of 20% is sufficient. At high speeds the layers will not have enough time to properly adhere. The filament also needs to be heated faster, which can lead to jams in the hot end and ruin extrusion of the part. For industrial purposes injection molding and die-casting are currently much more efficient methods to mass produce intricate parts.

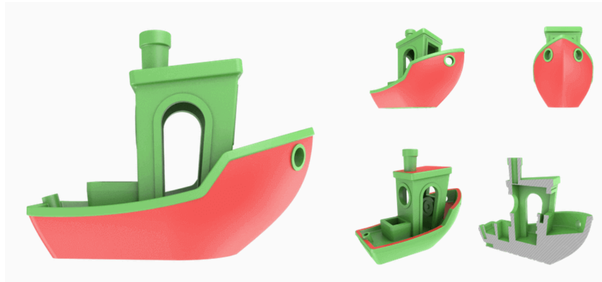

Figure 14: Small Boat Used to Benchmark 3D Printing Speed *[29]*.

### 2.3.3. Accuracy

Due to the top down nature of a standard 3D printer, there are certain complications with printing parts that contain overhangs, or unsupported sections. Since the printer prints from the ground up it must have something to build upon, so support structures need to be created for these sections. The parts will still turn out as intended and the support material is easy to remove. However, additional filament must be used to create the support structures, so it increases print times and uses more material than is necessary.

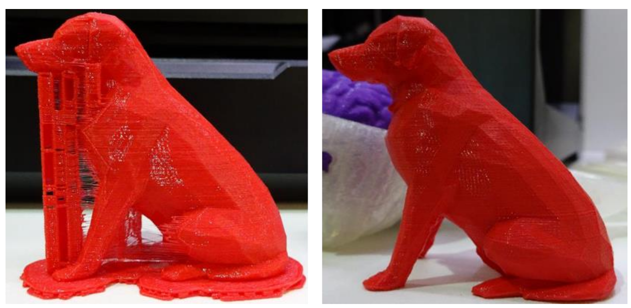

Figure 15: Support Structures Used to Print a Complex Shape *[30]*.

The accuracy of the physical part is limited by the resolution of the printer when compared to the computer model. The resolution is influenced by the size of the extruder nozzle, as well as the precision of the extruder movements. This resolution has two elements, the horizontal resolution, which is the smallest movement the extruder can make in the X and the Y axis, and the vertical resolution, which is the minimum thickness of a layer that the printer can produce in one pass. For both resolutions a smaller value indicates a greater ability for the printer to recreate fine details, which means that parts will be more accurate. A typical print layer is around 0.2 or 0.3 mm, but some printers can produce layers as thin as 0.02 mm [31].

### 2.3.4. Quality of Parts

A major limitation facing 3D printing is that, due to the surface finish and strength of most filament materials, it has limited practical purpose and is mostly used as a prototype material. Common flaws in the surface finish of parts include a rough surface, especially when using PLA material that will need to be sanded down. Sanding is not always an easy process with 3D printed parts, as there can be thin layers that are completely removed by sanding the part, which can be corrected by changing the fill percent, or adding a filling to the part. Often parts will also have visible stepping lines from the print layers. Most printers are also only able to print in one color at a time, so the parts may need to be painted to achieve the proper appearance. However, some printers today can print with multiple filament materials, which could mitigate this problem [32].

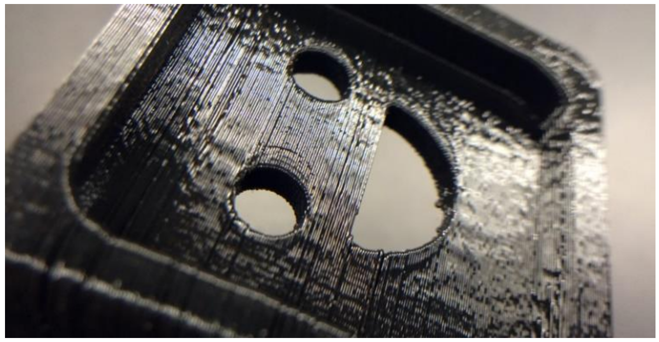

Figure 16: A PLA Printed Part with Visible Imperfections *[32]*.

For manufacturing purposes 3D printing is not a currently viable option due to its low strength and, more particularly, its strength in the Z-axis. For plastic parts such as ABS, SLA and polycarbonate parts they are only as strong as their weakest link. For example, ABS material may have a flex strength of 60 MPa off the shelf, but when printed, the Z-strength may only be 35 MPa. This is because the part is printed in layers, so the step lines are weak points on the part. If a flex test is run on the part, it will break on one of these lines [33].

## 2.4. Development

Future development of 3D printing could be used for a multitude of purposes. One source claims that 3D printers may create spare parts for ranges of different products, build houses and be used in bioprinting [34]. The concept is that, with efficient and reliable printing methods, a repair shop may be able to 3D print parts that are expensive to create through subtractive manufacturing methods. It is even possible to 3D print massive structures out of concrete with a large enough printer [35]. Creating less expensive printers that have large enough print beds to create housing materials may increase the number of houses that can be created through less conventional building materials. As mentioned in Section 2.2.2, there is also a distinct possibility that further development of printable materials, specifically cells and protecting printed cells, can lead to a revolution of creating living tissue, or even full organs with proper development [34].

### 2.4.1. New Materials

When considering development of materials, it is important to identify the major industries that 3D printing will have an impact on, and what materials they need to manufacture. As referenced in Section 2.2.2, the medical industry would gain incredible assets from funding in 3D printing. The potential to rapidly create a functional living tissue is important and currently a theoretical possibility, as claimed by Organovo [36]. The process shown in Figure 17, is an example of bioprinting where the organic material, bioink, is printed in a spheroid shape and suspended in a layer of biopaper gel. Multiple layers are printed and the bioink fuses together to form the final shape, customizable depending on the orientation of the printed spheroids. The final shape in Figure 17 is a tube that can be applied for simple blood vessels that “are capable of rearranging themselves after printing.” [36]. Further research in this field of 3D printing may yield the potential to 3D print organs, and Organovo believes that kidneys will be the first organ to be produced [36]. The time it takes to produce a working, compatible organ may not happen as fast as printing a thermoplastic, however it is an option that appeals to patients that do not want to wait for a donor organ. The cells used would be in high demand and likely low supply, however, and that would drive up costs for a printed organ but further research and development in this field will ideally mitigate these negative effects.

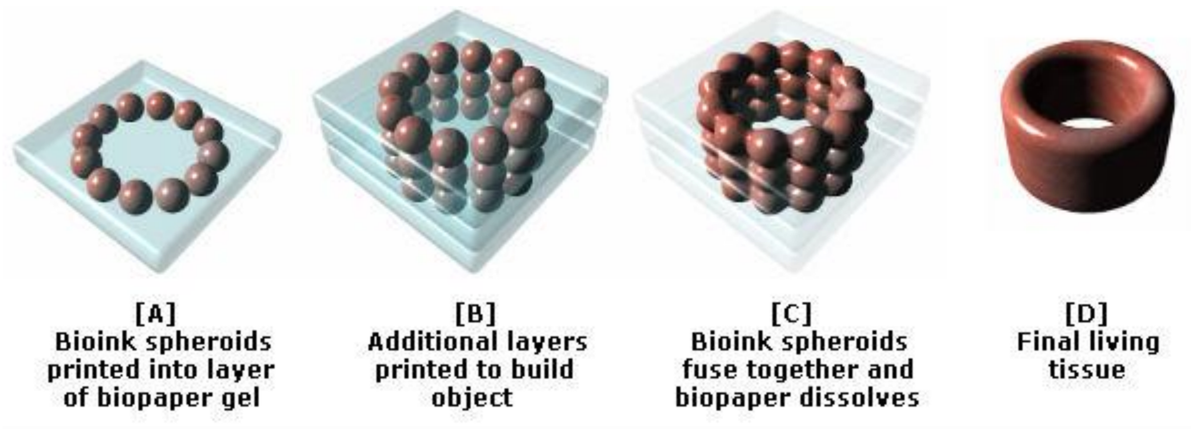


Figure 17: Organovo's concept of Bioprinting *[36]*.

In addition to the potential advantages in the medical field, there are many potential materials that can be further developed and become available less expensively and recreationally. Some of these materials include the following: heat-responsive polymers, conductive monomers, carbon nanotubes, and food [37]. Heat-responsive polymers have an interesting property where the material can be reshaped by exerting sufficient force, however the polymer reacts to heat and retakes its original printed shape [37]. A group at Virginia Tech could accurately print ionic liquid monomers in small volumes, and these monomers are conductive materials useful for electrical applications [38]. In addition to the electrical importance of this printing, the group was also able to create printed features “as small as 25µm” [37]. The small scale of identifiable features in this printed material has potential to be useful in the medical industry as well. Certain plastic filaments can be strengthened by use of carbon nanotubes, where the carbon nanotube ink is melted into plastic filament using microwaves [37]. The plastic filament will not melt, which allows the ink to fuse with the plastic. Food is another possible avenue for 3D printing, as a source claims that four different shapes of pasta can be printed in two minutes [37]. If this process of manufacturing food can prove to be more cost effective than buying the food, then it is reasonable to expect large chain restaurants, lower end restaurants, and families to purchase these printers and their “filaments” to create less expensive food.

# 3. Conveyor Belt 3D Printers

The specific concept our team explored was designing and building a 3D printer with a functioning conveyor belt system with an extruder that prints at an angle. The core aspect of these types of printers is the automation of the 3D printing process. Chapter 3 will address in depth research about the available type of automation for 3D printing that is available on the market. In addition to detailing different companies that produced the current designs on the market, there will also be discussion regarding the pros and cons of each design as well as the software used for printing preparation.

## 3.1. Why Angled Printing?

Since 3D printers have existed, printing from the ground up has been the standard layering method, with nearly all designs utilizing this method. These printers have proven reliable and are suitable for most applications, but this method does have its limitations. For one the size is limited by the build volume, which cannot exceed the size of the printer itself. If you desired to print a long part, such as an airplane wing, large sign, or long rod, you would have to either print the part in multiple sections or have an extraordinarily large printer to complete the print. In an angled printer the extruder prints layers that are angled at 45 degrees and moves horizontally with each layer. This means the axis aligned with the conveyor belt can be infinitely long, allowing for parts whose length greatly exceeds that of the printer itself. The only limitation is finding a structure to support the part once it exceeds the length of the printer itself.

Another advantage related to the continuous printing capabilities of an angled printer is the ability to print parts in series. On a normal printer you can only print one part at a time in most situations (an exception is printing multiple small parts as one layer). These parts also typically must be manually removed which risks damage to parts. On an angled printer that can print continuously the printer can keep printing parts and they will move down the conveyor belt once they are completed. The tensile force of the belt can peel the parts off or an edge can be used on the end of the belt to remove these parts automatically. After being removed a bin can be placed at the end of the printer to store completed parts.

Since printing into thin air is impossible, printing from the ground up still requires support material for any designs with hanging edges. Angled printing does not eliminate the need for support material, but since it prints in layers at 45 degrees, it is able to eliminate the need for support material for some overhangs compared to ground up layering.

## 3.2. Blackbelt 3D Printer

Blackbelt is an upstart 3D printing company from the Netherlands. The company's mission is to bring fresh wind to the 3D printing landscape by coming up with designs that they hope will become the new standards of the 3D printing industry. They envision that soon, even if everyone does not own a 3D printer, they will have a 3D printed part in their home. As of 2017 their only product is the Blackbelt 3D printer, which underwent a successful Kickstarter Campaign and began shipping printers in October 2017.

### 3.2.1. Basic Design


Figure 18: Blackbelt 3D Printer *[39]*.

In keeping with Blackbelt's mission to bring new standards to the 3D printing industry the Blackbelt 3D printer boasts several design features that differ from typical 3D printers. Most notably it is designed to allow for angled printing. This is done by angling the extruder and making the print bed a carbon fiber conveyor belt. The default angle is 45 degrees, but the print angle is adjustable to 34, 25 and 15 degrees as well. The printer can print many objects in series, as there is a lip at the end of the printer that acts to peel the objects off the belt when the print is completed. The belt then deposits them in a bin at the end of the printer. The conveyor also allows to print parts that are infinitely long. In practice if you have a table to support the parts after it leaves the printer the only limit to the lengths of parts created is the amount of filament available. In addition, the printer can print 340 mm x 340 mm on its X & Y axes (the infinitely long  is the Z- axis). It is also able to print overhangs with reduced support material, since it does not print from the ground up, but rather at 45-degree slices. An example of this is shown in Figure *19* [39].

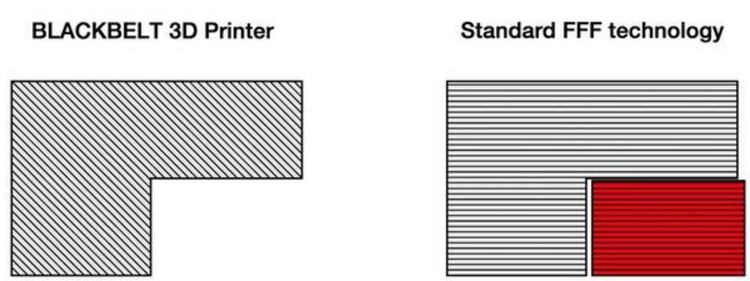


Figure 19: Blackbelt Layering vs. Standard Layering *[39]*.

The belt that acts as the print surface is made of carbon fiber and its sharp appearance is what gave the company its name. The intrinsic stiffness and low thermal expansion coefficient of the material coupled with its durability make it an ideal surface for printing. Another unique feature of the design is that it features easily interchangeable nozzle sizes for different 3D printing applications [39].

#### 3.2.2. Software

The Blackbelt printer uses an open source software called Cura that has been developed specifically for the Blackbelt printer. The software has default settings that are compatible with the Blackbelt printer, but also allows the user to input custom settings that could apply to a similar angled printer. The user can input the gantry angle, or the angle of the printer, and the nozzle diameter. The software comes with nearly all the standard customization options in normal printing software, such as layer height, wall thickness, infill and more. It is compatible with most standard part files and works by simply importing the part into Cura. From here Cura slices the part depending on the angle chosen and adds the required support material.

### 3.3. Printrbot's Printrbelt Design

Printrbot is a 3D printer manufacturing company based out of California, USA. According to the company's information page, their goal is to make the technology of 3D printing as accessible as possible [40]. The company, as of 2017, offers six different types of 3D printers, one being the Printrbelt, one CNC machine, 39 filaments, 56 individual accessories, etc. In addition to different 3D printer designs they offer standard 3D printer accessories including: material to print with those printers and individual spare parts to fix the printer. As part of their goal to make 3D printing accessible for as many people as possible, they make some of their 3D printer designs affordable for schools to purchase. It is their goal to help students learn about these technologies and become interested in the STEM fields.

#### 3.3.1. Basic Design

A comprehensive view of the Printrbelt can be seen in Figure 20, which shows the most important features of the design. The important specifications are also listed out on the product purchase page, the overall size is 20.25" x 13" x 14" and the build volume is 6" x 6" x ∞" (theoretically) [41]. The printer has recommendations for a filament material of 1.75mm PLA, a 0.2mm layer height, and a print speed of 30-60mm/s [41].

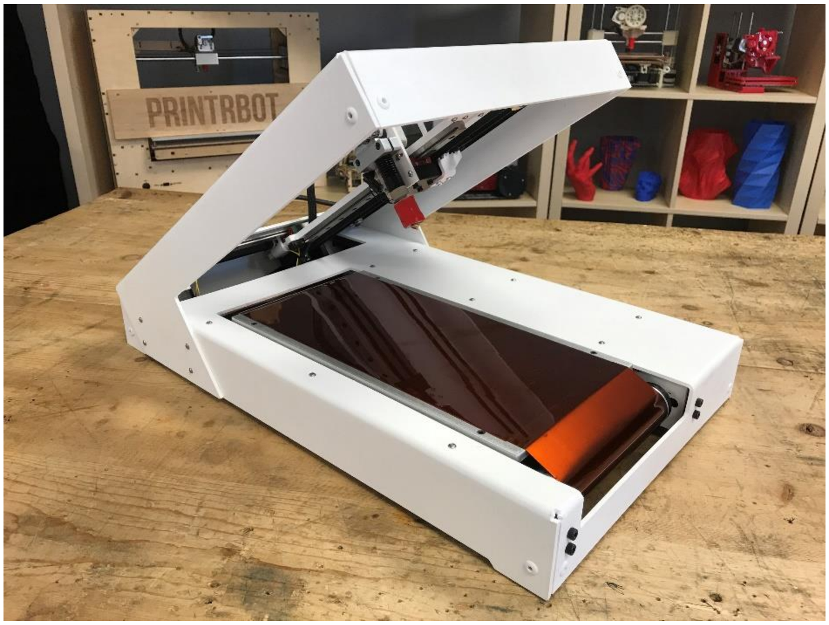


Figure 20: Printrbot's Printrbelt Design *[41]*.

One notable component of the Printrbelt is the design of the conveyor belt system. The belt is stainless steel covered in Kapton tape [41]. Kapton tape is a tape with a silicon adhesive; the tape itself has high thermal resistance, functions as a great electrical insulator, and is solvent resistant. In general, Kapton tape is used for 3D printing applications on the surface of the print bed due to its temperature resistance, compatibility with thermoplastics, and the ease with which a print can be removed from the tape. The design is relatively simple compared to a normal 3D printer. The print surface stays stationary while the belt and the extruder do the movement. The part is shifted along the belt, while the extruder moves up and down, left to right at a 45-degree angle and prints layers at that angle. To compare to normal 3D printing, it is like building a tall object, where the print bed automatically lowers every time the extruder adds a layer to the print. In this case, the belt moves the layers by a fixed increment after each layer is printed, so that the extruder is not required to move in the z direction, assuming z is the direction of the belt.

### 3.3.2. Software

On the information page for the Printrbelt, the founder and CEO of Printrbot, Brook Drumm, explains in a video that his actual inspiration for creating the Printrbelt was a challenge given to him by the actual software provider for the company, Polar3D [41]. According to Drumm, Polar3D created their own angled printing software and then asked if he wanted to create a printer that could work with their software to present at an exposition. Like Printrbot, Polar3D is also a 3D printer manufacturer with a focus on providing products to schools for education purposes. Polar3D’s printer uses polar coordinates, which they claim creates a larger build volume opposed to Cartesian or Delta coordinate systems, [42]. Polar3D also hosts an online cloud website for their slicing software, called the Polar Cloud. On this website a user can import designs or create them using an online software and link it directly to the website. Once the part is uploaded to the cloud, the creator can open the part on the website and make edits afforded in a typical slicing software [43]. The software begins by connecting to the correct printer, which means that a stable Wi-Fi or Ethernet connection between the printer and the Polar Cloud is necessary [43]. It is not clear from their cloud printing guide if angled printing is currently supported on the cloud or if the software is in the process of being integrated to the cloud.

### 3.3.3. Benefits and Disadvantages

The major advantage that the Printrbelt boasts on the market of automated 3D printers is that it can perform close to the standard of Blackbelt's design, for a fraction of the price. The Printrbelt sells for under 2,000 USD, where Blackbelt's lowest price iteration of their printer sells for 11,000 USD. For general automated printing, the Printrbelt is clearly the more economical option. The Printrbelt allows for quick production of multiple parts, regardless of length, and maintains a compact design that allows for easy transportation.

The major disadvantage of the Printrbelt design is that they offer much less in the advanced aspects of 3D printing. One of these aspects is build volume, as Blackbelt's dimensions are roughly 13" x 13" x ∞", whereas Printrbelt's dimensions are 6" x 6" x ∞". Printrbelt's design allows only half of the total height and width of Blackbelt's, which adds limitations to the printer's capabilities. In addition to build volume limitations, the Printrbelt has a fixed 45-degree angle for printing. The angle used is negligible for recreational printing, however the amount of support material required is different depending on the angle. For an advanced user who wants more options when it comes to customization, the Blackbelt has much more to offer in advanced specifications.

# 4. The Team's Design Plan

Our design plan takes place in three parts which align with the terms available to complete this project. Our general plan for A-term was to have a Bill of Materials (BOM) completed with all the necessary major parts so we can find out what parts are readily available on campus, and what parts are necessary to order at the start of B-Term. Our general plan for B-term was to order the parts, and get the printer working by the end of the seven weeks. Our plan for C-term was to finalize construction of the printer, begin testing, and finalize our report.

Angled printing is a new concept as of 2017 and the Blackbelt and Printrbelt printers are the only products available that are similar to our design. Information about how these designs perform is mostly limited to what the companies themselves say, due to the fact that they have not been in market long enough for people to discover and report possible flaws. Looking at the design choices of their printers and the reasoning for those choices our team determined certain features of those designs would be worth adding and determined aspects of their designs that we believed we could improve upon. The team also researched standard designs in 3D printers and developed ways to modify them to fit our angled design.

Figure 21: Automatic Removal on the Blackbelt 3D Printer *[39]*.

One aspect of the Blackbelt design the team thought was worth adding was a solid surface underneath the conveyor belt of the device called a build plate. This surface would attach to the bottom frame of the device and would serve to support the belt and maintain a flat surface underneath the prints. We can also situate the rollers and plate in such a fashion that the parts will peel off the end of the belt, automatically removing printed parts. This function is shown in Figure 21.

### 4.1. Functional Requirements

Our goal was to create a printer that is not bound by common restrictions of standard 3D printers. To accomplish this goal our printer must first be able to print layers at an angle that build off each other to create the desired shape. There were multiple approaches the team determined to be viable for the print angle of the printer, 30 degrees, 45 degrees and 60 degrees. This allowed us to analyze advantages and disadvantages of a lower angle, higher angle or something in between. The decision matrix we generated to compare these components is shown in Table *1*.

Table 1: Decision Matrix for Print Angle.

| **Print Angle** | Software Compatibility | Build Height | Required Support Material | Price for a Given Build Volume | Summation |
|---|---|---|---|---|---|
| 60 degrees | 0 | 3 | 3 | 3 | 18 |
| 45 degrees | 3 | 2 | 2 | 2 | 22 |
| 30 degrees | 3 | 1 | 1 | 1 | 17 |
| Weight | 4 | 3 | 3 | 2 | |

We chose the 45-degree angle because this angle offered the best balance of strength of print and build height for its price. It was important to the team to maximize print volume, while minimizing the cost of the printer. With a higher angle, less support material is needed, and a higher build height can be achieved. If we were to create the same build height for each angle, the 30-degree angle would cost the most as the top frame would have to extend much further to reach the same build height as the 45 degrees or 60 degrees. Based on these specifications, the 60-degree angle, would be the most effective choice, however open source software is not readily available for 60-degree angled printing, limiting our choice to 45 degrees.

By properly achieving the layered 45-degree printing our printer will also be able to achieve the other requirements of our design to print multiple parts in one command and be able to print parts of theoretically infinite length. If the build plate cannot be used to automatically remove the parts, then an additional mechanism to remove the parts as they reach the end of the printer must also be implemented. The printer must also meet standard 3D printer functions, such as a print surface that PLA material can properly adhere to, containing an LCD display to manually adjust the extruder and being able to interpret G-Code.

### 4.2. Design Specifications

Our printer shares many characteristics with typical 3D printers but contains several novel design considerations to print at an angle. The extruder system of our design is like that of a standard 3D printer that has been rotated 45 degrees. For the sake of simplicity with our design and printer we chose the Z-axis to be the axis that the conveyor lies on. The X-axis is the axis upon which the extruder moves side to side and the y-axis is the axis in which the conveyor moves up and down. To print multiple parts and print on an infinite axis the print surface must be constantly moving. A conveyor belt was determined to be the optimal way to achieve this function. The belt itself must be able to properly adhere to the PLA material used in the parts, while also being able to withstand the heat from the extruder hotend without melting. If the belt itself cannot meet these specifications, then an additional surface such as Kapton Tape or PEI sheets will be used. Our printer will also contain an Arduino board with an LCD display that will be used to jog the extruder. The board will contain a USB input that will allow us to transfer and execute the G-Code output from the Cura software to our printer. This Arduino board will be connected to Stepper motors used to move the extruder along the X and Y axes and the belting.

Since all the rods and belting must be contained within the top frame of the printer we had to develop adapters to hold the rods in place.

### 4.3. Software

Our team's plan for software is to use the open source Cura Slicing software that has compatibility with Blackbelt's printer. As shown in Figure 22, there are customizable options and angles that are compatible with our design. In addition to the major customizable options available, the G-code for the process can be directly edited and changed for a new printer that prints at an angle. The basic machine settings allow for control over build volume, as our design has different Z (Height) and X (Width) from Blackbelt's design. As can be seen in the G-code, there are certain actions that the printer will undergo, such as moving the conveyor belt to a certain position upon ending a print session, moving the extruder to the origin, etc. In addition to tampering with the G-code and the machine settings, we can also attempt to upload a unique printer to Cura using an open source software called OctoPrint. This software allows us to completely customize a printer and upload it to Cura, which will translate machine settings and G-code for us to use.

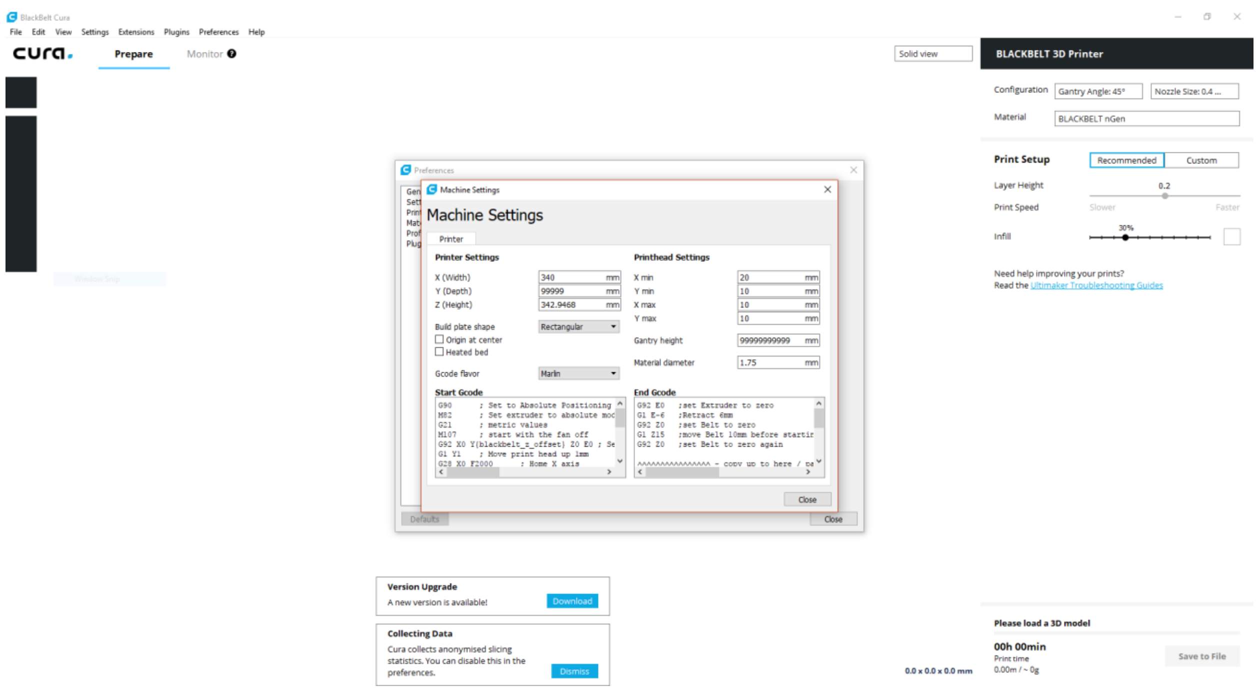


Figure 22: Cura software with Blackbelt Compatibility.

The options available for angled printing give our team confidence that software will be, at most, minor editing of machine settings to prevent crashes with our setup. With working settings, OctoPrint and Cura both have compatibility with loading files on an SD card and connecting that card to a Ramps 1.4 board to print. Due to the various open source software available, our group does not need a software engineer, nor needs to devote much time and effort into getting a printing program working, as the available software suffices.

### 4.4. Preliminary Testing and Simulations

Before our group decided to purchase any major components that could fail, we decided that it would be much more efficient to incorporate calculations and simulations into our design process. The major studies that our group completed were done with respect to the linear motion shaft and pulley pipe deflection and stress, the strength of the motion shafts in regard to resonant frequencies that could cause the stepper motors to skip steps, the heat protection of the layer of Kapton tape for covering our belt, and the power usage of our stepper motors and their drivers. The subsections of section 4.4 contain the relevant engineering analysis prior to execution.

#### 4.4.1. Print Surface Selection

Early testing on the conveyor belts revealed two belts that the PLA was able to adequately stick to. However, both belts had a glaring problem, if the extruder tip were to touch either belt it would melt the belt material within seconds. This is not a problem in an ideal print, but inevitably the extruder tip will touch the surface and it is possible that during a normal print the convection from the tip would be enough to melt the belt. It was determined that Kapton Tape or PEI sheets could be added to the belt to provide an acceptable print surface, while also preventing the belt from melting. In depth thermal test results are provided later in this section. The Slip Top Tan Nylon belt was chosen as both belts were acceptable surfaces to print on, but the Tan Nylon belt was able to withstand a higher temperature than the Cut Resistant PVC belt before melting and would thus require less additional layering to prevent damage during printing. To choose between Kapton Tape and PEI as the print surface, the following decision matrix was generated. Printing directly to the belt was included as a comparison.

Table 2: Decision Matrix for Belt Surface.

| Surface | Thermal Resistance | Adhesion | Cost | Durability | Application | Print Preparation | Summation |
|---|---|---|---|---|---|---|---|
| Only Belt | 0 | 1 | 3 | 1 | 3 | 3 | 31 |
| Kapton | 3 | 3 | 2 | 2 | 1 | 2 | 49 |
| PEI | 3 | 3 | 2 | 3 | 2 | 1 | 54 |
| Weight | 6 | 3 | 5 | 4 | 2 | 1 | |

PEI edged out Kapton tape by a slim margin as our best option for print surface. Both objects performed similar about thermal resistance, as both would act as acceptable thermal insulators to protect the belt and both have sufficient adhesion to remain attached to the belt during use. PEI was determined to have slightly better durability and is easier to apply and the team determined the relatively low cost of PEI compared to Kapton tape was enough to make it the better option, since both surfaces would eventually need to be replaced.

#### 4.4.2. Thermal Study for Print Surface

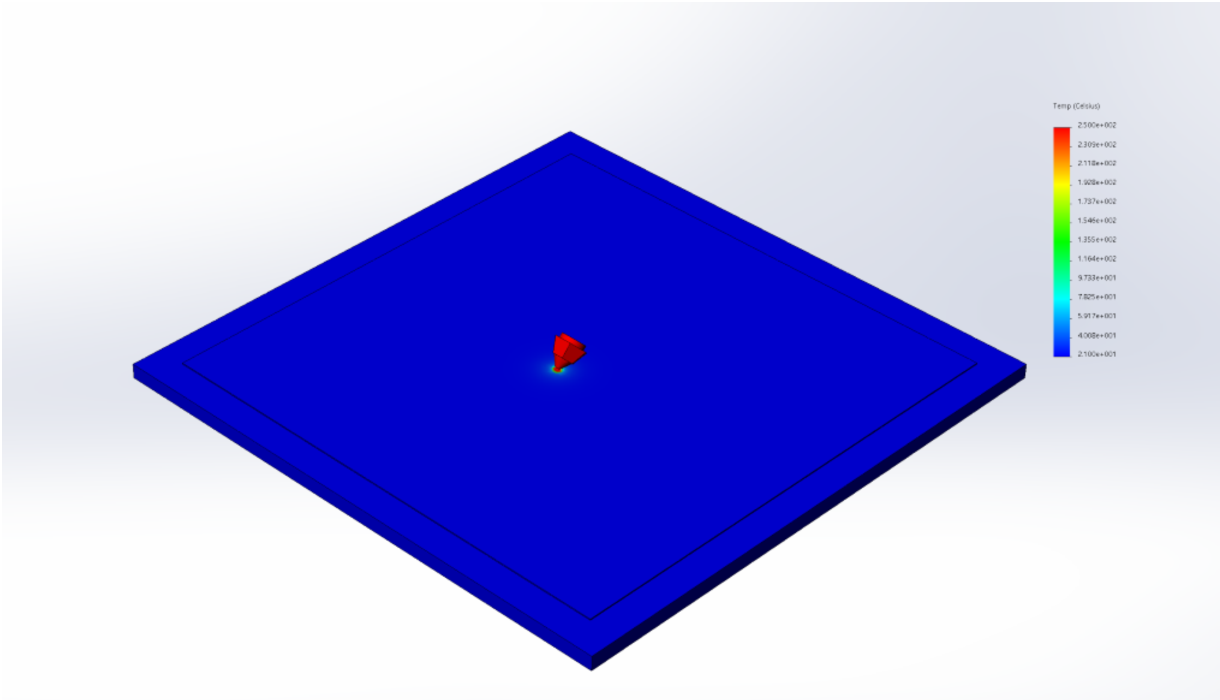


Figure 23: Thermal Study, Iso-View

To ensure the safety of the conveyor belt during normal use and during accidental crashes, a thermal study was conducted.

The tip of the extruder was separated from the rest of the assembly and modified. To obtain more accurate results in the case that the extruder tip crashed into the conveyor belt, a small slice was taken out of the extruder tip to allow for more contact area during the study. This was done to approximate the surface contact area that would result from the deformation of the conveyor belt and PEI during a crash into the bed.

- The extruder tip was set to remain at 250 degrees Celsius for the duration of the study.

- 250 degrees Celsius was chosen because it represents a worst-case scenario. The printer will support mainly PLA and PET filaments. PLA prints at roughly 210 degrees Celsius and PET prints at roughly 240 degrees Celsius. 250 degrees Celsius was chosen to provide a buffer in the case that the extruder over heated.

- The belt and PEI were given initial temperatures of 21 Degrees Celsius to represent room temperature.

- The thickness of the PEI was first set to 0.05” but was increased to 0.1” to model two stacked layer of tape after one layer was deemed to be insufficient. The results of the study can be seen in the isometric view, Figure *23*, and in the side sectioned view, Figure *24*.

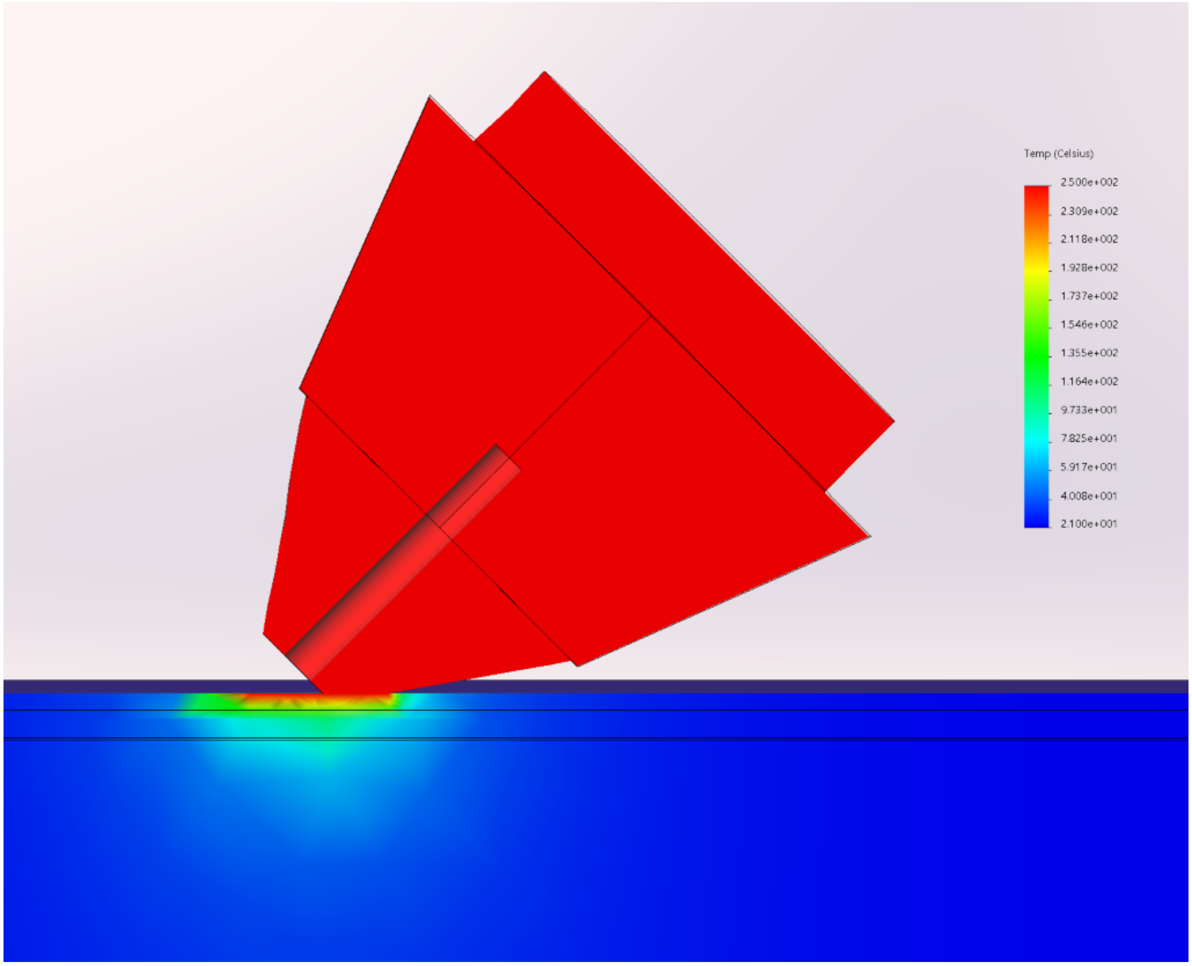


Figure 24: Thermal Study, Side Sectioned View.

Table *3* lists the maximum temperatures in the conveyor belt part in the study after 30 seconds of contact.

Table 3: Maximum Belt Temperatures.

| Location | Value (Celsius) | X (mm) | Y (mm) | Z (mm) | Components |
|---|---|---|---|---|---|
| 14954 | 1.1060E+02 | -1.5875 | 3.048 | 3.9688 | belt-1 |
| 118549 | 9.8750E+01 | -1.5875 | 3.048 | 4.3656 | belt-1 |
| 134934 | 9.7070E+01 | -1.1906 | 3.048 | 3.9688 | belt-1 |
| 134933 | 9.1080E+01 | -1.9844 | 3.048 | 3.9688 | belt-1 |
| 118550 | 9.0620E+01 | -1.5875 | 3.048 | 3.5719 | belt-1 |
| 496752 | 8.8170E+01 | -1.4492 | 2.7614 | 3.9435 | belt-1 |
| 6498 | 8.6950E+01 | -1.5875 | 3.048 | 4.7625 | belt-1 |

| | | | | | |
|---|---|---|---|---|---|
| 104889 | 8.5260E+01 | -1.1906 | 3.048 | 4.3656 | belt-1 |
| 11962 | 8.3570E+01 | -0.79375 | 3.048 | 3.9688 | belt-1 |
| 143943 | 8.2480E+01 | -1.1906 | 3.048 | 4.7625 | belt-1 |

The maximum allowed temperature of the conveyor belt material is roughly 120 degrees Celsius. However, after 30 seconds of contact between the extruder tip and PEI and the PEI with the conveyor belt, the maximum temperature in the belt is only 110.6 degrees Celsius. Therefore, two 5-mil layers of PEI should be enough to protect the conveyor belt for at least 30 seconds if the extruder crashes into the bed.

### 4.4.3. Static Beam and Pulley Deflection

Before purchasing linear motion shafts and pulleys, we wanted to make sure that we would purchase beams strong enough to handle a 10-pound load from the extruder and pulleys strong enough to handle a 50-pound load from the belt. The equations that we used to determine the maximum stress and deflection acting on the pulleys and motion shafts are shown in Figure 25.

$$\text{Deflection: } \Delta = (5(w) * (l)^4)/(384 * E * I)$$
$$\text{Max Stress: } \sigma = (-w * l)/(8 * Z)$$

Figure 25: Deflection and Max Stress Equations *[44]*.

For the deflection equation, the variable “w” stands for the distributed load and its units are pound-force per unit length. The variable “l” stands for length, “E” stands for Young’s Modulus, where aluminum is roughly 10 million psi, and “I” is the second moment of area. For a hollow pipe, “I” is equivalent to: $\frac{\pi}{64} * (OD^4 - ID^4)$ [45]. For a solid pipe, “I” is equivalent to: $\frac{\pi}{64} * (D^4)$ [45]. The distributed load that we used for our pulleys is equivalent to the maximum tension of our belt, 50 pounds per inch of width [46]. With a length of 18 inches, outer diameter of 2.38 inches, and inner diameter of 1.939 inches, our deflection on the pulleys came out to be $2.70 * 10^{-5}$ inches. For the stress equation, the “w” variable is slightly different, it is just a load, measured in pound-force, and the “Z” variable is the second moment of area “I” divided by the distance from the central axis to the outer diameter. Since our load is 50 pounds, and the distance from the center of the pipe to the outer diameter is 1.19 inches, our maximum stress came out to be -9.51 psi. As far as our motion shaft deflection goes, we reduced the projected load to 10 pounds, our length changed to 19.685 inches, and our diameter changed to 0.47 inches. This deflection on our motion shafts came out to be $2.54 * 10^{-3}$ inches, which is still within a reasonable factor of safety. The distance from the central axis to the outer diameter for our motion shafts came out to be about 0.236 inches, which brings our maximum stress on the rods to about 150 psi. The dynamic studies and calculations for the forces on the linear motion shafts is detailed in subsection 4.4.4.

#### 4.4.4. Resonant Frequencies and Dynamic Forces

A vibration study was conducted to ensure that the printer would not reach resonant frequencies during normal use. First, the maximum achievable frequency of printer movement was calculated. From printing software known as Slic3r, the maximum typical acceleration of an extruder assembly was discovered to be 2 (m/s^2). The minimum distance that the printhead could move before switching directions was calculated by multiplying the extrusion thickness, 0.45mm, by two which comes to 0.9mm.

Therefore:

0.9mm = 0.5 * 2000 m/s^2 * t^2

t = 0.035 sec, and max velocity = 60 mm/s which is within the range of typical values according to Slic3r.

The minimum amount of time to travel 0.9mm is therefore 0.03 sec

The max attainable frequency is then equal to = 1/(0.03) Hz = 33.333 Hz

The first five mode shapes and frequencies can be seen in Figure *26* through Figure *30*. The first mode has lowest frequency 84.188 Hz, more than double the printer's max attainable frequency.

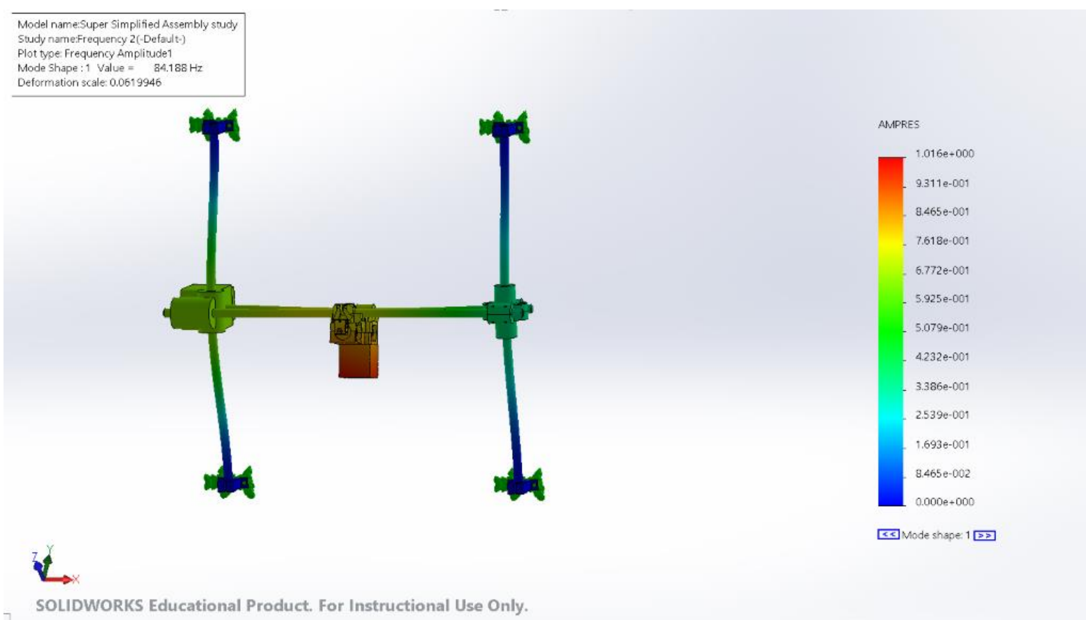


Figure 26: Vibration Study, Mode 1

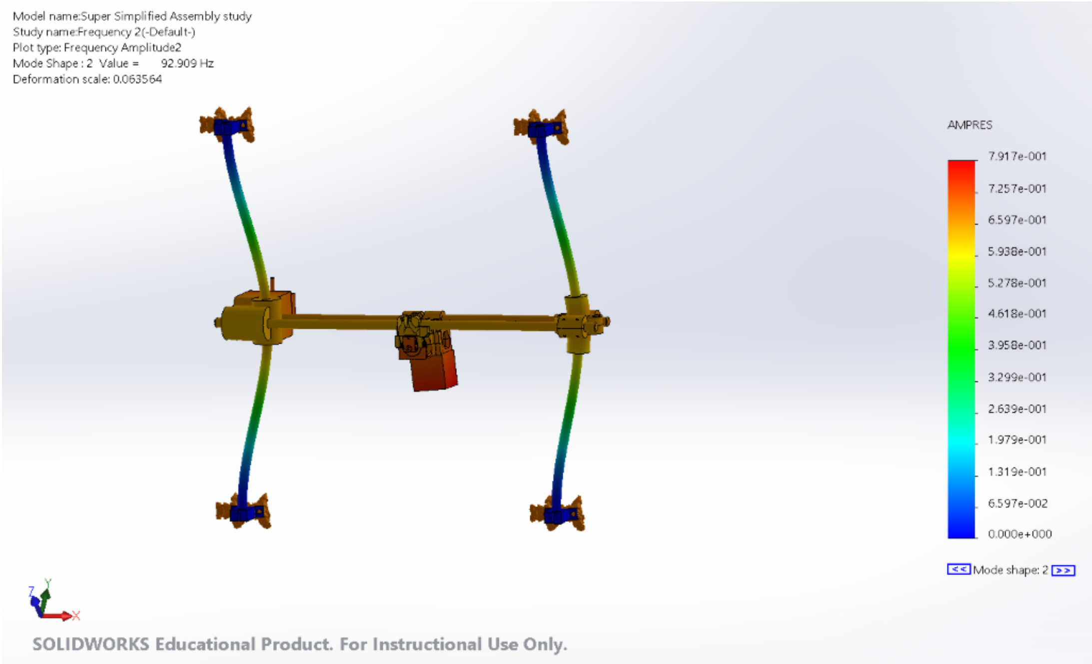


Figure 27: Vibration Study, Mode 2

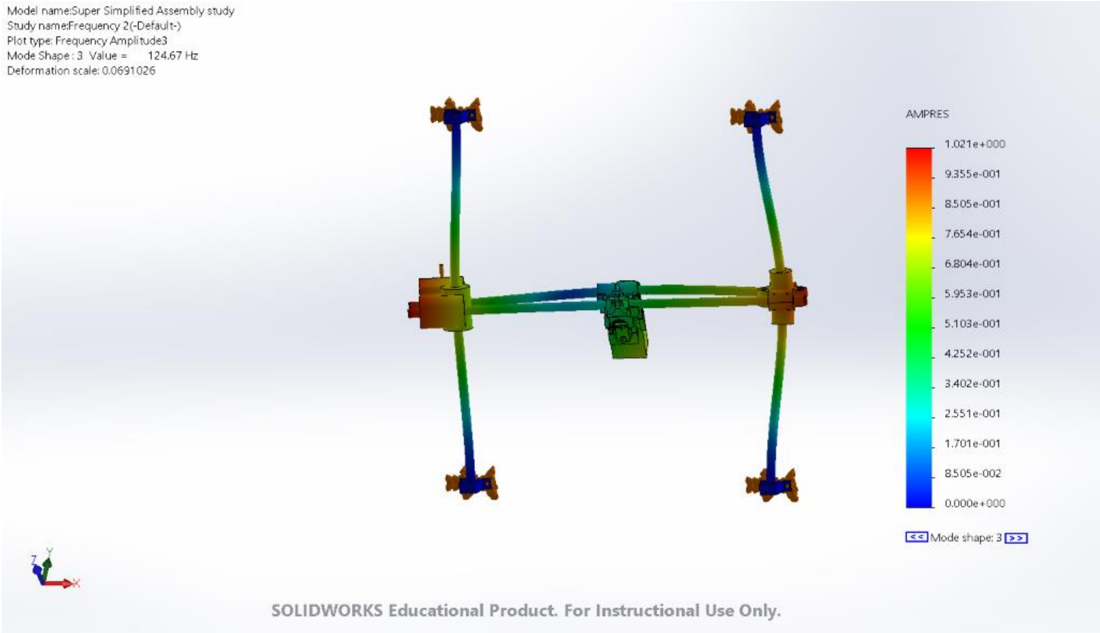


Figure 28: Vibration Study, Mode 3

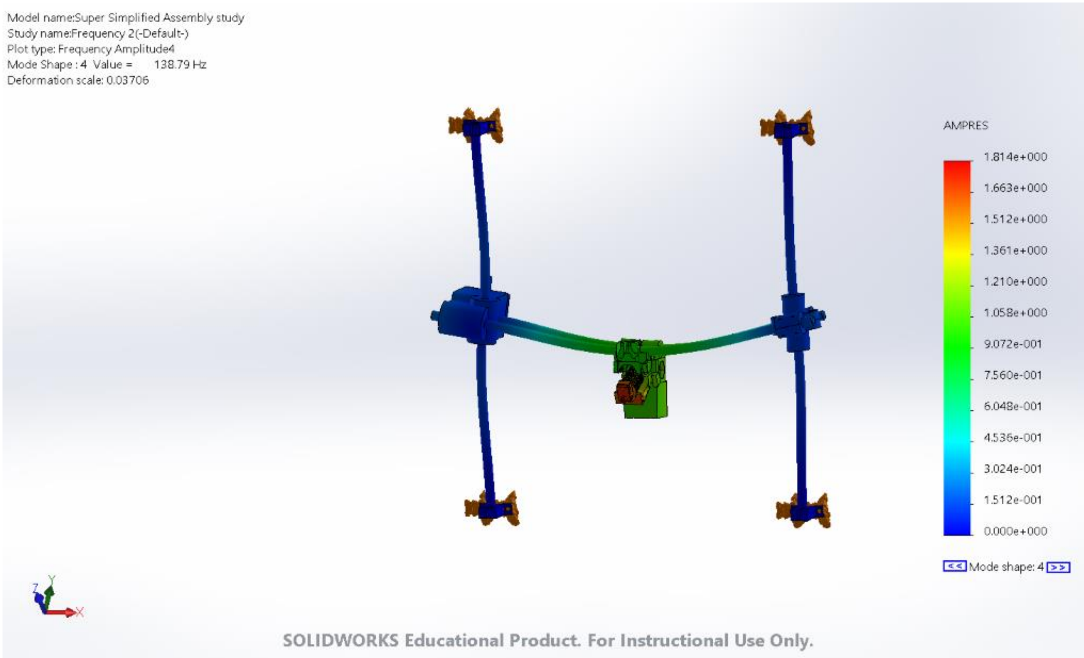


Figure 29: Vibration Study, Mode 4

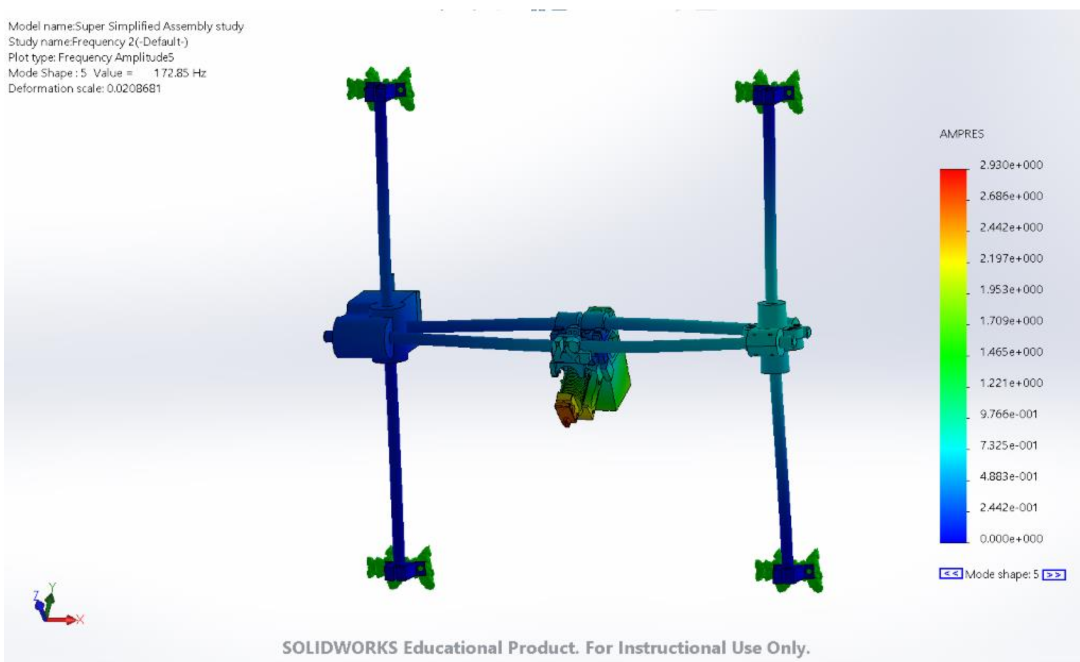


Figure 30: Vibration Study, Mode 5

To find the maximum deflection during typical printing, two studies were conducted in which horizontal, and then vertical, forces were applied cyclically to the assembly. The magnitude of the force was calculated by multiplying the weight of the extruder assembly, 0.4995 kg by the max printing acceleration, 2 m/s^2, which gave a force of 1 N. This force was applied at frequencies attained during normal printer movement ranging from 0 to 17 Hz.

The results can be seen in the deformation plots in Figure *31* and Figure *32*. However, although the plots indicate that the max deformation would roughly equal a negligible 0.0025 mm, these results must not be taken too seriously.

Firstly, further studies should be conducted with frequencies ranging from zero to the max attainable frequency of the printer head, 33.3 Hz.  Secondly, the dampening factor for all materials in the assembly was assumed to be 0.1. Further research should be conducted to obtain realistic dampening factors for each material, especially that of the linear rods. However, it is worth noting that regardless of the actual dampening factors, assuming they are not zero, the assembly should deflect less dynamically than it does statically if it does not reach resonant frequencies, which it cannot. Furthermore, according to earlier studies, the maximum static deformation of the assembly is negligible for normal printing. To clarify, the static study consisted of forces on the x/y-axis assembly resulting from the effects of gravity and the max acceleration of the extruder/print head assembly.

The resulting deformation plots for 17 Hz can be seen in Figure *31* and Figure *32*.

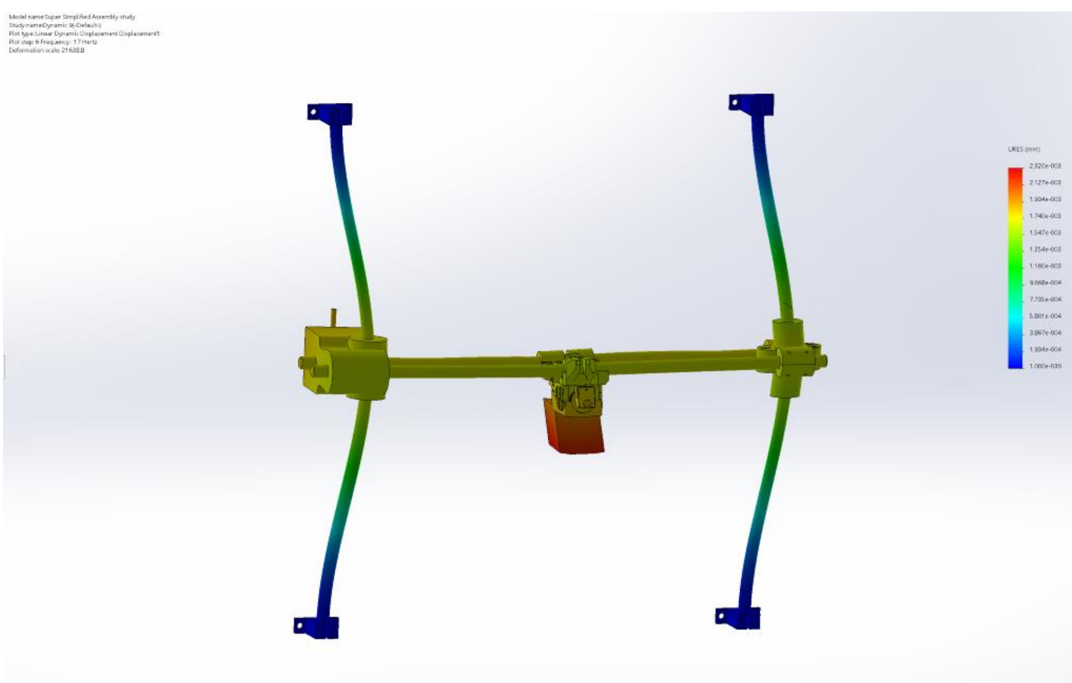


Figure 31: Dynamic Study, Horizontal Cyclic Force

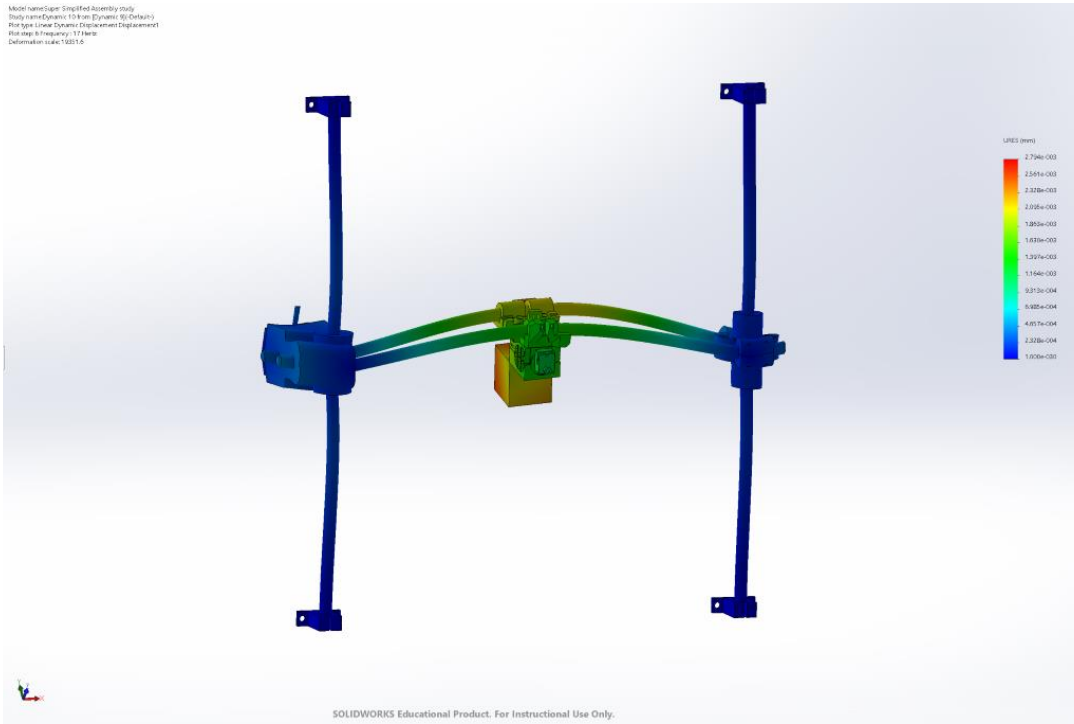


Figure 32: Dynamic Study, Vertical Cyclic Force

### 4.5. CAD Models

Throughout the design process it is inevitable that a prototype will undergo different iterations as the design is tested and improved. Our printer was no different. As we added different components to the printer assembly certain design choices were determined to be inadequate and had to be redesigned. The reasoning for this stemmed from the parts either not fitting together correctly or parts needing to be replaced after failing early design simulations. Other parts hard to be changed based on availability of certain standard parts and our ability to manufacture parts on WPI’s campus. This section details the three major stages of our prototype, going from our initial printer design and detailing all the design choices that brought us to the final model of the printer.

### 4.5.1. First Prototype

Figure 33: CAD Model of Our First Prototype

The first prototype of our design was just a simple model of how we intended our design to look. Many of the more detailed components were not yet added, since we anticipated significant changes to the design. We included a bottom frame made of 1-1/2-inch double 8020 aluminum framing. Each side is 2 feet long. This frame attaches to a similar top frame with a standard pivot part. A bracket was intended to be added to future designs to support the top frame and would have slots to set the printer at its various positions. The bottom frame houses the build plate which is made of nylon and attached directly to the frame. Attached to the top frame is the extruder assembly which is driven by stepper motors. The extruder assembly itself is inspired by the extruder used in the Prusa i3 MK2, which is pictured in Figure 34. We modified the carriage used in their design to be compatible with the linear motion shafts used in our design. The shafts that hold the extruder are 0.38 inches in diameter and 2 feet long. The design features four 5.75-inch feet made of 1-inch square 8020 framing as a way to ensure there is enough room for the conveyor belt and to provide easy access to the belt if there is a need for maintenance.

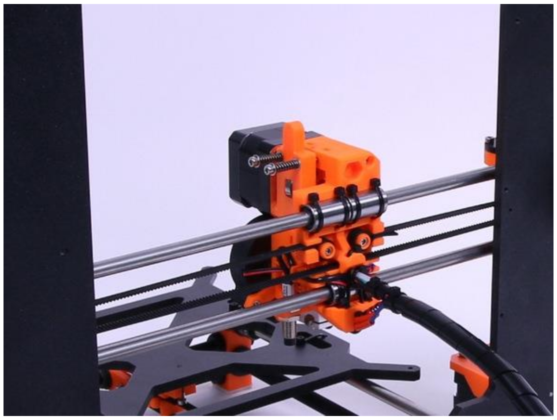

Figure 34: Extruder Assembly from the Prusa I3 MK2 *[47]*

### 4.5.2. Second Iteration

As we started adding more components into the design we realized certain components did not entirely fit together. We also found access to new parts that would reduce the cost of the printer. With these new insights into the design we updated our first prototype, giving us the second iteration of our design. After conducting the decision matrix in section 4.1, the team decided that 45-degree printing was the best option. We determined 60-degree printing was not compatible with our printing software and under 45-degree printing did not have any advantages over 45-degree printing. The pivot attachment in the original design was abandoned, instead we opted to make the connection a fixed angle, increasing the sturdiness of our design. Brackets were added at the base and toward the end of the printer to support the top frame.

The first major change to the second model of our design is the 8020-framing used in the top and bottom frames has been changed to reduce the cost of the parts. The bottom frame is still made of 1-1/2-inch 8020 framing but is now only single faced instead of double like the previous design. The frame is also now rectangular. The two bars on the length of the printer are 28 inches, while the frame for the width of the printer runs 20 inches, allowing us a roughly 20-inch build width. There are also four 4-inch-long feet added to the design, to be made from the leftover material from the bottom frame. The top frame has been modified as well and is now made of 1-inch square 8020 framing. The one bar that runs the width of the device is 20 inches long to match the bottom frame. The two bars that go up at a 45-degree angle are slightly more complicated. These bars are 24 inches long will be cut at a 45-degree angle and attach directly to the bottom frame, giving us a roughly 12-inch build height.

The pulley system that will drive the conveyor was added into this iteration of the design. Both pulleys are the same, with a 2.38-inch diameter and lengths of 18.25 inch. To reduce cost the pulleys will be made of pipe cut to length and filled in with solid rods toward the end of the pulley. The pulleys are connected to Nema 17 geared stepper motors with a 5 to 1 reduction; one on each side of the exterior of the device. The back pulley is located 2.75 inches from the device, while the front pulley is adjustable. Once the belt is installed the front pulley will be adjusted until the belt has enough tension to produce a flat surface over the nylon plate.

The extruder assembly attached to the top frame has also been modified and iterated on the current design. To ensure the extruder does not vibrate during use the rods used will now be 12 mm in diameter. Each rod is also 500 mm long. The adapters and mounts for the rods were adjusted in accordance with the new diameter. The extruder remains the model from the Prusa i3 MK2, with the carriage that connects the extruder to the rod modified to fit the new rods. Mounts for the bearings and stepper motors were also added to the design. These motors will drive the extruder along the X & Y axes. The motor is situated as such that the lowest point the motor can reach coincides with the surface of the build plate.

### 4.5.3. Current Model

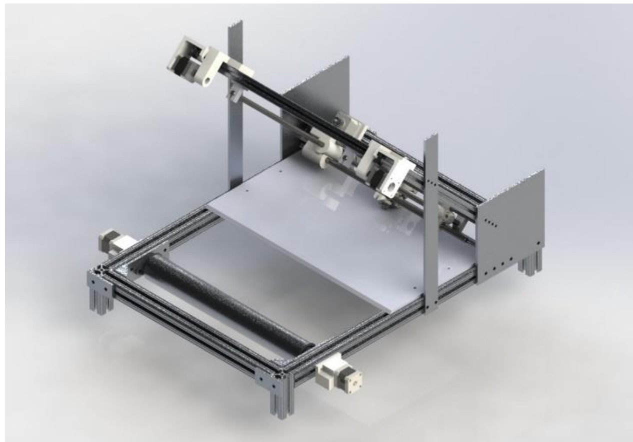

Figure 35: Model of our Current Design

The third iteration and current model of the printer is mostly like the second iteration of the design. The bottom and top frames remain the same, as does the pulley system and build plate. Material properties were added to the design to allow us to conduct various studies on the design in Solidworks.

Most of the changes in this iteration come from the extruder assembly. The stepper motors and pulley systems were refined to ensure that every gear is in line with one another. Modifications were made to both X-Y adapter parts to accommodate the belting that attaches to each of the stepper motors. The X-Y adapter with a Stepper Motor mount was heavily modified in this iteration. The previous design was running into the side of the frame and some of the pulley mounts, so the stepper motor was placed on top of the adapter instead of being level with the adapter as in previous designs. This cleared up all the previous interferences. A pulley system will be used so that the belt is still level with the other side of the assembly. Holders for bearings were added to the adapter to facilitate this pulley system. With these changes to the printer our current build volume is determined to be about 15 inches wide by 11.75 inches high, with the length of the print being theoretically infinite.

## 4.6. Parts

The parts used in the printer can be broken down into three major categories; standard parts, machined parts and 3-D printed parts. We tried to use standard parts wherever possible to ensure the parts will properly fit together. Since angled 3-D printing is still a novel idea, there are parts in our printer that are specifically designed by us, bringing us to our other two types of parts. Machined parts, which are standard parts that will be modified in the machine shop to fit our design and custom 3-D printed parts, made of ABS, for parts that we created with a precise design.

### 4.6.1. Standard

For creating a simple 3D printer design, our group decided to include as many standard parts as possible. Our first standard part is the frame, which we decided on the popular 8020 extruded aluminum as shown in Figure 1, as it is a common and generally inexpensive material that works well for general purpose framing. The aluminum is strong enough to hold up to the loads of an extruder and multiple stepper motors, as well as maintaining the advantage of having machined slots, which allow for simple assembly. Manufacturers also produce brackets and fasteners that are specifically compatible with the different sizes and rail styles of 8020. In addition to the 8020, we purchased a 3' x .25" x 1.5" aluminum bar. The bar is cut into two 1.5' pieces and are used as support arms for the uppermost part of the top frame. In addition to that aluminum bar, we purchased two 8" x 8" x .25" aluminum sheets that we drilled holes into to fix the bottom of the top frame to the back of the bottom frame. For the printbed, we purchased a simple 1' x 2' x 0.25" nylon sheet; we drilled holes in this sheet and fixed it to the bottom frame.

Based on our calculations for a static beam deflection under an exaggerated extruder load, we decided to purchase linear motion shafts with 12mm diameters, and 500mm lengths. The 500mm length is to attempt to maximize the total width of our belt, as the belt is about 460mm wide, and to maximize the height of the print. We have ordered four of these rods, two of which are intended to guide our extruder in the X-direction, and the other two are intended to guide our extruder in the Y-direction. Based on this decision for motion shafts, our linear motion bearings and shaft supports revolved around this 12mm diameter. The linear bearings are shown in Figure *36* on the left, and the base mounted shaft supports are shown on the right in the same figure. Our design incorporates seven linear bearings, 3 of which are contained within the extruder assembly and then two are slotted within a custom plastic part for each of the Y-axis rods. The base mounted shaft supports act as a solid fixture for the Y-axis rods, each rod has a shaft support at either end to fix the position of the rod.

Figure 36: 12mm Linear Motion Shafts and Base Mounted Shaft Supports *[48] [49]*.

Based on our calculation for the total power required for our normal and geared stepper motors in addition to our E3D-V6 hotend, we found that, with a safety factor of two, a 100-Watt power supply would suffice for our printer's power needs. In addition to the power supply, we also needed our stepper motors and geared stepper motors to move the extruder assembly and the conveyor belt system respectively. We bought four stepper motors, two for the Y-axis, one for the X-axis, and one on the extruder itself; we also bought two geared steppers for the conveyor belt; we used two stepper motors for each movement to eliminate backlash. We needed stepper motor driver boards to run these stepper motors. We bought one expansion board that could drive four stepper motors, and a board with an Arduino that could drive four stepper motors as well.

To finish our Y-axis and X-axis assembly, we needed toothless bearings that could fit a timing belt, which would move the extruder assembly. The bearings are mounted near the bottom of the angled frame in a custom 3D printed part. We bought one package that had plenty of these types of radial bearings. We also needed a kit that had pulleys fit for stepper motors and a timing belt. We found a kit that had theses pulleys and 5m of timing belt that worked for our design. For the stepper motors at the top of the printer, we wanted to make sure that their shafts had additional support, so we purchased radial ball bearings that are mounted in another custom 3D printed part, which connects to the frame of the printer, to provide support to the shaft.

We modeled our extruder assembly after the Prusa i3 extruder. We bought two fans, one for cooling filament and one for cooling the hotend. In addition to the cooling fans, we used the E3D V6 Hot-end, which we had on-hand, and the I3 MKS2 Extruder Gear, which we also had on-hand. We did have to make a custom X-carriage for our design, as the Prusa i3 design has much smaller linear bearings in their version of the X-carriage.

#### 4.6.2. Modified

Conveyor Belt: Although it was intended to be purchased as a closed loop conveyor belt, this proved too expensive. Instead, 3D printed tools were made to cleanly cut the conveyor belt at a fixed angle after which the two ends were attached. Loctite Rapid Repair was used to attach the two ends of the belt after testing sufficiently proved that the glue would produce an acceptable connection between the two ends of the belt. If the rubber repair had not proved strong enough, additional fasteners, such as staples and seems, would have been tested in combinations with the rubber repair until desirable results were achieved.

Base Mounted Shaft Support: This standard part attaches the linear rods of the y-axis to the top frame assembly. However, to prevent interference with the conveyor belt during operation of the printer, one of the top corners must be trimmed down. It is important that the shaft supports be mounted in such a location because this allows the zero-height position of the extruder to be closer to the center of the printbed.

3D Printer Extruder Nozzle: Unfortunately, the sides of standard 3D printer nozzles would collide with the bed if the tip was made coincident with the bed while the extruder is at 45 degrees. To resolve this, the sides of the hexagonal ratcheting surfaces of the nozzles must be chamfered.

Pulley Pipe: We only need 18 inches of pipe for each pulley, since we need to potentially make modifications, we must order 4 feet of pipe. If the pipe were to be cut incorrectly, this would give us excess material to account for any error in hacksawing.

#### 4.6.3. Machined

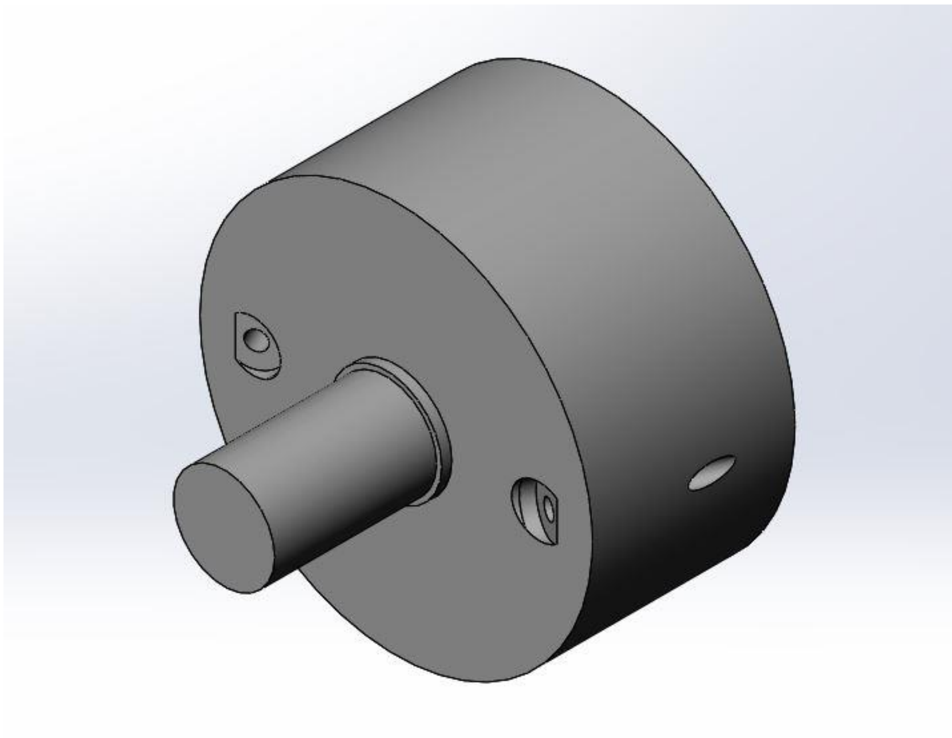

Figure 37: Belt Roller Idler Insert

Inserted into the ends of the hollow idler conveyor pulley, this will function as the axle of the roller for use with the rotary bearing. The larger end is inserted into the roller itself and secured with the two tapped and angled screw holes against the inner walls of the pulley. The smaller end is inserted into the rotational bearing with the small lip preventing the larger face from rubbing against the bearing during use. It will be made using a lathe except for the screw holes which will be drilled and tapped after.

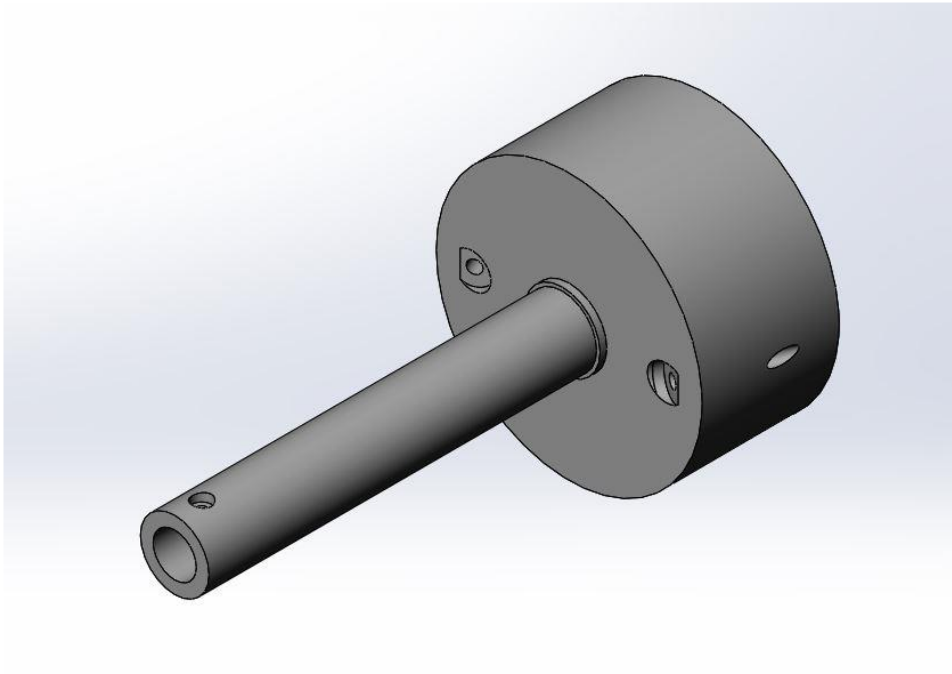

Figure 38: Belt Roller Driver Insert

Inserted into the ends of the hollow driver conveyor pulley, this will function as the axle of the roller for use with the rotary bearing as well as a coupler between the geared stepper motors and the driver pulley. The larger end is inserted into the roller itself and secured with the two tapped and angled screw holes against the inner walls of the pulley. The smaller end is inserted through the rotational bearing, with the small lip preventing the larger face from rubbing against the bearing during use, and then goes through the extruded aluminum framing and connects to the gear stepper motors. It will be made using a lathe except for the screw holes which will be drilled and tapped after.

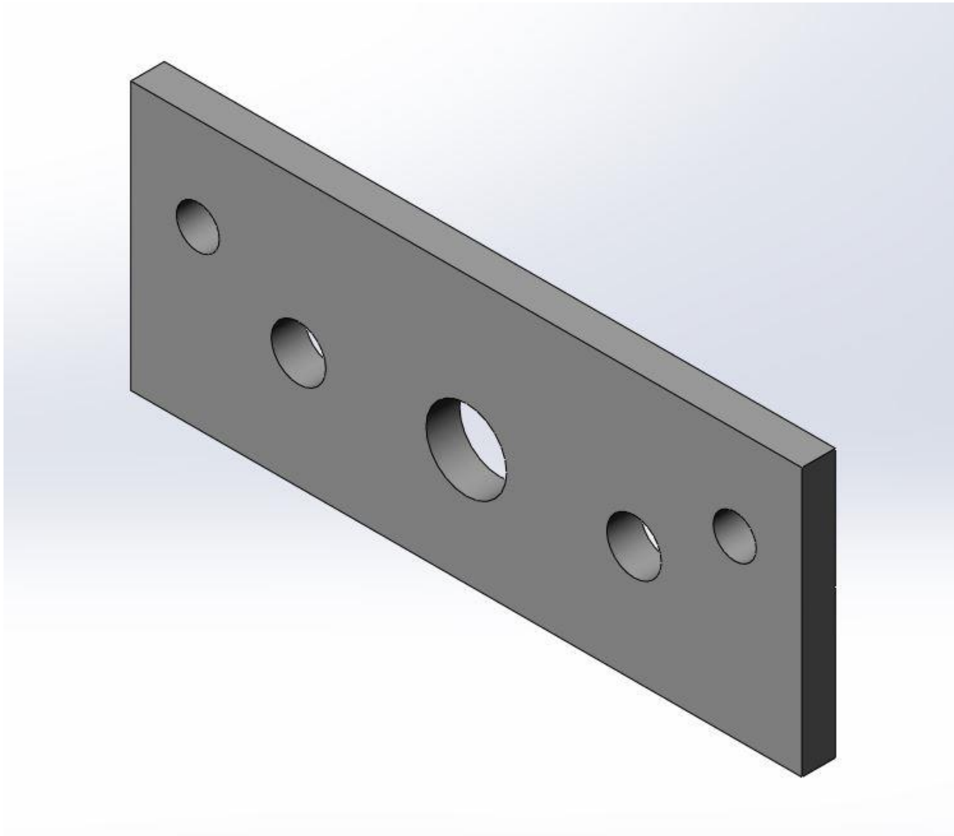

Figure 39: Mounting Bracket for Belt Roller Insert

This part serves as a mounting system for the roller bearing and allows the idler roller to be easily moved forward and backward for adding belt tension. It included a through hole that will allow the shaft of the belt roller driver insert to securely pass through an identically sized hole in the extruded aluminum frame. It was manufactured on a CNC mill.

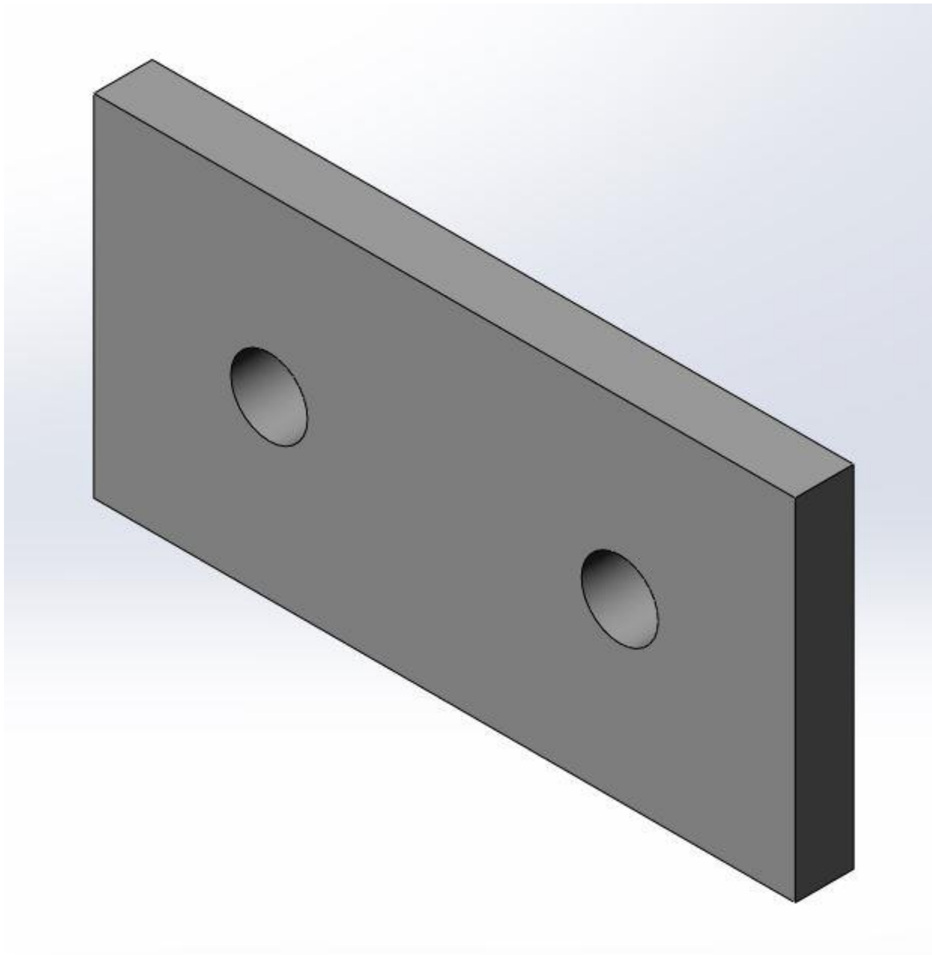

Figure 40: 1.5" Bracket

This bracket will serve to connect the feet of the printer to the four corners of the bottom frame. It is sold as a standard part, but we will be using left over materials to machine it due to its high price. It will be made on a CNC mill.

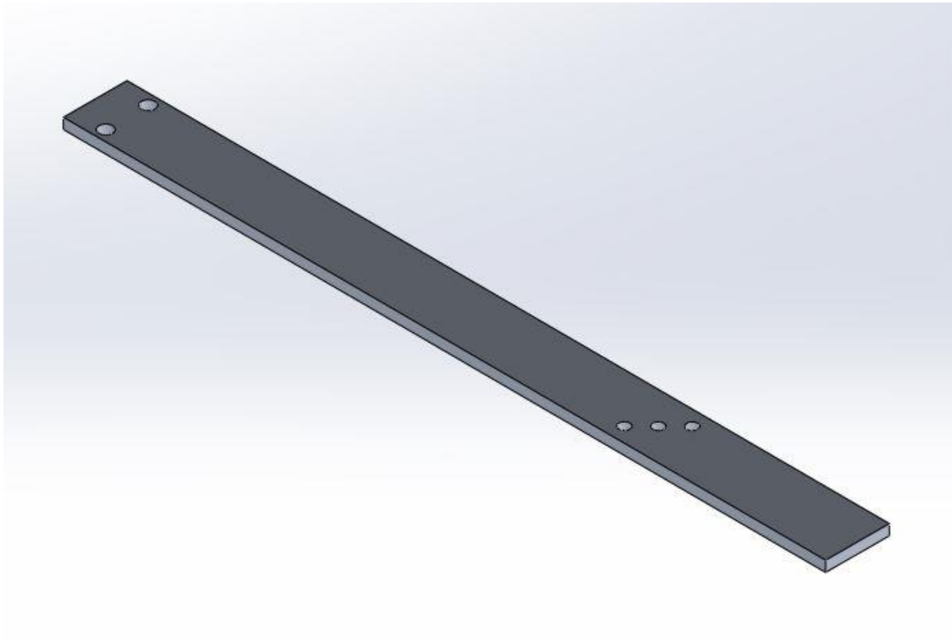

Figure 41: Side Support

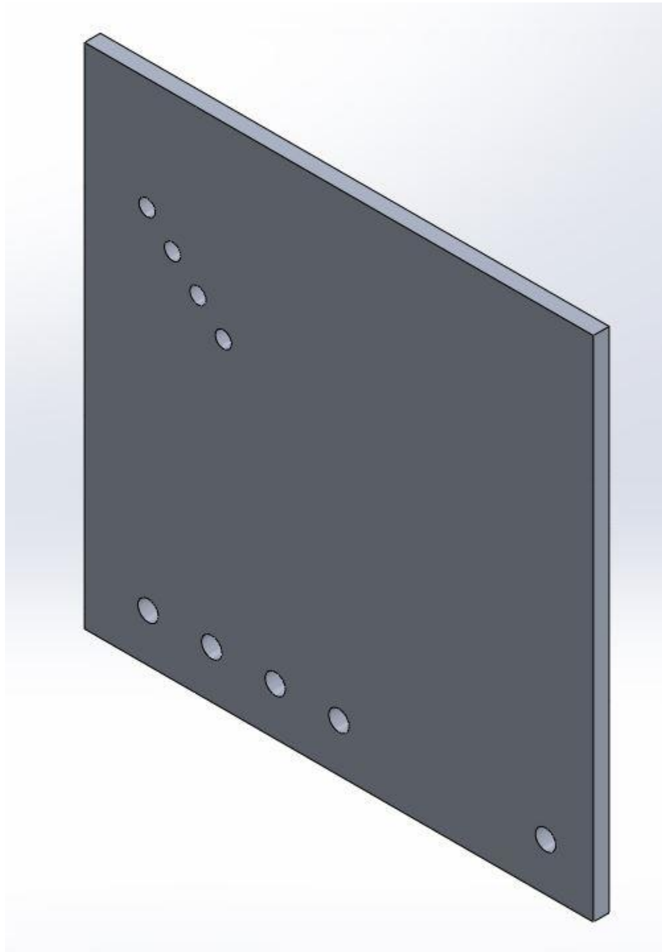

Figure 42: Connector Support

Created from a sheet of aluminum, the parts in Figure *41* and Figure *42* will serve as the structure and support between the extruded aluminum bottom and top frames. They will be manufactured using a CNC mill.

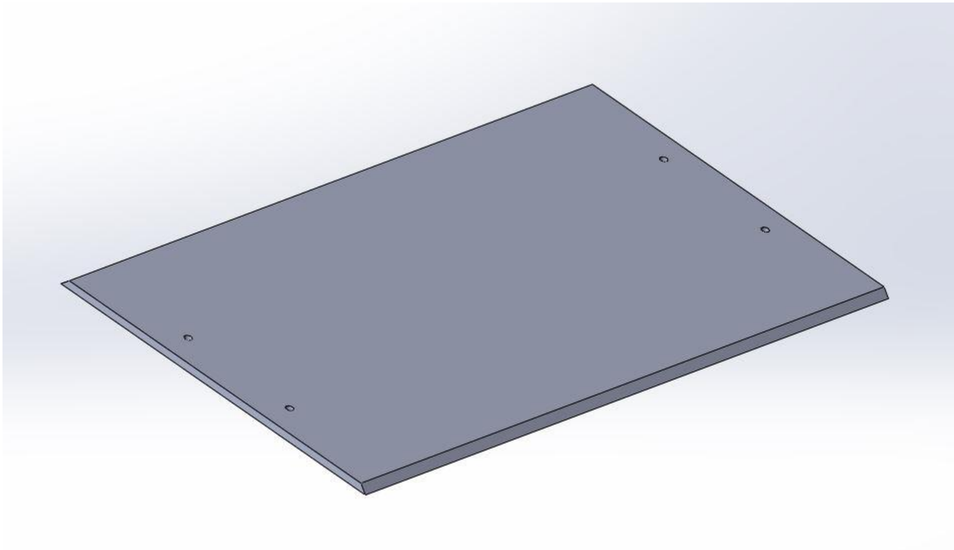

Figure 43: Printbed

The printbed will support the conveyor belt during printing and will be CNC milled out of nylon to allow the belt to easily slide over and around it.

### 4.6.4. Custom 3-D Printed

Many parts were designed that are unique to our 3-D printer, due to the complex nature of some of these designs it was determined 3-D printing the parts was the most efficient method. All parts are made of either PET or PLA material and were printed using on campus 3-D printing facilities. PET material was preferred for all parts but difficulties with printing some of the larger parts with complicated geometry, such as the XY-Axis Adapter with Stepper Motor Mount called for PLA for easier more reliable 3D printing.

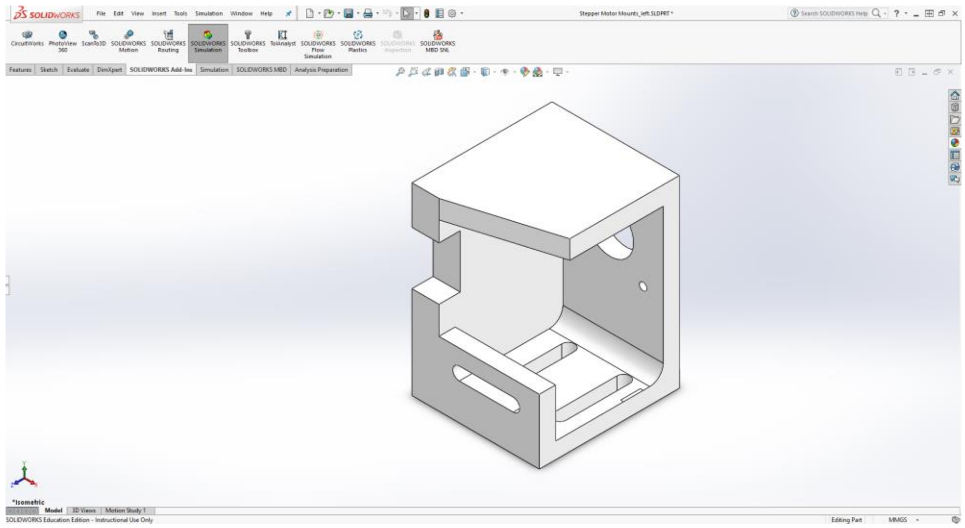

Figure 44: Stepper Motor Mount.

The Stepper Motor Mounts are attached directly to the top frame and have holes that line up with the screws on the back of the Nema 17 motors. Figure *44* shows the final design of our stepper motor mounts, this one is for the stepper motor on the left looking at the printer straight forward. Our original designs stems from the standard Nema 17 plastic motor mounts, however we needed to change the interface which connects the mounts to the frame, as our frame is the 8020-extruded aluminum, where the standard mounts are not designed to interface with extruded aluminum. The other changes we made were increasing the total thickness of the part as it must hold the stepper motor at a height of 1 foot while moving the load of the extruder up the frame.

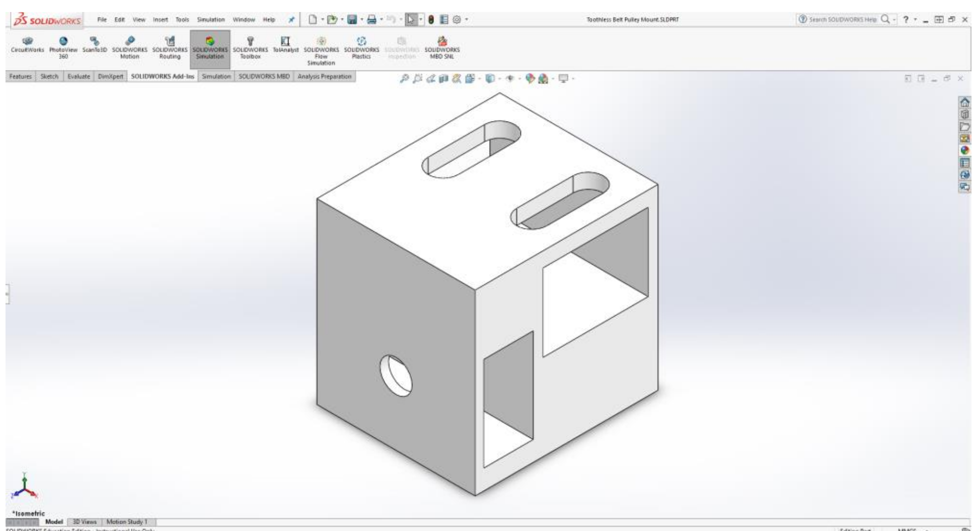

Figure 45: Toothless Belt Pulley Mount.

The Toothless Belt Pulley Mount is intended to mount a toothless pulley in the thinner cut, using a shaft that allows the pulley to freely rotate while the shaft is fixed in the mount itself. The pulley provides a place for the belt to loop. The orientation of the pulley is ensured to be in line with the geared pulley on the Y-axis stepper motors so that there will be no motion that could create a corkscrew effect on the belt. Our original design had a smaller hole for the pulley itself, as the manufacturer did not give out the part thickness in the specifications, however we edited the part such that we could maintain the parallel pulleys while increasing the thickness of the hole.

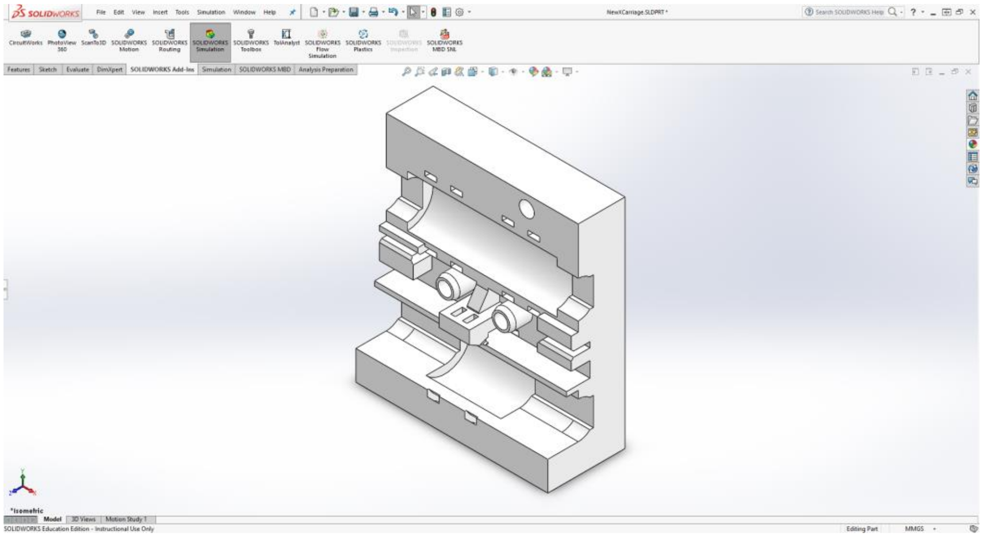

Figure 46: X-Axis Extruder Carriage.

The X-Axis Extruder Carriage is a modified version of Prusa's i3 X-carriage model. The CAD model for their X-carriage was difficult to change to fit our parts using feature recognition, and we opted to make our own, while maintaining important features present on Prusa's model. We created the slots for the bearings at 22mm wide, the thickness of our bearings, and created small holes for zip ties so that the bearings would stay locked in place. We also created the belt loop zone, which is defined by the two conical pins and the bridge below it. The timing belt loops around each of the conical pins and pinches in the small slots on the sides of the item. The belt then loops around the other parts in the extruder axis assembly. The two conical pins also have holes with countersinks to accommodate screws to attach to the hotend extruder, and there is a screw hole at the top as well to attach to the rest of the extruder.

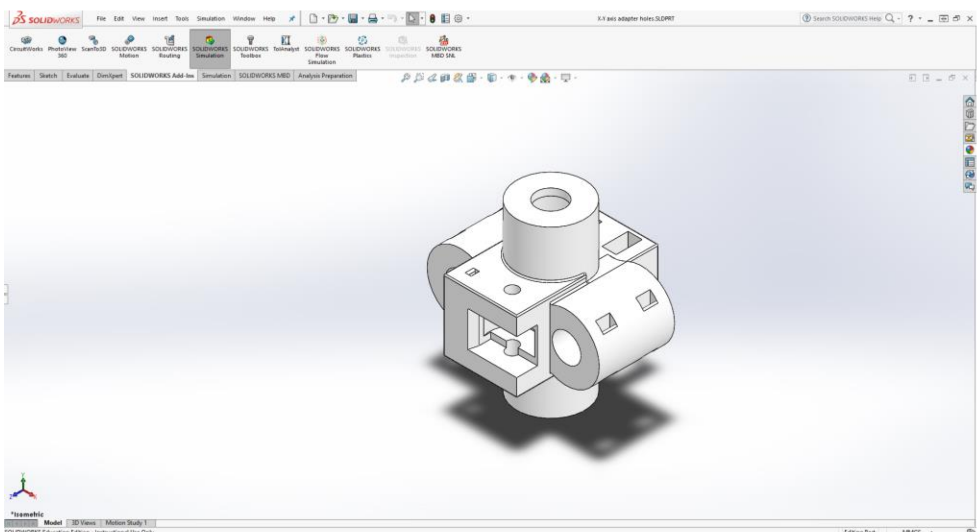

Figure 47: X-Y Axis Adapter

The X-Y Axis Adapter is intended to connect the X-axis rails with one of the Y-axis rails. There are holes on the right and the left of the part that clamp the linear motion shafts in the X-direction, while also maintaining the space in the middle of the part to slot two linear bearings for one of the linear motion shafts in the Y-direction. This part also contains a slot for a toothless pulley to allow the timing belt from the extruder to loop around it. It also contains holes on the far side that loop the timing belt between one of the Y-axis stepper motors and one of the toothless pulley mounts. This ensures that when the stepper motor moves in the Y-axis, this part moves accordingly in the Y-direction and subsequently moves the extruder in the Y-axis.

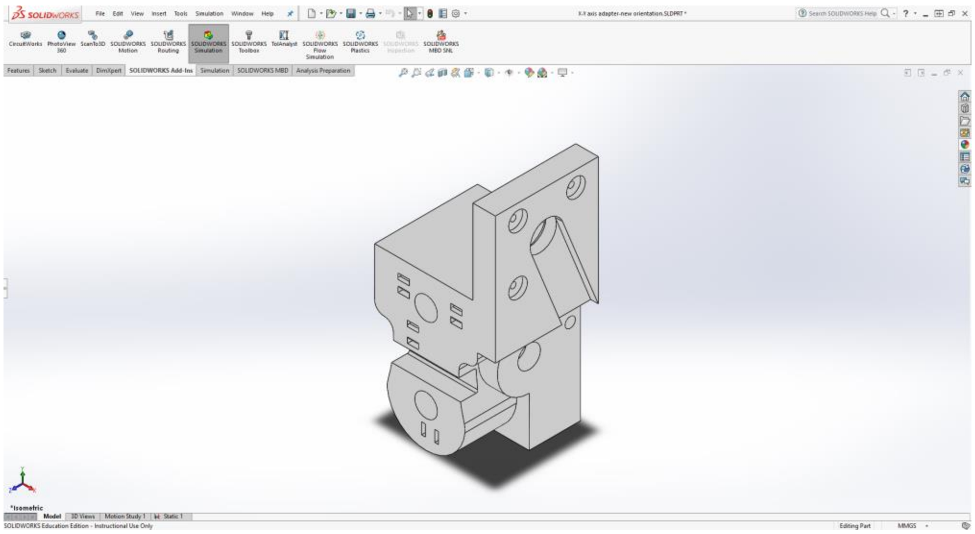

Figure 48: X-Y Axis Adapter with Stepper Motor Mount

In addition to what the other X-Y Axis Adapter performs, this part contains mounting capabilities for a stepper motor. The shaft of the stepper motor fits trough the center hole on the top right side of the part, where a geared pulley will mate with the shaft. There is another geared pulley spot where the belt will contact, and this is how the timing belt is driven in the X-direction. The timing belt loops between the two pulleys, and the pulley on the bottom is mated with a shaft that is mated to another geared pulley. That geared pulley is in line with the extruder X-carriage and the X-Y axis adapter and actuates motion equivalent to the motor output. There are two holes on the front-left of the part that clamp on the X-axis motion shafts, and one hole on the front-right that clamps on the Y-axis motion shaft. There is a slot above the bottom X-axis shaft hole that allows the timing belt for the other Y-axis stepper motor to slide by. There are holes that pinch one end of the belt, allowing this part to move freely along the Y-axis.

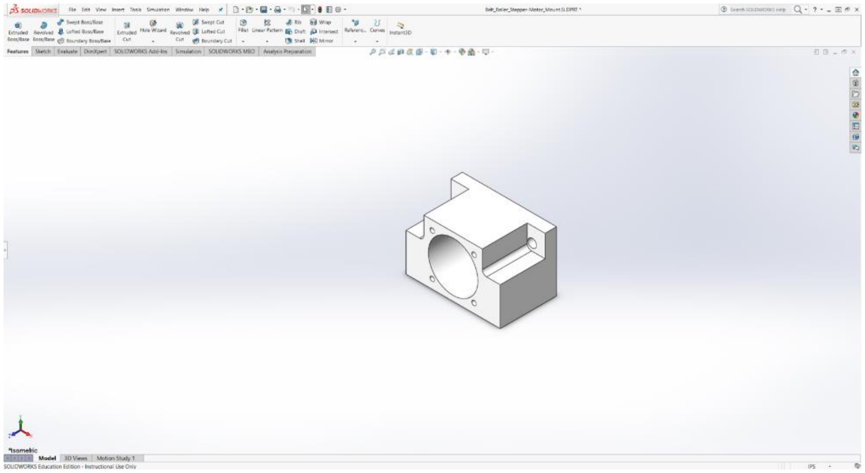

Figure 49: Geared Stepper Motor Mount

The Geared Stepper Motor Mount is necessary to mount the geared stepper motors to the frame so that they can move the pulley assembly. The screws on the further face mount to the frame, and the holes on the closer face are to mount the stepper motor to the structure. The hole centered on the part is designed to fit the planetary gearbox within such that the shaft of the motor is far enough forward to mate with the pulley inserts.

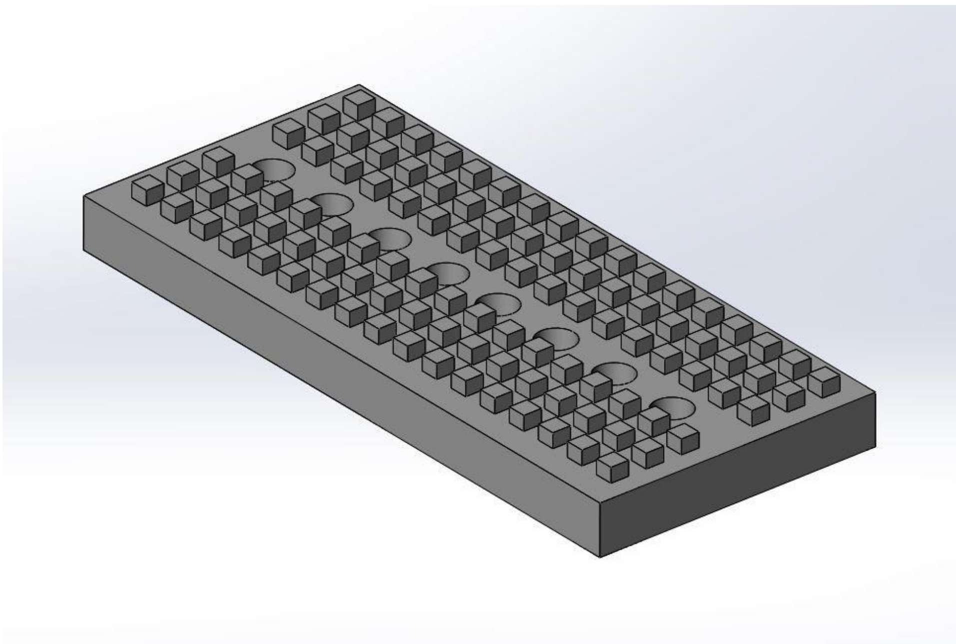

Figure 50: Hand Gripper for Conveyor Belt Slicer Version 1

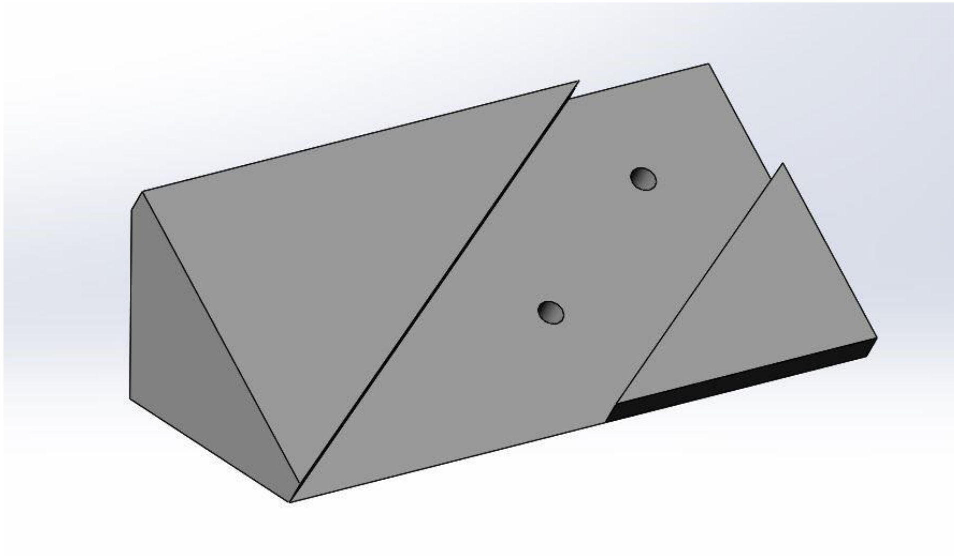

Figure 51: Conveyor Belt Slicer Version 1

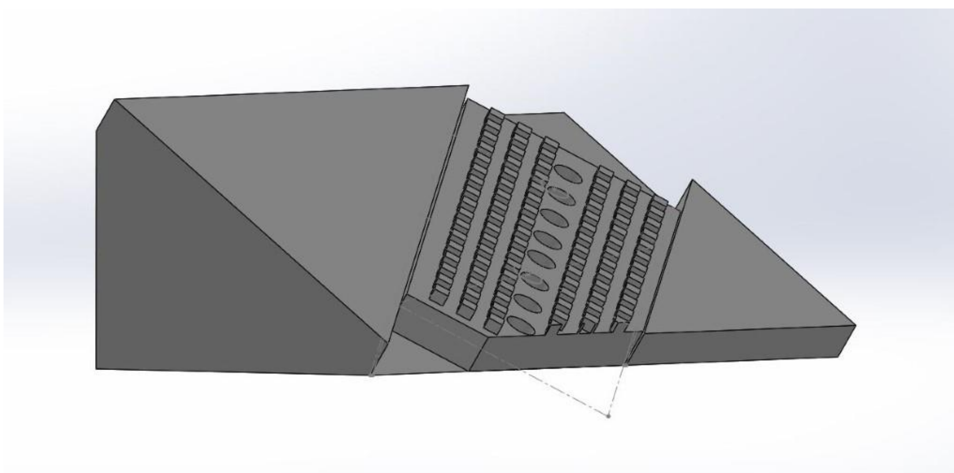

Figure 52: Conveyor Belt Slicer Version 1 Assembled

A single edged razor blade is inserted between the Slicer and the Gripper and secured with standard M-hardware. The device is used to cut the conveyor belt material through and through at 45 degrees. The gripper was trimmed after manufacturing to prevent it from interfering with the belt.

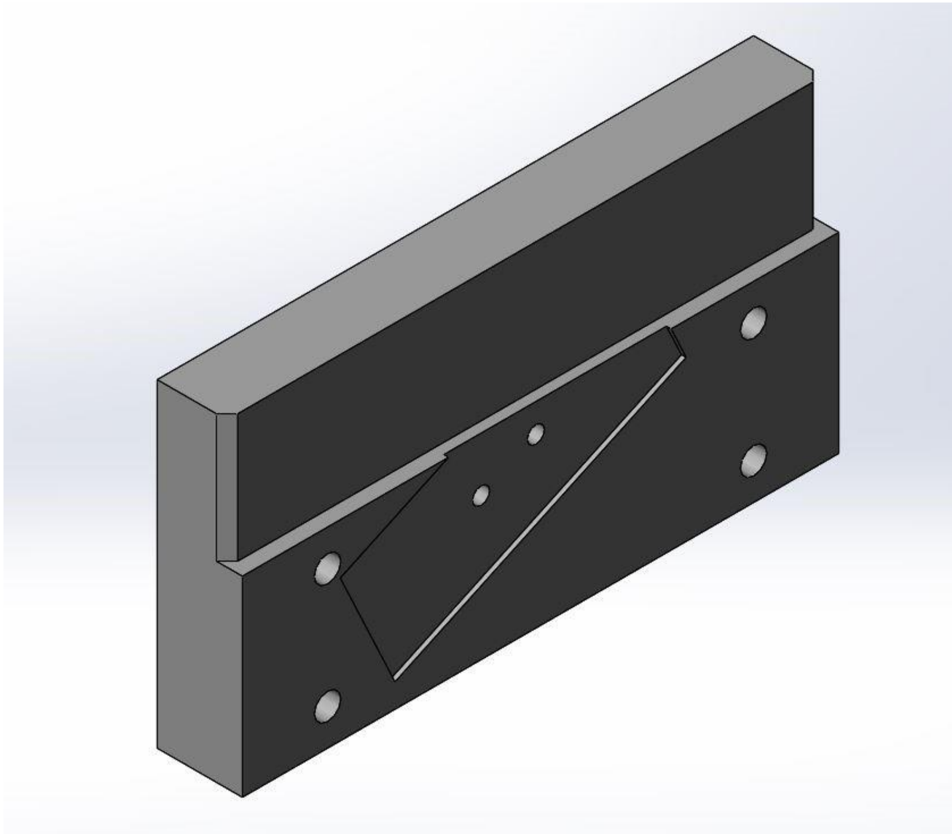

Figure 53: Conveyor Belt Slicer Version 2, Halve-A

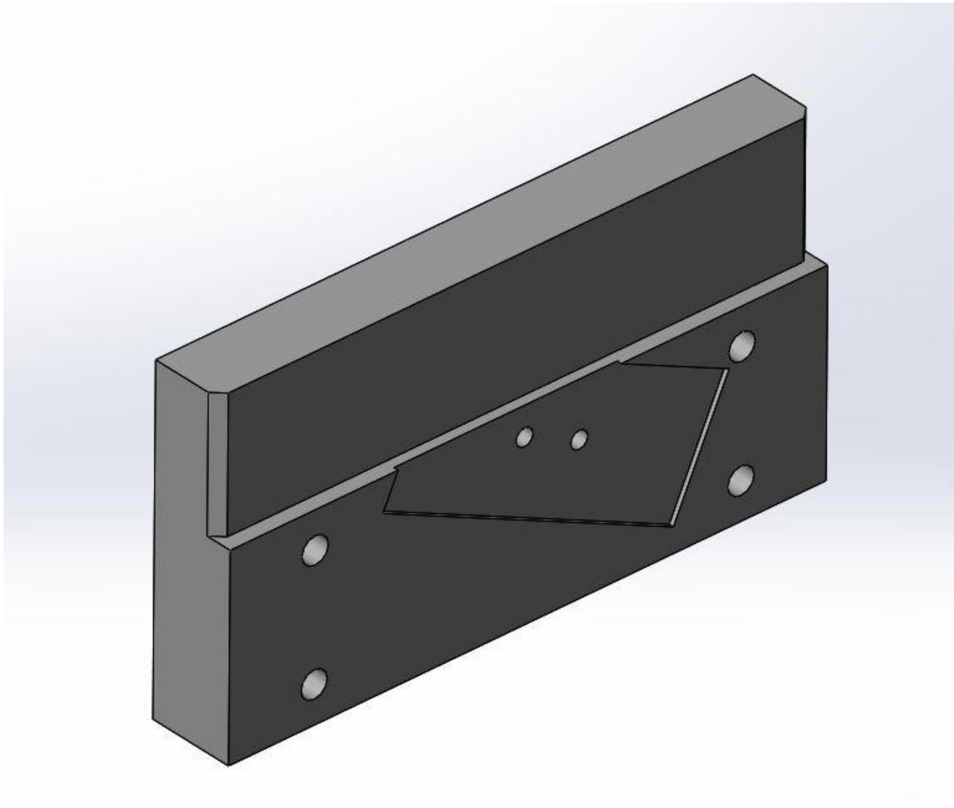

Figure 54: Conveyor Belt Slicer Version 2, Halve-B

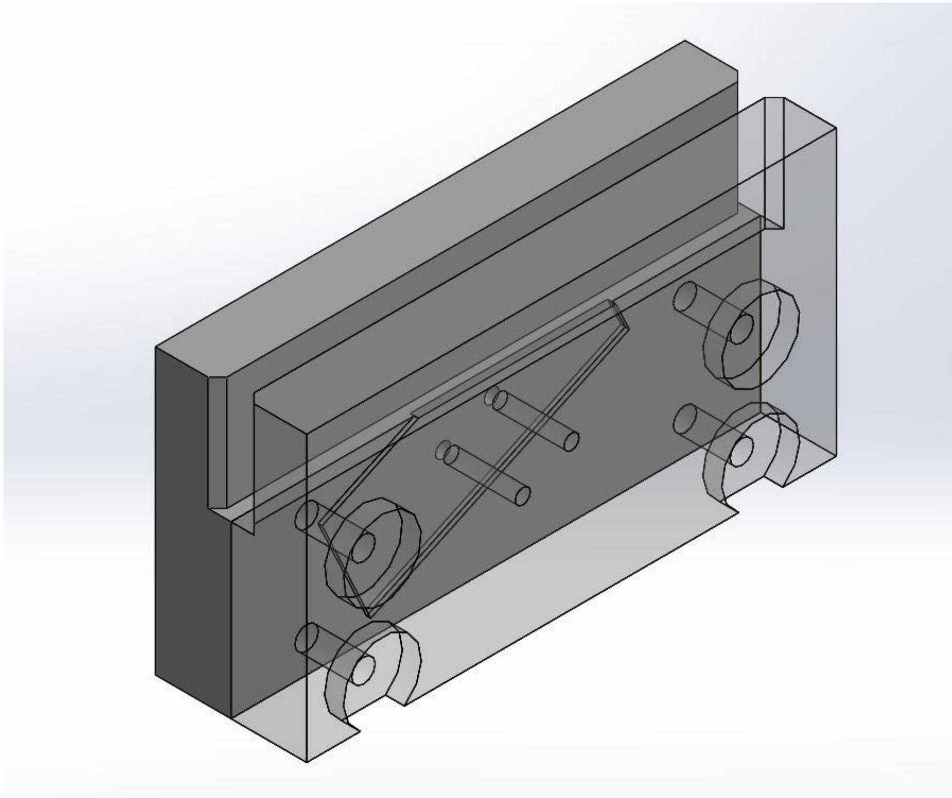

Figure 55: Conveyor Belt Slicer Version 2 Assembled

A single edged razor blade is inserted between the A and B Halves of the device. It was intended to be used to cut through the middle of the conveyor belt material: the belt would simply be fed through the gap in the top of the device and the razor would cut it equally. In practice however, this proved difficult to perform accurately.

### 4.7. BOM Table

Our final Bill of Materials (BOM) Table can be seen in Table 4, this table compares the values of what the department funded, what the group spent in total, and what the total cost of the entire printer assembly would be if it were to be made from scratch. Based on the results, our group had to spend roughly $100 of our own money to complete the project as our budget was only $600 without including shipping. The amazing factor to note is that the total cost of all the parts in the printer comes out to about $900, which is even less expensive than the lowest price automated angled printer on the market, the Printrbelt. The Printrbelt has a cost of about $1700, nearly double that of our printer.

| Part | Department | Group | Market Value | Vendor | Quantity | Description |
|---|---|---|---|---|---|---|
| Linear motion 12mm Ball bushing (4-pack) | $39.92 | $0 | $39.92 | Amazon | 2 | 4-pack of 12mm Linear Ball Bearings |
| 100-Watt 12V DC, 8.5 power supply | $12.99 | $0 | $12.99 | Amazon | 1 | Power Supply for Printer |
| Toothless Bearings | $8.99 | $0 | $8.99 | Amazon | 1 | Toothless Bearings for Timing Belt |
| Drill-pro Kit | $16.99 | $0 | $16.99 | Amazon | 1 | Timing Belt |
| Base-Mounted Shaft Supports for 12mm Shaft Diameter | $15.98 | $0 | $15.98 | Amazon | 2 | Shaft supports for 12mm Linear Motion Shaft |
| Witbot CNC Shield Expansion Board | $12.98 | $0 | $12.98 | Amazon | 1 | Stepper Motor Driver Board |
| Radial Ball Bearings | $3.74 | $0 | $3.74 | Amazon | 1 | Stepper Motor Shaft Support |
| Longruner GRBL CNC Shield Expansion Board | $18.88 | $0 | $18.88 | Amazon | 1 | Stepper Motor Driver Board |
| Black Brushless DC Cooling Blower Fan | $2.32 | $0 | $2.32 | Amazon | 1 | Filament Cooling Fan |
| DC Fan | $6.94 | $0 | $6.94 | Amazon | 1 | Hotend Fan |
| 16x2 Parallel Character LCD | $7.10 | $0 | $7.10 | Crystalfontz | 1 | User Interface |
| Nema-17 Stepper Motor w/ Gear Ratio 5:1 | $26.30 | $0 | $26.30 | OMC-Stepperonline | 3 | Geared Steppers for Drive Pulley |
| Nema-17 Stepper Motor | $59.80 | $0 | $59.80 | Digikey | 4 | Stepper Motors for Extruder |
| Rotary Encoder | $1.22 | $0 | $1.22 | Digikey | 1 | Control Interface |
| Momentary-on-off switch | $3.84 | $0 | $3.84 | Digikey | 2 | Control Interface |
| Linear Motion Shaft | $64.28 | $0 | $64.28 | McMaster-Carr | 4 | Motion Shafts (12mm x 500mm) |
| Nylon Sheet | $41.74 | | $41.74 | McMaster-Carr | 1 | Printbed (12”x24”) |
| 4-Ply Tan Nylon Conveyor Belting | $78.16 | $0 | $78.16 | McMaster-Carr | 1 | Conveyor Belt (18” x 48”) |
| Corner Brackets (1”) | $23.16 | $0 | $23.16 | McMaster-Carr | 4 | L Brackets for 1” frame |
| Mounted Sleeve Bearing | $43 | $0 | $43 | McMaster-Carr | 4 | Mounting Pulleys to Frame |
| Aluminum Sheet | $33.76 | $0 | $33.76 | McMaster-Carr | 2 | (8”x8”x1/4”) |
| Aluminum Rectangular Bar | $9.98 | $0 | $9.98 | McMaster-Carr | 1 | (1/4” x 1.5” x 36”) |
| Aluminum Pipe | $39.47 | $0 | $39.47 | OnlineMetals | 1 | Pulley Material |
| Aluminum Bar | $24.06 | $0 | $24.06 | OnlineMetals | 1 | Pulley Material |
| E3d V6 Hotend | $0 | $0 | $38 | MatterHackers | 1 | Hotend |
| Extruder Gear | $0 | $0 | $12.99 | Newegg | 1 | Hobbed Gear |
| Rapid Rubber Repair | $0 | $80 | $80 | Grainger | 1 | Fixing Conveyor Belt |
| 1” Screws and Fasteners | $0 | $20 | $20 | McMaster-Carr | 5 | Mounting Top Frame |
| 1.5” Screws and Fasteners | $0 | $0 | $30 | McMaster-Carr | 8 | Mounting Bottom Frame |
| 1.5” Corner Brackets | $0 | $0 | $37.84 | McMaster-Carr | 4 | Mounting Bottom Frame |
| 1.5” 8020 Stock | $0 | $0 | $61.94 | McMaster-Carr | 1 | 120” Frame |
| 1” 8020 Stock | $0 | $0 | $26.38 | McMaster-Carr | 1 | 80” Frame |
| **Total** | **$595.60** | **$100** | **$902.75** | **N/A** | **N/A** | **N/A** |

Table 4: Final Bill of Materials.

# 5. Construction

Chapter 5 is primarily focused on the essential machining and modification operations performed to complete the mechanical assembly of the printer. In addition to the operations, it details the assembly itself of the printer throughout its various stages.

## 5.1. Modified

Section 5.1 organizes subsections that detail operations that require exclusively non-powered operations, such as hacksawing or manual tapping. In addition to these operations, we include operations that use a hand-powered drill as we do not qualify that as machining.

### 5.1.1. Conveyor Belt

After receiving four feet of the desired conveyor material we designed and 3D printed the device, shown in *Figure 50 through Figure 55.* This device cut the belt at a 45-degree angle, allowing us adequate surface area to apply the Loctite Rapid Repair. We ran some tests on scrap belt material prior to working on our actual belt, and it was determined the glue was able to withstand an adequate amount of force to hold the belt together during regular usage.

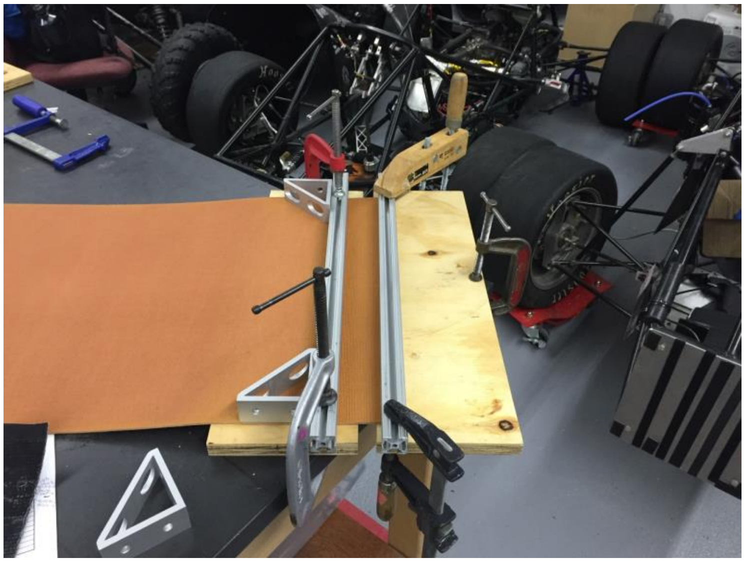

Figure 56: Belt Clamping Setup

During the cutting operation, we fixed the belt in place as shown in Figure *56* and used squares to fix a straight edge next to the surface to be cut. Blocks of wood were placed under the belt, allowing us to cut the belt into open air, which was determined to be the optimal cutting surface. The other end was cut using the same process, but with the cutting face reversed, so that the two cuts would mate together to form a flat surface. It took a few attempts, but eventually both ends of the belt were cut to an acceptable angle. One end of the belt was then fixed in place and the Loctite Rapid Repair was applied to its surface. The other end was then applied to this surface and fixed in place. Weights were added to further ensure that there was no movement in the belt. The glue was given three days to set and, once it was done, proved that it was able to withstand the tensile force when the belt was fully tightened. This provided us with a closed loop belt with proper functionality at a fraction of the cost it would have taken to purchase one.

### 5.1.2. Base Mounted Shaft Support

We only needed minor modifications to make our base-mounted shaft supports work with our design. Recalling from Chapter 5, these parts are intended to hold the linear motion shafts that the extruder assembly moves along. Therefore, it is important that these parts can be securely attached to the frame as any loss of rigidity will negatively impact the quality of a print or cause a crash. The most important operation on the parts were the filing. The shaft supports that are connected to the bottom of the top frame, according to our CAD designs, interfere with the belt. This is due to the support having a tall rectangular profile that extends beyond what is needed for support. To account for the motion of the belt, this rectangular profile needed to be hand-filed, as the parts are too small for the belt sander. They were filed at an angle to allow the belt to freely move past the part. In addition to the filing, the recommended mounting screw is an M5, which is roughly a 13/64-inch hole. The screws for mounting parts to the top frame had a diameter of 0.25 inches, so we had to use a hand drill with a drill bit that would give us a little over 0.05 inches of extra room. The reason for such a tight specification is that the thickness of the material surrounding the hole is less than 0.25 inches, therefore any hole larger than what fits the screw could significantly impact the rigidity of the part. We also needed to get screws with a smaller profile than the standard 8020-framing screws, as the standard screws have a large profile that interfere with the part. We found screws that had a smaller profile and fit the same sized fasteners, and these screws were also the right length, as they did not require washers to secure the shaft support to the frame.

### 5.1.3. Extruder Nozzle

There is not much modification that we need to do for the extruder nozzle outside of filing one of the sharper edges as we cannot have this edge impede the movement of the conveyor belt. The issue with filing the edge is that these edges on the nozzle are essential to tighten and loosen the nozzle. The loss of one edge is not going to make it impossible to remove, however we must be careful when we file the edge, as we want to file the correct one. To determine the correct edge, we constructed the entire assembly and then tightened the nozzle as much as necessary for printing, and then attached the assembly to the frame. When we found out which edge will interfere with the belt on the actual printer, we then removed the extruder assembly and filed the appropriate edge.

## 5.2. Machined

The operations outlined in the subsections of section 5.2 are the major machining operations that required use of powered machinery to obtain satisfactory results. These subsections would not include operations that were completed solely by hacksaw, manual tapping, or a handheld power drill.

### 5.2.1. 8020-Frame and Feet

The first step for our machining process was to machine the 8020-aluminum framing to provide the general structure for the printer. We needed to cut the pieces to length according to our CAD model dimensions; the best machine available to do this was the horizontal band saw, which can be seen in Figure *57*, in the Washburn Shop. The only other methods available to cut a piece of 8020 to length would be the vertical band saw, which would give us less consistent cuts, or to use a hacksaw, which would be even more unrefined than the vertical band saw. The desired length for the bars parallel to the z-direction on the bottom frame were at least 28 inches and we evaluated the lengths at approximately 30 inches and 30.1 inches; the desired length for the bars orthogonal to the z-direction on the bottom frame were 20 inches and we evaluated the lengths at approximately 19.8 inches and 19.9 inches. We had extra material, which allowed us to extend the length of the parallel bars by 2 inches, so we utilized the extra material accordingly. The outcomes of the lengths were within a reasonable margin and we used a non-ferrous buffing wheel, that can be seen in Figure *83* in Appendix A, to give a smooth surface finish to the faces subject to the band saw. A neat feature on the band saw is that there is an adjustable bar that lies flush with the end face of the stock material, so that parts of equal length can be cut very close to the same length. This factor of part consistency is what made the horizontal band saw the proper choice.


Figure 57: Horizontal Band Saw in Washburn Shops.

In addition to the bottom frame, we used the horizontal band saw to cut the 8020 for the top frame. The bars that are orthogonal to the z-direction were designed at 21 inches, and we evaluated the lengths at approximately 20.94 and 20.98 inches. The bars that were cut at an angle, however, were not as simple. As shown in Figure *58*, we rotated the right grip on the vice to an angle of 45 degrees, and we ensured this angle by using a triangle device that has a 45-degree angle between two edges. We then loaded our stock in the vice, up to the point where we wanted to make the cut, roughly 23 inches to the shorter side and 24 inches to the longer side. The left grip on the vice could then be pushed up against the stock and tightly grip the stock at that 45-degree angle. Our actual lengths came out to 23.93 and 23.9 inches for the longer sides and 22.94 and 22.97 for the shorter sides. We also tested the resulting angle by comparing it against the triangle; this was done by placing the triangle flush against a flat table and then resting the face of the 45-degree cut against the 45-degree face of the triangle and determining if the parts were flush against each other. We could not discern any deviation in the angle, and with a protractor, we measured the angles to be 44.9 degrees. If we use the measured lengths, however the angles will come out to be 44.7 degrees and 42.9 degrees. We can attribute the discrepancy between the desired and resultant angles by assuming error in measurement, or error during calibration of the cut. This problem is not a difficult fix though, as our back connectors were drilled along a 45-degree line, and the 8020 is fixed to the connectors which set the aluminum at the proper angle.

Figure 58: Preparation of the Angled Cut.

In addition to the general frame, we prepared the band saw to cut the feet to lift the frame. We had no theoretical upper bound on the length of the feet, however we did need to satisfy a minimum height requirement of 3.5 inches, as we want the top face of each foot to be flush with the top face of the bottom framing, which requires 1.5 inches of length. We also must account for the diameter of the pulley and the thickness of the conveyor belt, as those combine for 1.405 inches. We decided to cut the feet at a length of 4 inches since we had the extra material, and our resulting lengths were 4.13, 4.09, 4.05, and 4.04 inches. The finished cuts can be seen in Figure *59*. The relevant measurements for all cuts are represented neatly in Table *5*.

Figure 59: Final Band Saw Cuts for 8020 Framing.

We needed to make sure that these cuts would be safe to handle, so we used the non-ferrous buffing wheel, which can be seen in Figure *83* in Appendix A. The wheel spins downwards relative to the operator and requires an initial spin downward before turning the machine on to guarantee that the wheel will spin in the correct direction. The reason for the spin direction is to direct sparks towards the ground and away from the operator. We used this wheel to slightly round off every edge to ensure safe handling of the frame components.

Figure 60: Drilling Notches for the Pulley Inserts

Our last machining operation on the 8020 framing was drilling notches into the bottom frame on the pieces parallel to the z-direction. The purpose of these notches is to allow the shaft of the pulley insert to mate with the shaft of the geared stepper motor, thus driving the front pulley. We machined one notch on each side since our design incorporates two geared stepper motors. Initially we used a 0.60-inch diameter drill bit, and we calculated the feeds and speeds using the surface feet/min for aluminum found in Figure *84* in Appendix A, and then, using our bit diameter, found the optimal RPM from the chart in Figure *85* in Appendix A, which happened to work on the forward 2 setting on the third orientation of the drill press, seen in Figure *86* in Appendix A. The RPM setting was set to 1060, as this was the only setting that was close enough to the RPM calculated from the feeds and speeds. We found that the 0.60-inch diameter bit would get stuck after a few pecks, we attempted to use oil to keep the drill from getting stuck, however this still did not keep the bit from getting stuck. We opted to use a smaller diameter bit, about 0.40-inches, and then followed up with the larger bit as it has less material to cut through. This method significantly improved the drilling process with the 0.60-inch bit. After drilling the notches, we used a hacksaw to cut away the small amount of material left on the top of the notch, and then filed the sharp edges. Finally, we cleaned the excess aluminum off the part with the coolant in the Haas Minimill.

Table 5: Tabulated Results for Frame Machining.

| Piece | Length (in) | Angle (Degrees) |
|---|---|---|
| Parallel Side 1 (Bottom) | 30 | - |
| Parallel Side 2 (Bottom) | 30.1 | - |
| Orthogonal Side 1 (Bottom) | 19.8 | - |
| Orthogonal Side 2 (Bottom) | 19.9 | - |
| Foot 1 | 4.13 | - |
| Foot 2 | 4.09 | - |
| Foot 3 | 4.05 | - |
| Foot 4 | 4.04 | - |
| Orthogonal Side 1 (Top) | 20.94 | - |
| Orthogonal Side 2 (Top) | 20.98 | - |
| Angled Side 1 (Top) | 23.9 | 44.7 |
| Angled Side 2 (Top) | 23.93 | 42.9 |

### 5.2.2. Pulley Pipe

We ordered 4 feet of the Schedule 80 6061 aluminum pipe for our pulleys, as we needed about 36 inches of that length in total for our pulleys. The machine shop does not allow pipes to be cut on the vertical band saw. This is a general rule of thumb; as machine shop rules prohibit anything cylindrical to be cut on the vertical band saw unless it can be tightly secured. In addition to this, there is a potential that there will not be enough teeth engaged in the material when cutting a pipe. While cylindrical parts can be cut on the horizontal band saw, pipes cannot be cut according to the rules of the on-campus machine shop. This left us with the option of hacksawing the pipe. Initially we used a fine-bladed hacksaw, and this blade gave a clean cut, however the operation took about 20 minutes to complete. For the second cut, we used a coarse hacksaw and completed the operation within 5 minutes. The efficiency tradeoff was that the saw was more difficult to control during the cutting operation and left a cut that was uneven. Our solution to the uneven cut was to use the belt sander, as shown in Figure *91* in Appendix A, to smooth out the end-faces of the pipe. The faces came out relatively smooth, and that was reasonable for our purpose, as the flatness of the faces was not totally necessary. We only needed the faces flat enough to allow our pulley inserts to easily slot into the hollow ends.

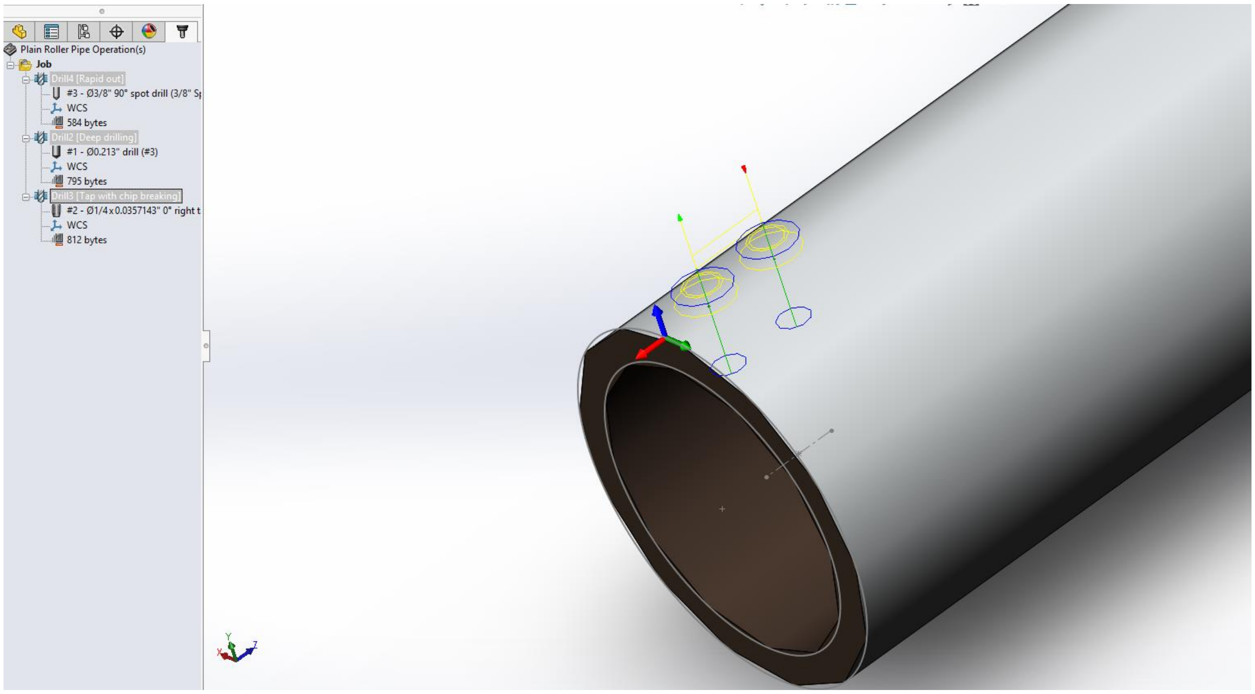

Figure 61: Cam Operation for Pulley Pipe.

The final operation that we needed to perform on the pipe was to drill holes for the set screws that would drive through the pipe and into the inserts and tap these holes. The purpose of set screws is to ensure that the pipe moves exactly how the insert moves, and those inserts, on the drive pulley, are driven by the geared stepper motion, which exacts the proper motion for printing. The screws are 5/16-inch diameter and 1/4-inch length set screws with 38 threads per inch. We used six of these screws, spaced at 120 degrees, for each pulley insert. This totals 24 set screws, and 12 individual operations of drilling and tapping the holes. Figure *61* shows the CAM operation for the pulley pipe. Initially a spot drill was used to prepare the hole for the thru-hole operation by the drill bit. After the thru-hole was made, the tapping operation took place, where the threads for the set screws were made.

### 5.2.3. Belt Roller Idler & Driver Inserts

To create the Belt Roller Idler & Driver Inserts a CNC Milling Operation was designed on a 6061 Extruded Aluminum rod of 2.125-inch diameter and one foot in length. While the two inserts are similar in design, the Driver Insert is longer and has a threaded hole for the set screw that attaches it to the geared stepper motor that drives the pulley. As such the CAM operations for both parts are similar. The first step was to cut the stock into two 3-inch sections so that it was easier to fixture in the mill. In this operation the only tool we used was the 1/2-inch diameter, 3/8-inch end mill, so after assembling that tool, securing the part and setting our tool and work offsets the part was ready to be machined. The first operation was the facing operation shown in Figure 62 which faces the top of the stock to give it the appropriate length of 1.85 inches and a smooth surface finish.

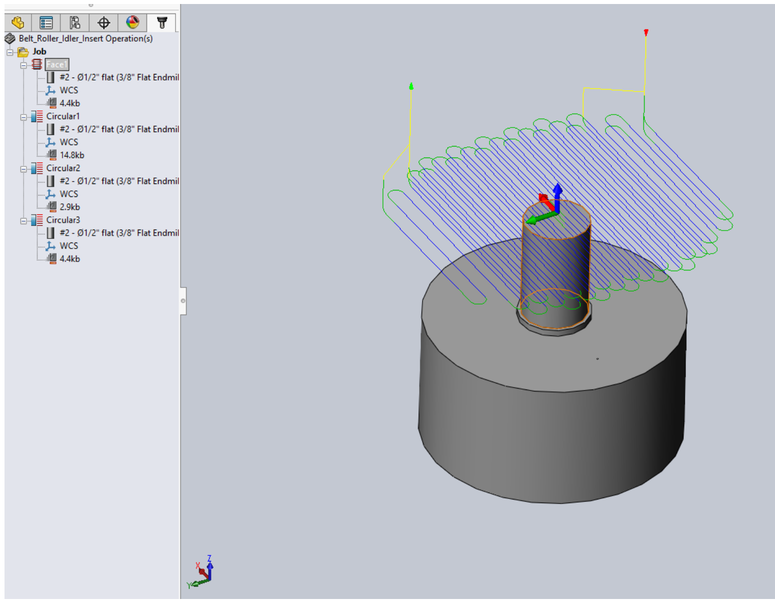


Figure 62: Facing Operation for the Belt Roller Idler Insert.

With the part at an appropriate length the next three steps were circular operations to give the part the appropriate shape. These operations were done with the same 3/8-inch end mill as the previous operation. The first one of these operations is to create the part of the pulley that will insert into the bearing to allow the pulley motion. This operation is pictured in Figure *63*, it contours the part to a 0.5-inch diameter of and extends 0.80 inches down the part.

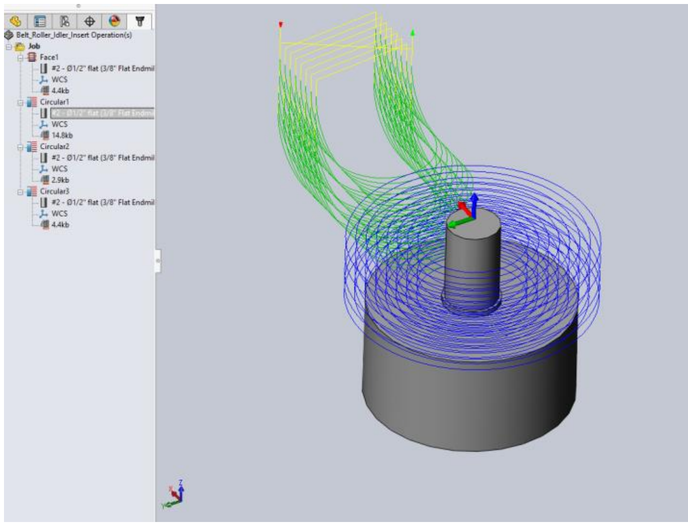

Figure 63: The First Circular Operation on the Idler Insert.

The second circular operation, shown in Figure 64 creates a small ring around the previous shaft of the idler. This is to create a buffer so that the pulley does not rub up against the surface of the bearings and can rotate freely. This feature is 0.55 inches in diameter and 0.05 inches long.

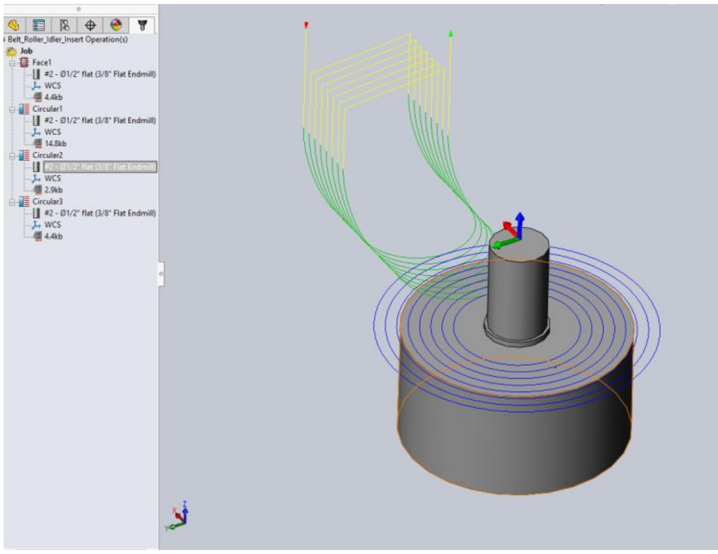

Figure 64: The Second Circular Operation on the Idler Insert

The third and final circular operation on the Idler insert was to create the base of the insert which will be the section that fits into the pulley pipes. This operation, shown in Figure 65 takes the section to a 1.94-inch diameter and extends to the bottom of the pulley, 1 inch from the previous operation.

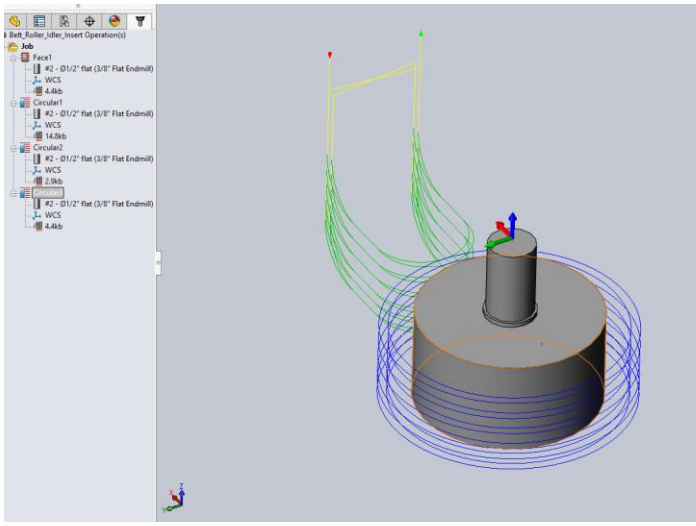

Figure 65: The Third Circular Operation on the Idler Insert.

After completing these operations were completed we were left with parts like the one in Figure 66. Since the bottom of the part needed to be fixtured, not all of it could be contoured to the correct diameter and we were left with excess material on the bottom of the part. This excess material was cut off using the horizontal band saw.

Figure 66: Idler Insert After Milling Operations.

The driver inserts are like the idler insets in shape, however they have a longer shaft with a threaded hole on the end. Both these features are to allow it to reach and attach to the geared stepper motor which drives the pulley. The stock for these parts was the same as those used for the idler pulley and was cut to in two halves of 6-inch length. Unlike the Idler Inserts a CNC Lathe turning operation was used to machine the Driver Inserts.

The turning operation pictured in Figure 67 shapes the part into three different circular sections. The first takes the part down to a diameter of 0.5 inches and goes 2.83 inches down the part. This section of the pulley goes through the sleeve bearings and connects over the geared stepper motor shafts. Next a buffer is created that is 0.55 inches in diameter and extends 0.05 inches from the previous feature. The third and final section of the driver insert creates the base which will be inserted into the pulley pipe to create the full pulley assembly. This section has a diameter of 1.94 inches which extends 1 inch from the previous operation to the bottom of the part.

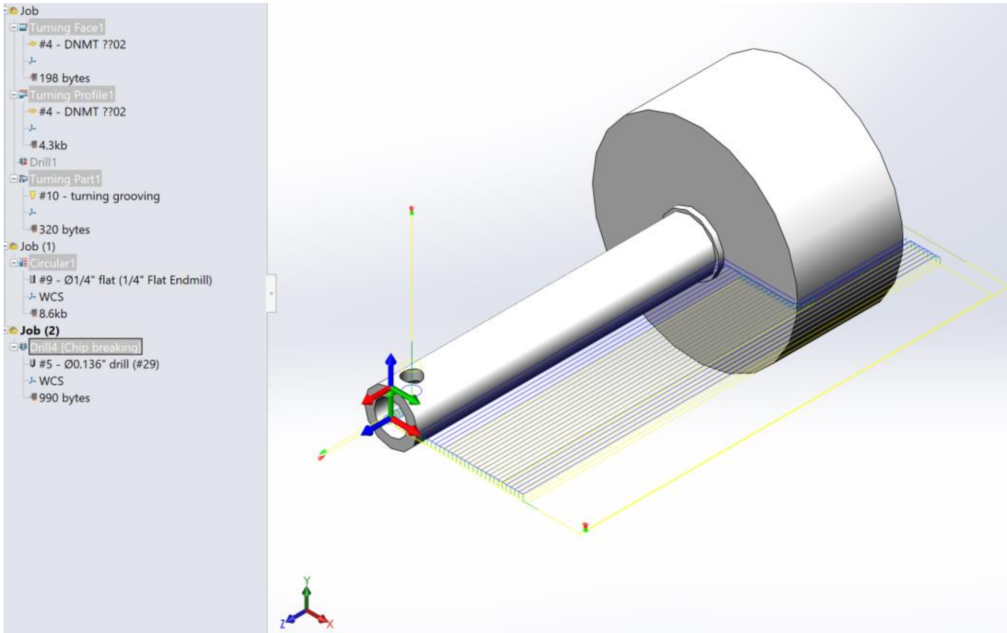


Figure 67: CAM Operation for Driver Insert

From here two holes needed to be drilled into the driver insert. Originally, we had planned to perform both operations on the mill, but due to time constraints the team opted to drill both holes using a drill press. The first hole is on the top of the part at the end of the shaft structure of the part. This is where the shaft of the geared stepper motor is attached to the Driver Insert. This part was designed as a press fit and as such was drilled to a diameter of 0.31 inches to match the diameter of the geared stepper motor shaft. It extends 0.59 inches into the shaft. The second hole was for a set screw to further secure the geared stepper motor to the pulley insert. The hole was a through hole drilled to a diameter of 0.136 inches. This hole was then threaded using an 8-32 diameter thread so that an 8-32 set screw could be used to attach the driver insert to the geared stepper motor shaft.

### 5.2.4. Sleeve Bearing Mounts

With the notches and the pulley inserts machined, we still needed to fabricate a part to secure our end sleeve bearing to the frame due to the inclusion of the nylon build plate in the design. The build plate made it necessary for the pulleys to be mounted below the midpoint of the extruded Aluminum frame where there was no way to fasten the sleeve bearings without modifications. Therefore, we designed a plate for each pulley, with dimensions of 5 inches wide by 2 inches tall. We discussed the initial design concept in chapter 5, and the CAD representation is shown in Figure *39*. To reiterate, the part is necessary such that we can mount a sleeve bearing to the frame to act as supports for our pulley inserts. We initially cut the material from aluminum stock in the machine shop using the vertical band saw, which can be seen in Figure *87* in Appendix A. We used a band velocity of about 4500 feet/minute as our material thickness was under 0.5 inches. The calculation for band velocity is based on the material and the thickness of the material, as shown in Figure *88* in Appendix A.

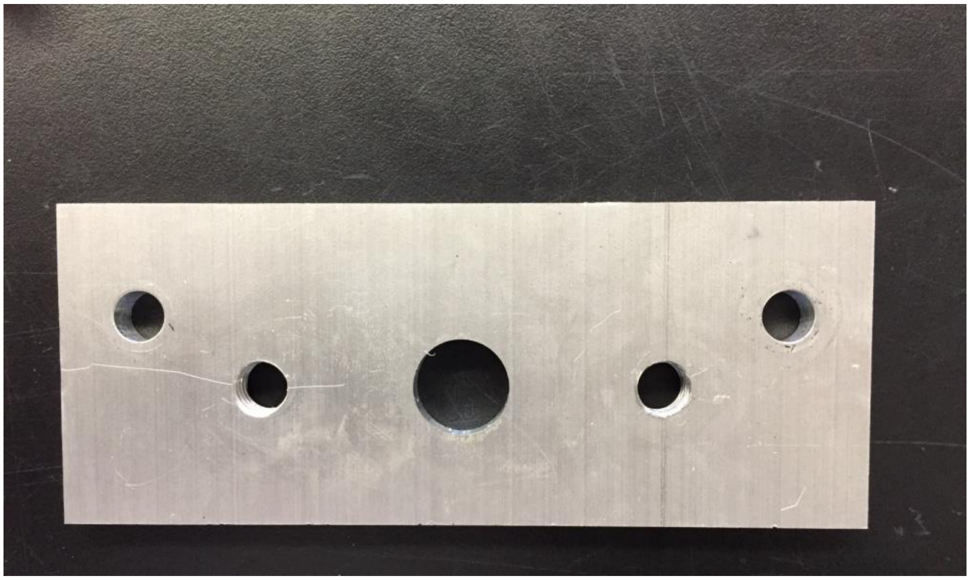

Figure 68: Sleeve Bearing Mount.

Figure *68* shows one of the results for our sleeve bearing mounts. Once the part was cut to length, we created a CAM operation, shown in Figure *69*, to finalize the features on the parts. We used a face-mill shown in Figure *93* in Appendix A, with small incremental passes of about 0.03 inches to make the faces of the part flat. For a brief explanation of the CAM process, we intended to drill the holes in the plates and then drill holes into a small piece of stock. The purpose of this piece of stock is to secure the plate with a screw and fastener. The drilling process is followed by a facing operation, where the endmill does passes around each face of the plate, ensuring the 5-inch by 2-inch dimensions. For the endmill to completely face the part, the part must have all four faces completely exposed. The stock that is secured to the plate is secured in the vice so that the plate does not move during the facing operation. The holes for mounting the sleeve bearing to the plate still required a tapping operation, however, and this was to be completed manually.

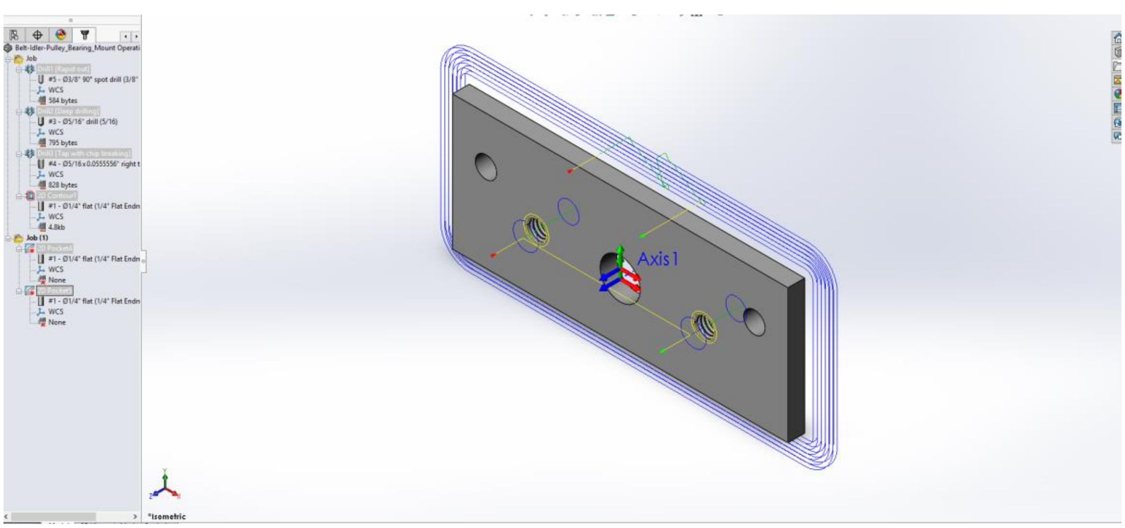


Figure 69: CAM Operation for Sleeve-Bearing Mount.

The 8020 mount holes had to be large enough to accommodate the 5/16-inch screw, while not being so large that it interferes with the other holes on the plate, nor too big for the profile of the screw. We decided to use a 3/8-inch drill bit to perform this operation. The holes for the sleeve bearing to mount on to the plate were designed as 5/16-inch to accommodate a thread of 3/8-inch. We chose the thread size based on the chart that delegates proper taps for hole diameters, shown in Figure *92* in Appendix A. The resulting dimensions from machining are represented in Table *6*. Since this part was machined and probed each time, and the bits and endmills were consistent for each operation, the accuracy of the parts should be within 0.001” tolerances. The discrepancies shown in Table *6* are likely due to inaccuracies in measurement due to low accuracy calipers.

Table 6: Sleeve Bearing Mount Dimensions

| **Piece** | **Mount Hole 1 (in)** | **Mount Hole 2 (in)** | **Thread Hole 1 (in)** | **Thread Hole 2 (in)** | **Clearance Hole (in)** |
|---|---|---|---|---|---|
| Mount 1 | 0.319 | 0.315 | 0.315 | 0.315 | 0.601 |
| Mount 2 | 0.319 | 0.314 | 0.314 | 0.314 | 0.602 |
| Mount 3 | 0.315 | 0.314 | 0.314 | 0.317 | 0.600 |
| Mount 4 | 0.314 | 0.317 | 0.315 | 0.315 | 0.600 |

Figure 70: Inside Corner Bracket.

Once the parts were cut and drilled to specification, we wanted to affirm the validity of mounts. We discovered that the corner brackets in the front, shown in Figure *90* in Appendix A, were too large, and blocked the front mounts from aligning over the notches on the 8020. Our solution to this problem was to hacksaw the hypotenuse of the triangle-shaped corner bracket off, and half of the length that interferes with the plate. The sharp edges were filed down for safe handling. The resulting bracket can be seen in Figure *70*. These brackets, while they do not provide the same structural integrity of the original bracket, keep the structure rigid and do not interfere with our mounts. Since our tail pulley is not as close to the back of the printer as our driven pulley is close to the front of the printer, we did not have to perform the same operation on the corner brackets at the back of the printer.

### 5.2.5. Ball Bearings and Press Fit Bearing Mounts

The pulley sleeve bearings that were purchased from McMaster-Carr were originally thought to be ball bearings. The sleeve bearings proved to have too much resistance during torque testing of the belt and a new bearing design was made accordingly. Six 0.5-inch inner diameter bearings (1.375-inch outer diameter) were purchased online. Although only four would be necessary for the printer, extras were purchased to save time in the case that defective bearings were received. To house the new bearing and to serve as an interface between the bearing and the sleeve bearing mounts, a press fit bearing mount was designed.

On hand scrap Aluminum 3-inch*2-inch*0.75-inch stock was used to make the parts. The press fit bearing mount consists of a center bore sized two-thousandths below the outer diameter of the ball bearings, a centered clearance through hole for the shafts of the pulley inserts, and counter bored through holes spaced identically to the previously used sleeve bearings. The press fit bearing mount containing these features can be seen in Figure *71*.

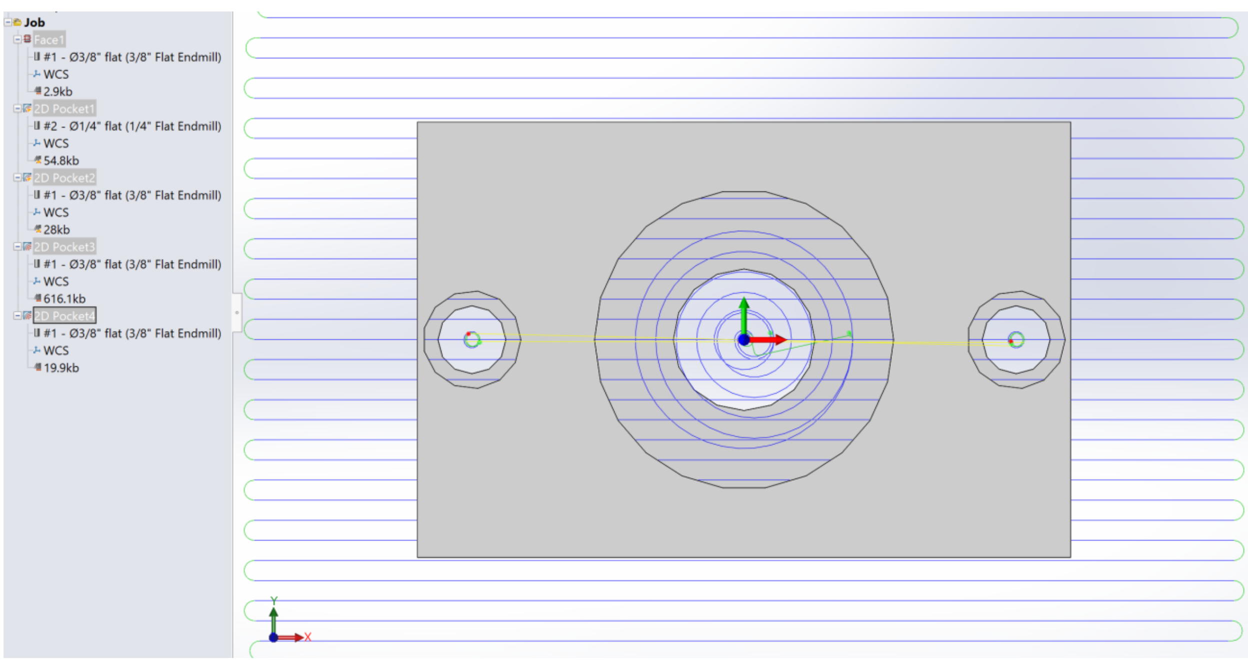


Figure 71: Press Fit Bearing Mount

The scrap Aluminum bars were cut into equal lengths of just under 3-inches on the vertical band saw. Only relatively short pieces of scrap were available and, while the part design called for blocks at least 3-inches in length, blocks of roughly 2.8-inches in length were used for the parts. This lead to the left and right sides of the block being thin or non-existent adjacent to the counter bored through holes. While this made for less appealing parts, it did not affect their function.

The press fit bearing mounts were manufactured on a vertical CNC mill through five operations all but one of which employed 3/8-inch endmills. The first operation faced the positive Z-surface to a height of 0.6-inches from 0.75-inches to ensure that the final part would be the same thickness, with the ball bearings inserted, as the original sleeve bearings. The second operation used a 1/4-inch endmill to create the through holes using a pocket operation and the third operation used a 3/8-inch endmill to counter bore them. Next, the center hole was created using a pocket operation and while the tolerances for the rest of the features were left at a default of 0.0004-inch, the center hole for the bearing was set to 0.0001-inch to ensure a proper fit. Only the CAM tolerance for the center hole was modified because tighter tolerances produce much larger g-code files and require more time to machine. The last operation cut the center clearance through hole using a 3/8-inch endmill and a pocket operation. Thanks to the high maximum spindle speed of the mill used to machine these parts they each only took roughly five and half minutes to machine. If they had been made on the smaller milling machines available in the machining lab they would have taken about twice the machining time.

#### 5.2.6. Feet Connectors, Back Connectors, and Side Supports

Machining operations for the feet connectors did not require the same level of accuracy as the sleeve bearing mounts did. We simply used a vertical band saw to cut into the aluminum stock from the shop to create our brackets. We deviated from our initial design of this part, from Chapter 5, as we had much more stock available to work with. We decided to create an “L” shape of the holes for the bracket. This allows for the bracket to connect at two points with the foot and at two points with the frame. This doubles the amount of connections from our initial design and makes for a much stronger connection. The result of these operations can be seen in Figure *72*.

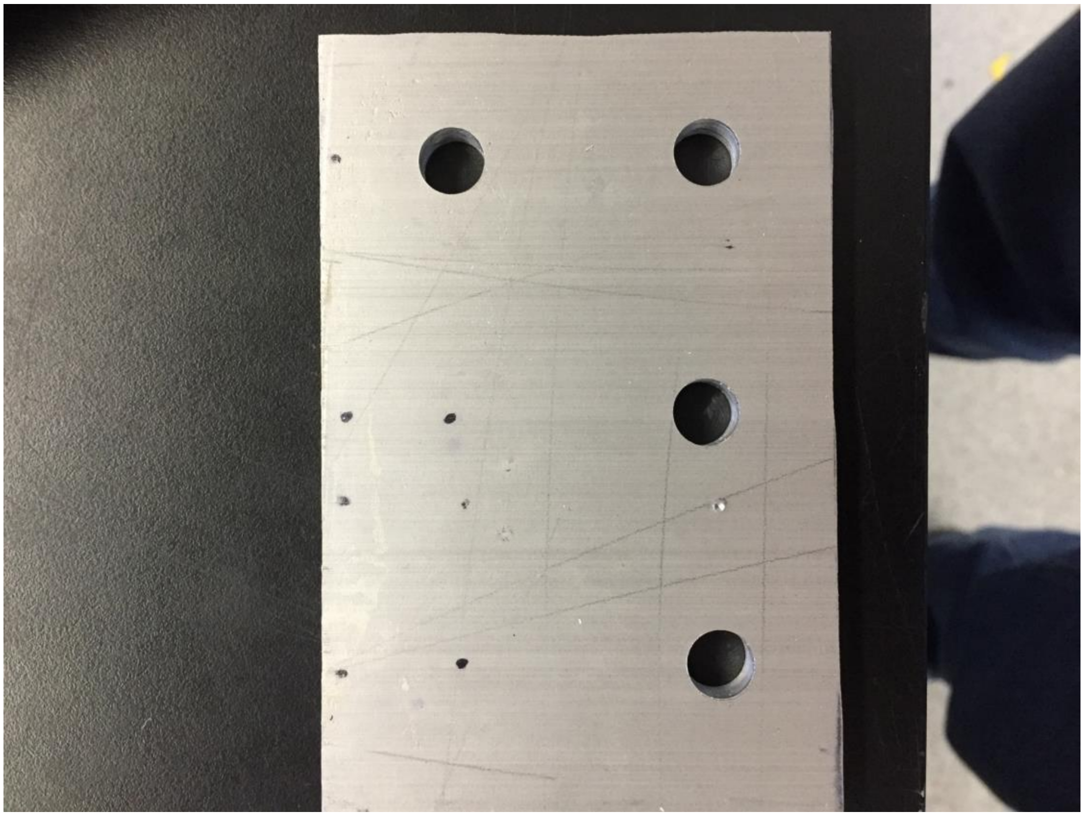

Figure 72: Foot Connector Bracket.

After the feet connectors were machined, we wanted to work on the back connectors, which would connect the bottom 8020-frame to the top 8020-frame. The difficult part in machining these 8-inch x 8-inch plates was that we needed to machine 4 holes along the x-axis to connect with the bottom frame, while we needed machine 4 holes very close to 45 degrees from the x-axis. We marked the plates with lines along which indicated where the holes should be drilled. The holes for the top frame came out to an average of 0.315 inches, which was good as the hole needed to accommodate the 0.25-inch screw diameter but not be larger than the profile of the screw, which is about 0.5 inches. The holes for the bottom frame came out to an average of 0.421 inches and, for similar reasons, was ideal for our screws. A resulting connector can be seen in Figure *73*.

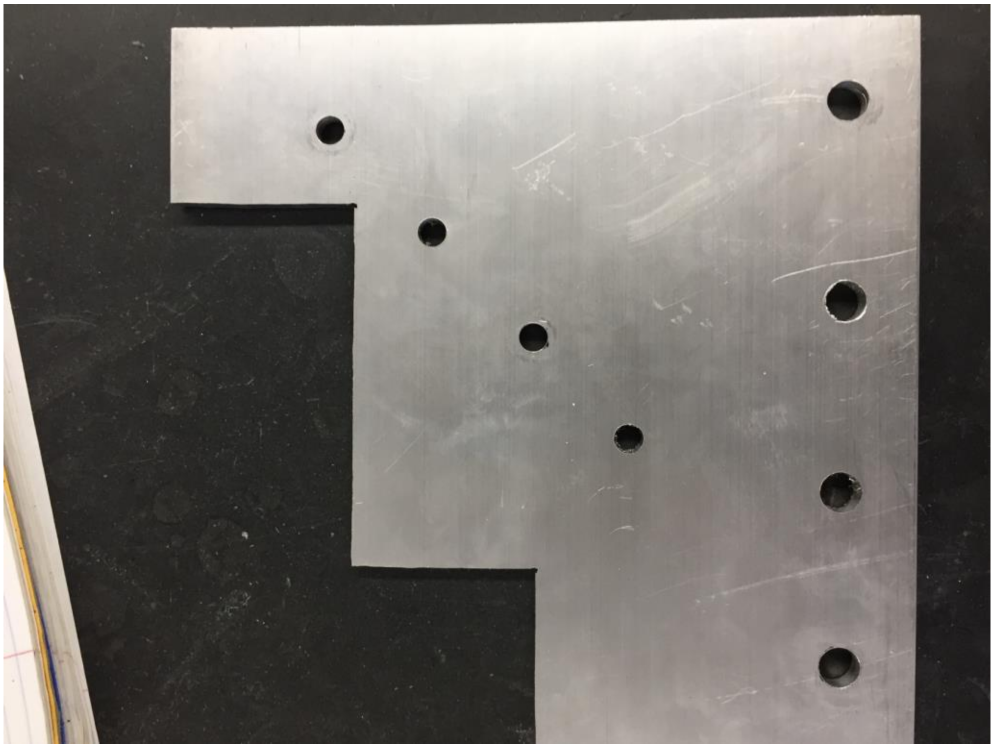

Figure 73: Back Connectors for Top-Bottom Frame Connection.

The final major pieces that were added to connect the frame were the side supports. These supports, as discussed in Chapter 5, were intended to be used as additional support for the higher points of the top frame, since the extruder moving to the top of the frame could cause potential structural issues without proper support. In our design, we intended for these bars to be orthogonal to the top frame and form a triangle with the top frame and the bottom frame, to maximize support. We drilled holes for the screws to connect the frames together; we discovered, however, that with the orthogonal orientation, that the bar would interfere with the geared stepper motor mounts, and those cannot be moved. We discussed translating the bar further down the top frame to accommodate for the mount interference, but we quickly realized that the top part of the bar would be close to the bottom of the top frame, effectively nullifying the purpose of the side support. We decided to make the side support orthogonal to the bottom frame instead, as there would be no interference with the geared stepper mount and the top of the support connected near the highest point of the top frame, while not interfering with any custom 3D printed parts that attach near the top of the frame. The resulting holes came out to be 0.310 inches for the top hole and 0.408 inches for the bottom holes.

### 5.3. 3D Printed Parts

Once the parts we designed were printed, we had to analyze how well they would integrate into the printer. Every part was given a specific tolerance in which it would work, however some parts were lacking in terms of design and we had to revisit the CAD to get them to work. Parts that needed to be iterated were reprinted and we used PET instead of ABS.

#### 5.3.1. X-Y Axis Adapters

The X-Y Axis Adapters both had to undergo significant changes to be implemented in our design. For starters the holes to fit in the extruder shafts were too small. If this was their only problem, then we could have modified the holes and had a usable part, but in part design we neglected to design a way to clamp the extruder belt so that it would be able to move the X-Axis assembly in the Y-direction. As designed the belt would simply pass over the adapter, not moving it as intended. Slots were designed to achieve this purpose in both adapters. An additional slot was also designed in both adapters to house the teethed stepper motor pulleys. The stepper motor that is mounted on an X-Y Axis Adapter is raised at a higher level than the rest of the belting it is supposed to drive. Still the belt itself must move in a perfectly straight manner, so a feature was added to the adapter to guide the belting. This feature guides the belting from the pulley on the stepper motor to a peg on the edge of the adapter. The peg will guide the belt into the configuration needed for it to move in a straight line along the X-Axis. Additionally, this part was broken into two halves, which will be connected after printing. This allows us to fit the bearings for the extruder shafts inside the adapter.

#### 5.3.2. Modified X-Carriage

The X-carriage that we had initially printed worked with the larger diameter of the bearings, however the bearings were longer than we designed for, and we could not fit two bearings in the top slot, nor could we fit one in the bottom slot. This could have been solved by simply filing the parts in these locations, however, we decided, as a group, that the thickness of the walls surrounding the bearings should be much thicker than what we had designed. We used Prusa's extruder CAD model, and their X-carriage contains much smaller bearings to support a much smaller motion shaft. We added significant thickness to the left and right of the bearing slots to accommodate for larger bearings, as well as increased the width of the slot for the bearings. The Prusa model also did not have slots revolved about the center axis of the bearing slot for zip ties. The Prusa X-carriage does have these slots for zip ties on their extruder assemblies but were not included in their CAD model we retrieved, and as such we had to model them and then reprint our X-carriage to meet this standard. Our X-carriage, when compared to Prusa's, maintains proper distances from the center for mounting holes, and overall proportions. We did not model some of the nicer features, such as the ribs that extend out from the body of the part, since these are designed to cleanly guide wires, but are not integral in the functionality of the extruder itself.

#### 5.3.3. Geared Stepper Motor Mounts

The geared stepper motor mounts were one of the parts that came out nearly perfect for integration. The only outstanding issues was that the holes for mounting the part to the frame needed to be filed wide enough to accommodate a screw and the profile of the standard 8020-screws was too large. The thickness, however, was satisfactory in that washers were not required to completely fix the part. We decided to print the part again, opting to use PET instead of ABS as the filament. PET and ABS are comparable when it comes to strength, but PET is easier to print, and we redesigned the holes so that no filing was necessary. The result was that we had a part that integrated perfectly for frame mounting, and the holes to mount the motor were integrated perfectly as well. This part was then lined up with the notches on the 8020-framing and secured in place.

#### 5.3.4. Stepper Motor Mounts

Our stepper motor mounts also came out nearly perfect for integration. The thickness of the material around the slots where we would fasten the part to the printer was too large, however. This is a simple fix though, as we could just use a power drill to put a countersink in the material, allowing the screw to reach the fastener in the 8020-frame. In addition to this issue, we found that our design had the stepper motor attached to the mount with no support either on the sides or below it. We decided to add support material on the bottom and on the side that would face the bottom of the printer. This is to help if the screws that hold the motor in place loosen, we have material to ensure the motor does not fall and break. In addition to this, we designed countersinks for the profile of the screw in the CAD file to minimize unnecessary drilling.

#### 5.3.5. Toothless Pulley Mounts

The toothless pulley mounts full dimensions were not given to us on the product page, therefore we estimated the thickness at about 8 mm. When we received the part, the thickness was measured to 10 mm. We determined that we could file the walls surrounding the bearing to accommodate for this extra 2 mm of thickness. We discovered, however, that the resulting wall thickness would be less than a millimeter. This result does not necessarily make the part useless, but we wanted a reasonable degree of safety; therefore, we improved the thickness of the slot to 10 mm, and improved the outside wall thickness to 2 mm. These parts properly hold the pulley, and the 5 mm shaft that holds the pulley in place properly fits in the holes.

### 5.4. Belt Tensioner

To ensure that the belt would be driven when the pulleys were turned, we designed a simple belt tensioner to keep the belt on the pulleys. We initially used some minor rubber material on the aluminum pulleys as well, to ensure that the belt properly gripped the pulley. As for the tensioning system itself, the final system can be seen in Figure *74*. We used a coated steel wire to ensure that the system itself would not break under tension. We looped the coated wire by using the small aluminum brackets and fastening the screws in the brackets to ensure the closed loop would stay. We looped the wire itself around the miniature pulleys and then tied the wire to the actual tensioner. The “hook” end of the tensioner was then fixed to the first loop that fastened to the screw of the pulley plate. The miniature pulley was then looped to a screw that was fastened to the back of the frame.

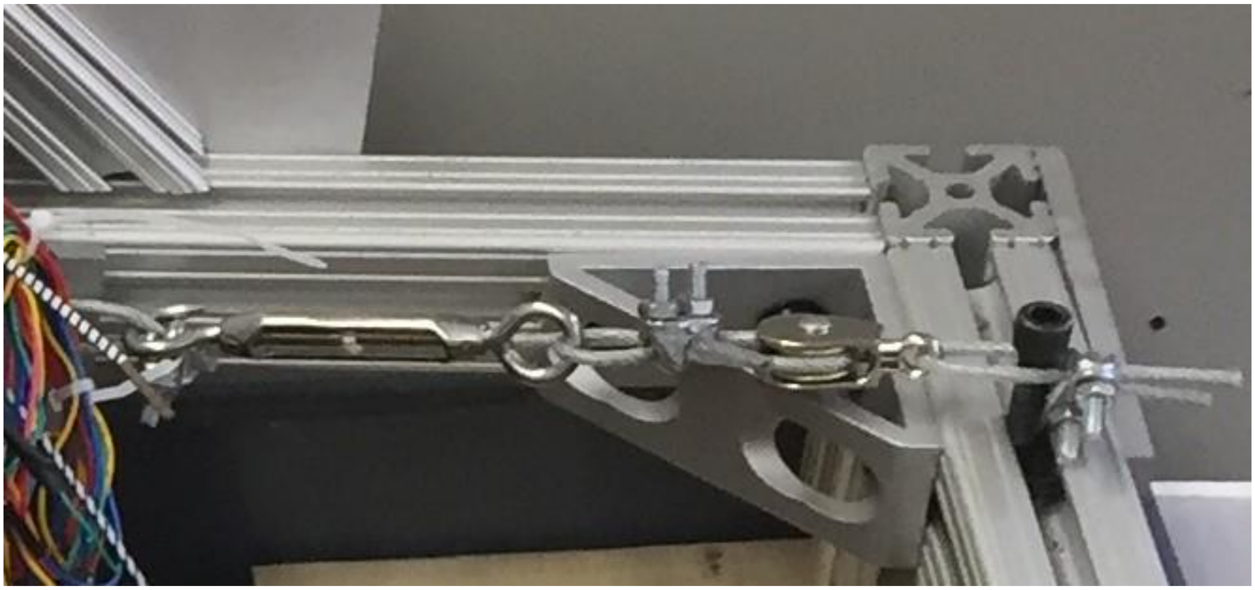

Figure 74: Belt Tensioner System.

The plates are pulled back when the tensioner is twisted, thus increasing the tension on the belt as the plates pull the pulley inserts backwards and subsequently pull the pulleys backward. This stretched out the belt, however, and we had to cut the steel wires shorter such that we could use the tensioner to account for any slack created by the belt loosening. Unfortunately, we were unable to measure the tension itself, however we do know that the tension is less than the yield strength of the rubber repair glue used for attaching the belt, and less than the maximum tension of the belt itself. We adjusted each side to equate the tensions as best as we could, however our design would leave room for improvement as eventually the belt will slide to one side depending on how close the tension is on each side.

### 5.5. Synthesis

Major construction of the printer took place in three distinct stages. Stage 1 involved constructing the major components of the bottom frame. This includes the bottom frame combined with the sleeve bearing mounts, the pulley inserts attached to the pulleys, the conveyor belt, the geared stepper motors, and the belt tensioners. The process for assembling this was to connect the sleeve bearing assemblies to the appropriate 8020 bars. The next step was to connect the drive and tail pulleys to one bearing mount and loop the belt over the pulleys. We then slid the second bar on. Once that step was finished, we attached the geared stepper motor shafts to the drive pulley inserts and set screw them into place. We then attached the geared stepper motor mounts to the frame with screws and fasteners and then pushed the drive pulley inserts into the pipe to get the mount flush with the surface of the frame. We then slid the build plate under the belt and fastened it to the frame before we tensioned the belt. We then attached the tensioners, which were each attached to the screw on the sleeve bearing mounts closest to the back of the frame. The other end was attached to a rotating screw in a cable tensioner. The other end of this cable tensioner was looped onto a screw at the back of the frame. The cable tensioner allowed us to twist it, which pulled the rotating screw further toward the back of the frame and pulled the sleeve bearing mount, along with the tail pulley, further back. This device allowed us to have an even tension between the two sides of the belt, ensuring that it would not slip or corkscrew. The result of these steps can be seen in Figure *75*.

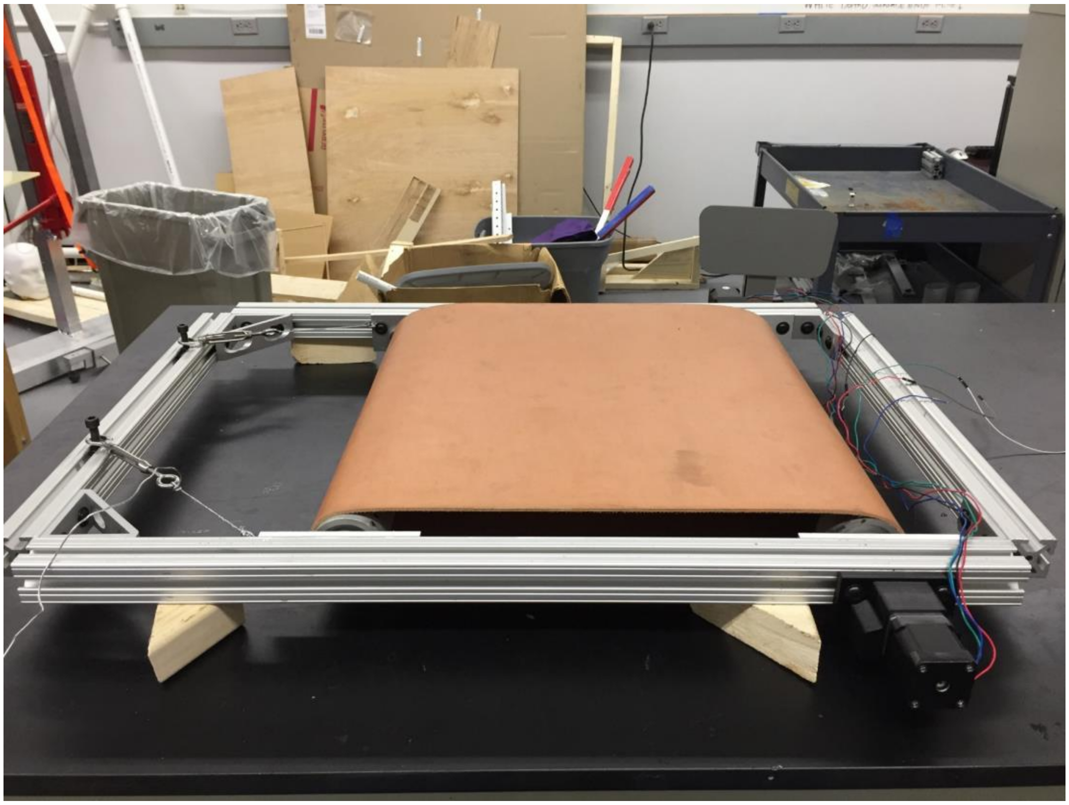

Figure 75: Stage 1 of Printer Construction.

Stage 2 of printer construction was assembly of the top frame machined components and connecting the top frame to the bottom frame. The top frame was much simpler than the bottom frame, in that there were no major machined components like the pulley or bearing mounts. We simply had the 4 bars of extruded aluminum and connected them with L-brackets to secure their locations. The bottom bar of the 8020 was moved up roughly 2.5 inches from the top face of the bottom frame as our linear motion shafts were not the same length as the side lengths of the top frame. We decided to move the bottom bar in our design as the motion shafts can avoid the belt tensioners, the belt, and we can maximize the build height. We then fixed our base-mounted shaft supports to the bottom and top bar on the frame. We then attached the back connectors and the side supports to the bottom frame, and then slid the top frame down into place along the line of fasteners in the holes on the supports. At this stage, we had attached the two Y-axis end-stops as well, though they could have been attached afterwards with little difficulty. The result of stage two of printer construction can be seen in Figure *76*.

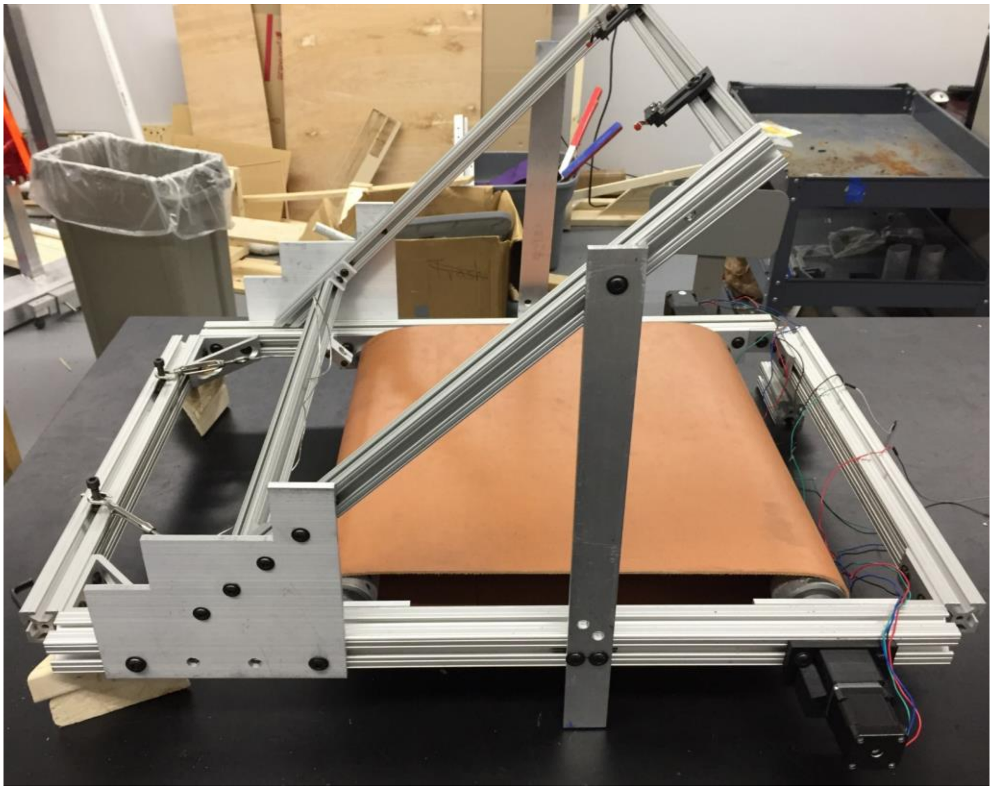

Figure 76: Stage 2 of Printer Construction.

Stage 3 of printer construction focused on attaching the extruder assembly, namely the extruder, x-carriage, x-y axis adapters, and the y-axis stepper motor mounts. Initially we put our base-mounted shaft supports on the orthogonal bars and mounted them. We then clamped two of our linear motion shafts to one of the adapters and zip tied it in place. We then attached the extruder to the X-carriage using M3 screws and slid the X-carriage on the motion shafts. The other adapter was then added to the free end of the motion shafts and zip tied in place. Afterwards we were able to slide the other two motion shafts through the base mounted shaft supports and properly align the supports to allow the rods to lie parallel. After we did this, we attached the Y-axis stepper motor mounts and the toothless pulley mount. Unfortunately, even with the adapters at the extreme ends of the X-axis motion shafts, the holes for the Y-axis timing belt on the adapters did not line up with the timing pulley and the toothless pulley. Even if we had moved the x-axis orientation, such that one belt could pinch an adapter, we would run into the issue of the belt binding on the Y-axis and getting stuck while actuating motion. In addition, we also added the nylon build plate. The results of all the components added to the printer can be seen in Figure *77*.

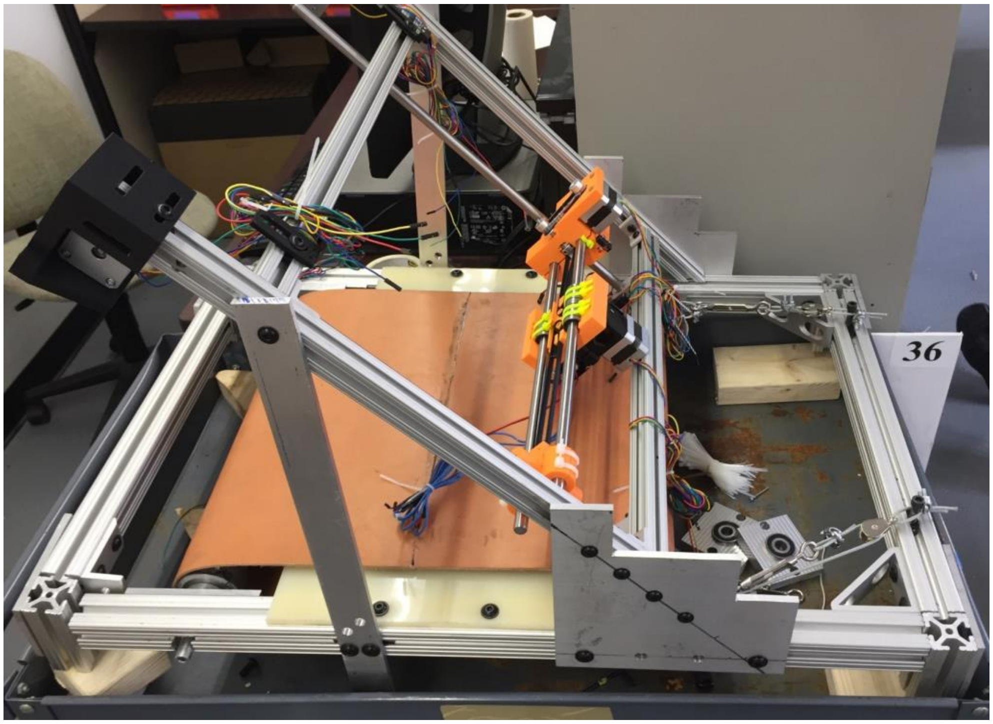


Figure 77: Stage 3 of Printer Construction.

# 6. Results

Chapter 6 includes all our results post-construction. It includes analyzation of the accuracy and performance of the electronics and control interface for the printer. It also details the results of the prints, the deviation, and how to improve and modify infrastructure to realize more effective results.

## 6.1. Electronics

Section 6.1 details the results obtained regarding the electronics and control interface for the printer. It includes analysis of the performance of the major components by comparing empirical data with standard metrics.

### 6.1.1. Hotend and Thermistor

To validate the accuracy of the thermistor recording the temperature for the hotend, we needed to properly connect the thermistor to the driver board and observe the displayed temperature on the LCD interface. The eye test showed that the thermistor was reading temperature accurately as the LCD read out ~25 ºC when at room temperature. In addition to this, we observed that the LCD read out 0 ºC when the thermistor was not plugged into the thermistor terminals on the board, which indicates that there is no potential being read by the terminals while disconnected. This is important in considering the readings, as the instrument which interprets the temperature is proven to be properly calibrated and shows no deviation in temperature due to some arbitrary existing potential.

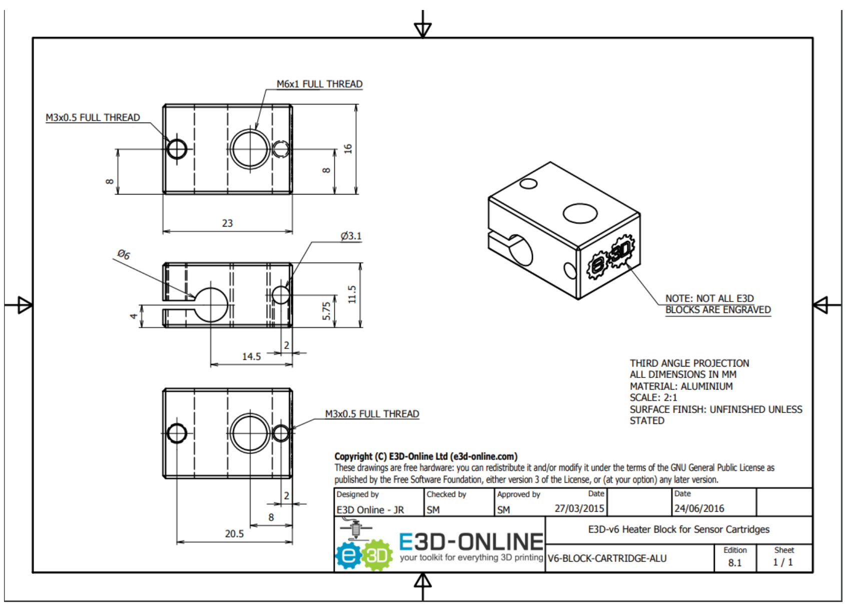


Figure 78: Aluminum Block used for Recording Temperature *[50]*.

In addition to the room temperature reading and the calibration, we needed to validate that the hotend would reach the designated temperatures for printing. When we interact with the LCD by telling it to preheat PLA, we want to ensure that the hotend heats up properly. The LCD may tell us that temperature on the hotend is rising, however we still cannot confirm if that temperature is accurate without thermal imaging or through use of a thermocouple. We initially tried to use thermal imaging to record the temperature of the hotend, however we had difficulty as the surface of the hotend reflected and our thermal camera could not focus on any part of the surface or nozzle. We resorted to the use of a thermocouple, shown in Figure *94*, in Appendix A.

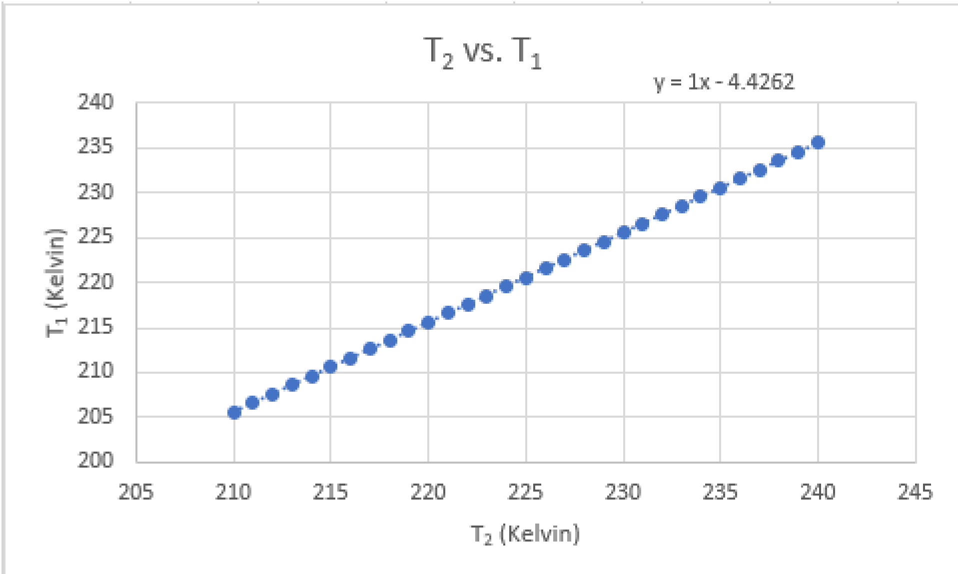


Figure 79: Relationship Between $T_2$ (Internal) and $T_1$ (External).

We obtained readings of 25 ºC when using the thermocouple at room temperature. This was an expected result, and we tested this result by also testing the thermocouple against the Prusa MK3 printers in the lab. The output of the thermocouple was also 25 ºC when tested against the Prusa hotend. We then tested accuracy of our thermistor at higher temperatures using the preheat PLA function on the control interface, which preheats the hotend to 215 ºC. When we tested our thermocouple against the hotend, specifically on the aluminum block of the nozzle, we obtained readings that were in the range of 205 ºC ± 1 ºC. We had three theories about the discrepancy. It was either a calibration issue with the thermocouple at higher temperatures, our thermistor was inaccurate at higher temperatures, or we did not wait long enough for the block of aluminum to reach a temperature equilibrium. To discern the correct theory, we conducted a test against the Prusa MK3 hotends. We preheated the hotend for PLA temperature once again, waited for the process to complete and then tested the thermocouple again. We found that the results against the Prusa hotends were 204 ºC ± 1 ºC and 205 ºC ± 1 ºC. This discredited our theory that our thermistor was inaccurate, however it was also a possibility that the Prusa thermistors were inaccurate. We set up a simple heat transfer conduction equation for how long we had waited for the transfer to occur to determine that the block had sufficient time to heat up, $\left(\frac{Q}{t}\right) = k * A * (\frac{T2-T1}{x})$. The cross-sectional area and length which we used in the calculation can be found in Figure *78*. The cross-sectional area is 11.5 mm by 23mm and the length is 8mm. We also used an average thermal conductivity for aluminum, 205 W/m * K [51]. The left side of the equation is substituted with the power from the hotend, 30 Watts. Using these numbers, we calculated that the temperature differential between the inside of the hotend and the outside is 4.4 $^{o}$C. This means that if the internal temperature of the hotend is 215 $^{o}$C, then the outside should read 210.6 $^{o}$C within ± 1 $^{o}$C. Figure *79* shows the relationship between $T_2$ and $T_1$ for a range of given temperatures. Given a value for $T_2$, which represents the inside of the block, the graph shows the result for the outside of the block due to conduction. The relationship is linear since every other factor is constant regardless of temperature. The reason we likely do not see this 4-degree discrepancy at room temperature is that the hotend is given sufficient time to reach the equilibrium temperature of the room prior to measurement. Factors that our calculations did not include are convection and radiation. It is reasonable to conclude that the difference in output temperature from the thermocouple and thermistor are due to heat losses from conduction, convection, and radiation. In addition to this, we believe the 5-degree discrepancy accounting for conduction is due to convection and radiation.

### 6.1.2. Stepper Motors

The stepper motors were the next components we wanted to ensure were working properly. We initially tested the extruder motor to confirm that aspects of our code were working as intended. We specified in the code that we wanted the motor to cease operation when the thermistor reads below the extrusion temperature for PLA. We tested this by plugging the motor into the driver board and attempting to turn the motor. The motor shaft was locked, and therefore receiving signal, but would not turn on command. This indicated to us that the motor would not turn below a given temperature. We then confirmed this by preheating the hotend to the PLA print temperature, and we were able to turn the shaft of the motor. In addition to the cold extrusion function, we ensured the feed rate on the extruder was accurate. The feed rate that we had set in the code was 25 mm/s, we confirmed this by feeding the filament into the hotend and marking a spot on the filament about 30 mm above the extruder assembly. We then ran the extruder for approximately one second and measured the distance of the mark to the extruder assembly. We ascertained this mark to be about 4.8mm from the extruder assembly. This indicated to us that the extruder gear was working within a reasonable degree of error, given the degree of human error in our measurements of the filament distance. We confirmed that the gear, that feeds the filament, and the idler do not slip at any point.

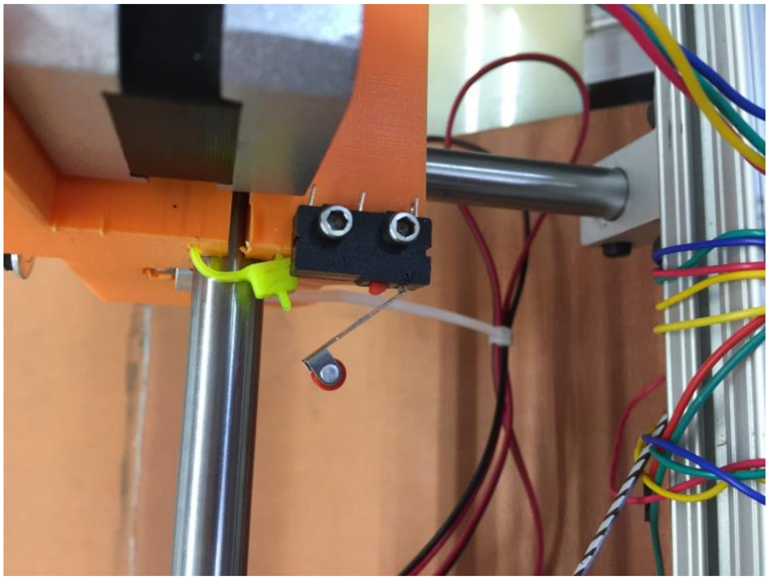

Figure 80: End stop for X-axis.

After extruder testing, we began to test our X-axis stepper motor. The X-axis motor drives the extruder assembly along a timing belt. We found that the pulleys which we designed our X-carriage around, were 1mm larger in diameter than we had designed. Therefore, the top line of the belt warps into the X-carriage as the belt pinching slots do not line up with the pulleys on the adapters. We accounted for this motion on the extreme ends of the belt by factoring in the diameter of the pulleys in the code for steps/mm. Results for the tests can be seen in Table *7*. After adjustment, the regions within 30mm of the maximum travel distance were within ± 0.05mm, which is a great result, however between 30mm – 40mm the results became significantly less accurate. This, again, is accounted for by the difference in the pulley diameters from what we had designed. One significant result is that the process was repeatable in telling the motor to move 200mm, its maximum distance. When told to move 200mm and then return home, the extruder returns to the same spot every time. We also used a hanging scale to find the maximum force necessary to move the extruder, which is 1.32 N, while the minimum is 1.12 N. The maximum is experienced near the extreme ends where the warped belt skews the alignment of the X-carriage. In addition to this motion, we placed an end stop on the adapter with a stepper motor. The homing function worked properly as the motor returned and triggered the switch every time, stopping motion.

Table 7: Command vs. Discrepancy in X-motion

| Test | Command (mm) | Discrepancy (mm) |
|---|---|---|
| Initial | +10 | 9.35 |
| Adjusted | +10 | 9.95 |
| Adjusted | +20 | 19.99 |
| Adjusted | +30 | 30.05 |
| Adjusted | +40 | 39.32 |
| Adjusted | +50 | 48.85 |
| Adjusted | +60 | 58.21 |
| Adjusted | +70 | 68.15 |
| Adjusted | +80 | 78.15 |
| Adjusted | +150 | 146.9 |

The motors that we were unable to test were the Y-axis and the geared stepper motors. The Y-axis 3D printed parts did not line up in plane, and this creates an issue for our timing belt as it would bind and skip steps when warped laterally. Due to inability to get the timing belt properly situated, we could not test the accuracy of the steps/mm resolution in the Y-direction. We believe that the command within the marlin code itself should be the same as the X-direction. This is because the pulleys used in the Y-direction are the same as the ones used in the X-direction. We did record that the motors actuated motion and that the motors were properly mirrored. With the marlin code, the extra extruder slot on the driver board mirrors Y-axis motion by default, which means that the motion should be counterclockwise when the actual Y-axis motor has a clockwise motion, so they move in the same direction and don't fight each other. This was a default setting within the code.

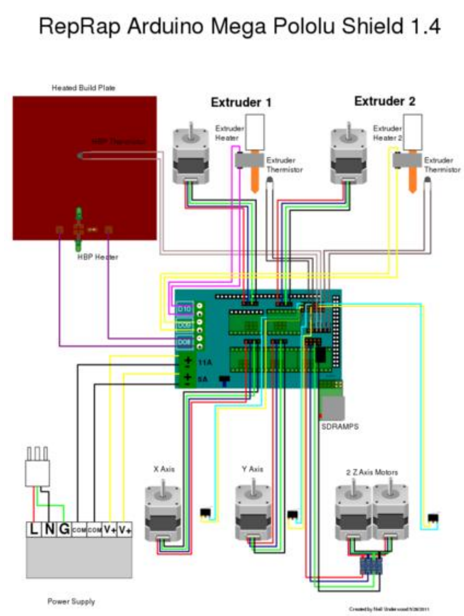


Figure 81: RAMPS 1.4 Wiring Diagram *[52]*.

The final axis to test was the Z-axis. We found that the geared motors would require different drivers than the standard A4988 drivers for NEMA 17 motors. We found drivers that were low voltage and high current, which was ideal for our geared stepper motors. Unfortunately, we could not safely put these drivers into the board as the hotend requires roughly 3 amps and the other motors all draw 0.3 amps. This left far less than 1.7 amps to drive our geared stepper motor. We tried to jump the signal from the Arduino to a CNC shield board where we were sure that it would receive enough current and not damage any circuitry. The issue was connecting the signal, ground, step, enable, and direction pins did not actually connect the signal from the Arduino to the second driver board. In addition to this, one of our consultants on this project stated that the output torque on the geared stepper motor would not be close to the 2 N*m (18 lb.-in) torque given in its specifications due to a lack of sufficient power during the ON-ON phase of the motor. We discuss the actual torque requirements in more detail in section 6.2.2. We discovered that the torque necessary would require both motors to run, and we could not code the motors to receive separate signal. As shown in Figure *79*, the wiring output on our board does not allow for separate signals to be sent to the Z-axis motors as both motors are driven by the same board. In terms of design, the gearbox ratio for both motors was ideal to run our system, but we did not have the capability of running either motor. One solution would be to have a single NEMA 17 with a gearbox that has double the advantage of the geared motors used in this project. This solution is further detailed in section 99.

#### 6.1.3. LCD Interface

We also needed to ensure that the LCD interface was working as intended. We found that the commands on the board itself were functioning properly. We obtained the results from the hotend in section 6.1.1 so we knew that our hotend was functioning properly. Testing the preheat temperatures is a simple process where we select “prepare” and “preheat” PLA or ABS, as those were the two default materials in our code. Manually adjusting the temperature to a given value is also possible as the sequence is simply “control”, “temperature”, and then selecting “nozzle temperature.” The feed rate on the extruder gear is not a manually adjustable option on the display itself. It is fixed at 25 mm/s but can be changed within the marlin code to theoretically any value. Like the extruder feed rate, the other motor travel velocities are fixed and can only be modified in the code. The other important functionality on the LCD is the manual adjustment of steps/mm. This value can be adjusted by going to “control”, “settings”, and then changing the steps/mm of each axis. This functionality has a lower limit of 5 steps/mm and an upper limit of 200 steps/mm. Our resultant step resolution was roughly 4.78 steps/mm which required us to change the resolution within the code and the lower limit as well. Our final test was to ensure that the LCD could read when an SD card was inserted, and that the Arduino was reading the g-code from the SD card. We could not run a test print since two of our four axes were non-operational, however the LCD did display the codes on the SD card and prepared the printer by preheating and homing the X-axis. Since it could not home the other two axes, the print failed.

### 6.2. Print Resolution

Results for print resolution are important in predicting the accuracy of a printed part. Section 6.2 determines how accurate our design is by comparing the resultant prints to the g-code. The main factor of discrepancy is due to the angle at which the extruder lies. Due to cuts that are slightly inaccurate from a lack of precision on a horizontal band saw, there is a difference between anticipated layering and the actual layering on printed parts.

### 6.2.1. Mathematical Deviation

To calculate the anticipated deviation due to angle discrepancy, we must make a few assumptions to simplify calculations. First, we assume the first layer height is equivalent to subsequent layer heights as this creates a uniform deviation per layer. Second, we assume that the distance between the nozzle and the bed is 0.1mm as this gives us a dimension from which we can mathematically calculate other dimensions. Lastly, we assume the angle between the extruder and the bed is 44 degrees. Despite the third assumption not agreeing with our results from Section 5.2.1, we attribute our assumption to the fact that we could not accurately measure the angle on the frame. Our angles were most accurately determined by measuring lengths with a tape measure and calculating the resultant angle. For computational analysis, a tape measure does not possess the instrumental accuracy to precisely calculate the angle, thus why we assume an angle within a reasonable margin of error. For computing the actual deviation, it is a simple calculation using the Pythagorean Theorem. For an easier to visualize case, we can calculate the deviation if our top frame was at an angle of 30 degrees. Using the Pythagorean Theorem, if both angles are at 45 degrees and the vertical side is at 0.1mm and the horizontal side is 0.1mm then the hypotenuse is at 0.141mm. When the top frame is at an angle of 30 degrees, due to our extruder orientation, the actual angle will be 60 degrees. Using this in the calculation, we can determine the horizontal length to be 0.17mm and the hypotenuse to be 0.2mm. Taking the differences in hypotenuses, due to a discrepancy of 15 degrees, it means a deviation of 0.0586mm at a layer height of 0.1mm.

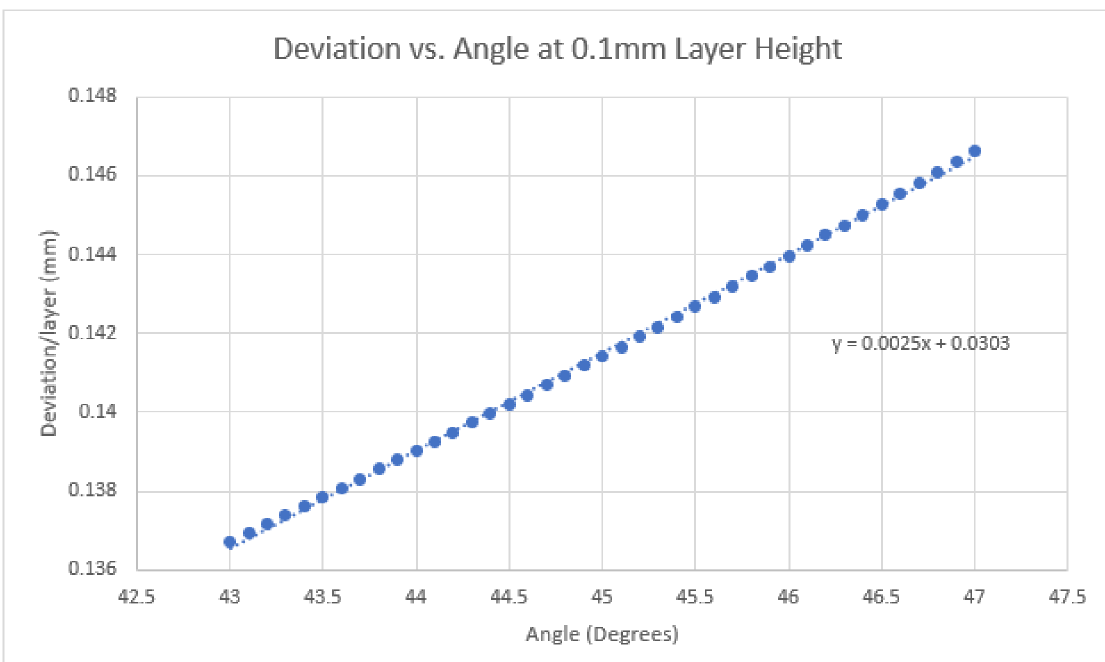


Figure 82: Graph of Deviation as a Function of Angle Between Extruder and Bed.

Using the same method as before, we can determine the deviation per layer if the frame angle was at 44 degrees. Since the angle between the hypotenuse and the vertical side is 46 degrees, we determine the horizontal length as 0.103mm and the hypotenuse as 0.144mm. This gives us a discrepancy of 0.00253mm per layer at a layer height of 0.1mm. This discrepancy is relatively small when for an individual layer, however if we use our build height of one foot as an example, roughly 305mm, that gives us 3050 layers, which results in a deviation of 7.73mm between the bottom and top layers. This is problematic for part accuracy when you take into consideration that a cube sliced by the software would result in a rhomboidal shape. There would also be additional minor warping of the part where there are overhangs. It is likely the deviation would not be exactly 0.00253mm per layer, as any of our assumptions might not be completely accurate, which would mean a slight difference in the actual deviation per layer. However, the chart in in Figure *82* accurately describes the relationship between the angle of the extruder and how much deviation would be experienced within the specified range of x-values. The trendline may not be accurate beyond the range of x-values shown, as the relationship between angle and deviation is not linear.

#### 6.2.2. Torque

Initially we ordered sleeve-mounted bearings to decrease the torque required by our geared stepper motors to drive the conveyor belt. Despite being advertised as bearings, the parts we received were bushings. These bushings caused increased the torque needed to run our system compared to bearings, which significantly decrease the necessary resultant torque. We conducted an analysis comparing the torque required to drive the pulleys using the bushing parts and the actual bearing parts. This analysis was done with a torque wrench shown in Figure *96* in Appendix A. The results are shown in Table *8*.

Table 8: Resultant Torque to Drive Pulleys.

| Test | Peak Bushing (lb.-in) | Peak Bearing (lb.-in) | Overall Bearing | Low avg. Bearing | High avg. Bearing |
|---|---|---|---|---|---|
| 1 | 34.8 | 27.2 | 15.3 | 8.4 | 17.3 |
| 2 | 35.1 | 20.2 | 12.2 | 10.2 | 16.2 |
| 3 | 35.2 | 18.6 | 12.3 | 10.8 | 16.1 |
| 4 | 35.1 | 20.3 | 14.6 | 11.2 | 17.8 |
| 5 | 35.4 | 19.1 | 13.9 | 9.8 | 16.4 |

The table describes the peak values of torque necessary to drive the belt. Overall a significant decrease in torque to drive the belt is seen from implementing bearings. The first bearing measurement is the only outlier and this discrepancy is due to a set screw rubbing against the frame, adding extra torque requirements to properly drive the belt. Since our geared stepper motors could drive roughly 18 lb.-in of torque, two of our motors could properly drive the belt using the bearing parts. The other values in the table are the general torque values that the wrench specified, tabulated as Overall bearing. This was the average value that the needle on the wrench would output during testing. The low average was the average output of torque required, during the stages where less torque was necessary. Similarly, the high average was the average output during higher points of necessary torque. These peaks generally occurred when the seam on the belt moved around the diameter of the pulleys.

## 6.3. Recommendations

Limitations in time and budget limit this printer to a proof of concept for angled printing. Certain components did not work entirely as expected and some design choices proved less than optimal while assembling the printer. Over the course of the project the team determined various ways to address some of these issues in future designs of the printer. This section details our recommendations for where future teams could improve the existing printer design.

### 6.3.1. Redesign Input to Drive Pulley

One of the biggest challenges in designing this printer was finding an acceptable way to drive the pulleys on the conveyor belt. Our design used a geared stepper motor that was controlled using a RAMPS 1.4 Driver Board and an Arduino Mega. The stepper motors required a large amount of torque to run the belt. This meant that they also required a large amount of current to run properly. The current was more than the driver boards, that we initially purchased, could handle. The team tried other solutions, such as powering the geared stepper motors from another board, while using the original RAMPS board to send the signal from the Arduino to control the motor. Ultimately this method was unsuccessful. It is possible that a team with more experience in electronics could have more success, but the team determined a couple of solutions to redesign the drive pulley system to work more effectively from a mechanical design perspective.

The first redesign method was to use a gearbox along with one of the NEMA 17 stepper motors like those used in our extruder assembly. These stepper motors require much less current than the geared stepper motors and we were able to control them using our RAMPS board, so they can be given the proper signal to drive the belt. The reason they were not be used in our initial design was because their output torque is much less than the required torque to drive the belt. To get around this problem a gearbox could be used to increase the output torque of the stepper motor to a sufficient torque to drive the belt.

The other solution would be to alleviate the torque necessary to drive the pulley. Based on the static pulley deflection results found in Section 4.4.3, we should have accounted for the deflection in the middle of the pulley and had the pulley taper outwards from the middle of the pipe. Using the result of the static deflection, we should have made the center of the pipe tapered outward to account for the static deflection, such that the middle of the pipe is the high point along the surface. This would solve the issue of the belt shifting to either side as the middle becomes an established high point, and this also reduces the amount of torque necessary to drive the belt as it reduces the total friction between the pulley and the belt which results in a lower torque necessary to drive the belt.

### 6.3.2. Implement a 6-Axis Driver Board

One of the major challenges our group faced in driving the belt was getting the correct signal to both geared stepper motors. The driver board had six-motor support, allowing us to control two stepper motors each in the x, y and z directions. However, there was only one driver slot for the z-axis, meaning the signal we sent to the geared stepper motors was the same for both motors. This limited the driver board to 5-axis operations. This was a problem, as the geared stepper motors were situated across from each other and, to drive the pulley correctly, they would need to move in opposite directions. Only one of the motors would move properly and one stepper motor was insufficient to meet the torque requirements to drive the belt. This problem could be addressed by implementing a six-axis driver board that allows independent input to all six axes. This would allow the proper signal to be sent to both stepper motors that drive the conveyor belt allowing for two stepper motors to be used as in our intended design. These recommendations along with those from section 6.3.1 should reduce the torque needed to move the belt, while also increasing the torque output from the stepper motors that move the belt. By implementing these changes, the belt should be able to move properly.

### 6.3.3. Implement Belt with Higher Thermal Capacity

As discussed in section 4.4.1 both nylon belt materials the team considered were suitable surfaces for PLA to adhere onto. However, both belts were subject to melting if the extruder touched their surface for more than thirty seconds. To get around this problem the team used 10 mil thick PEI sheets to protect the belt from this kind of melting. It is expensive, though, to purchase enough of these sheets to cover the belt. In addition, it adds maintenance in the form of making sure the sheets remain flat on the belts surface and it is inevitable that sheets will have to be replaced after a certain number of prints, due to the adhesive peeling and the sheets cracking.

Our focus on this project was to get the print to work properly and ultimately most of our budget went to assembling the various components of the printer. With the frame and extruder components mostly in place, a future team would be free to focus their budget and design on improving the conveyor belt of the printer so that it is able to withstand the heat from the extruder without melting. Our alternative solutions take inspiration from the designs used by Blackbelt and Printrbelt in their angled 3D printers. The ideal solution would be to use a carbon fiber belt like the one used by Blackbelt. This would be a surface that PLA can easily adhere to and a typical carbon fiber is able to withstand 3652°C [53], so the belt can easily withstand the roughly 250°C max temperature of our extruder. If the team had more budget to purchase such a belt, this is the solution the team would have used.

A second solution would be to construct a conveyor belt made from Kapton or PEI like that used in Printrbelt’s design. From our previous analysis in section 4.4.1 we know PEI and Kapton are both acceptable for both print adhesion and can withstand the 250°C max temperature of our extruder. By using either material directly as a belt this would avoid any issues that come with having to applying and reapplying the material to the belt. The belt would still have to be replaced periodically, but the process of replacing the belt itself would be easier than trying to apply the material to the surface of the belt and it would also be easier to maintain a flat surface. This method might save on cost, but would also require more design work, as there are currently no Kapton or PEI belts available, so either a custom order would have to be made, or the team would have to construct their own belt by layering standard Kapton or PEI sheets to the appropriate thickness. The current pulley system of the printer would also likely have to be redesigned around the new belt material, which might not be able withstand the tensile force currently applied to the belt when it is fully tensioned.

#### 6.3.4. Implement Heated Bed

Once full print functionality is achieved a heated bed could be implemented to improve the quality of prints, while also expanding the capabilities of the printer to include other materials beyond PLA, such as ABS, PET and other filaments. In its current form, the extruder can heat filament to around 250°C, enough to melt most filaments, but a heated bed is needed to prevent warping of the parts. Warping happens when the plastic on the edges of a part cool down more quickly than the plastic on the inside of the part. This causes the corners of a part to warp up, resulting in a deformed print. A heated bed keeps the part warm during the entire printing process, thus keeping the part at a temperature where it is malleable and will remain flat on the print surface [54].

With a moving belt, implementing a heated bed would require additional design considerations. For one the belt itself must be able to safely conduct the heat from the bed to the its surface in a reasonable amount of time. Our nylon print bed would likely have to be replaced with a glass or aluminum bed for increased conductivity as well. In its current orientation the print bed starts right under the extruder. The extruder would have to be moved forward slightly in the z-axis to accommodate a heated bed. This allows extra time to heat up the belt before it reaches the extruder, otherwise the belt would need to stop and be heated to an appropriate temperature each time it moves a step, resulting in longer print times.

#### 6.3.5. Milling Operations

To save time in the manufacturing process some parts in our design were machined using the drill press and band saws available in the machine shop on campus. These operations were done manually, so they were faster to complete than using the CNC Mills, as we did not have to spend any time programming CAM operations and preparing the mill for these operations. The downside of the time saved in machining these parts is that they do not exactly match the dimensions specified in our CAD model. In some cases, namely the bottom frame feet and the side supports, this discrepancy does not hinder the functionality of the parts and is primarily cosmetic. If the parts were to be machined more precisely using a CNC mill it may also make it easier to assemble and disassemble components, thus making the maintenance of the printer an easier process.

In hindsight the main area where CNC machining could have been used to improve the performance of the printer was in the angled cuts on the top frame of the printer. This is where the top frame that holds all our extruder assemblies attaches to our bottom frame at an angle of 45 degrees. This cut determines the angle that the extruder will print at and it is imperative that it is exactly 45 degrees, as Cura, the slicing software we planned on using with the printer, assumes the extruder is printing at an angle of exactly 45 degrees when generating the slicing of the part. This operates off the assumption that the Blackbelt printer software prints at 45 degrees. It is an accurate assumption, as the printer is roughly $10,000 USD and we can assume a tight tolerance on the available angles for that price. In our printer these cuts were made on a horizontal band saw where we rotated the vice 45 degrees to give us a 45-degree cut. Despite careful measurements to ensure the cut was at 45 degrees, the two frames were measured to be at 44.7 degrees and 42.9 degrees respectively upon closer inspection. While these differences seem minimal, as explained in section 6.2.1 even a small discrepancy between the print angle assumed by the slicing software and the actual print angle can lead to errors in printing.

The main solution to discrepancy between the slicer and the control interface is to mill the angled extruded aluminum. Milling gives a very fine tolerance to a part, as most Haas mills, for example, have a tolerance that is generally within ± 0.0001 [55]. Thus, an angled cut milled on a machine with the accuracy of a Haas mill would bring the angle to 45 degrees ± 0.0001 degrees.

### 6.3.6. G-Code Generator

If cuts made using the CNC mill are still not precise enough for the slicing software, one other solution to the issue of an off-tolerance cut is to modify the g-code generator for the Blackbelt Cura software. The software allows for selection of three different angles (30, 45, and 60), we can assume that there is a function within the g-code generator that determines how support material, brims, rafts, etc. are generated depending on the angle. A programmer could determine how to change these parameters for any arbitrary angle and adjust them accordingly for our printer. We attempted to contact Blackbelt about access to the g-code generator, but, as we expected, we had no success as that is a proprietary code.

Another potential solution to the issue is to simply fabricate our own g-code generator for the process at our angle. The shape itself is simple enough where our group could have potentially created a code to run the printer at the angle. The main trick is that the slicer must print the layers at the angle of the extruder to the bed. If we were to attempt to print a cube, it would result in a rhomboidal-shaped object at the resultant angle. The main aspect that we would not be able to figure out is how support material, brims, and rafts would work and where they would be printed to help the object. In the future, a computer science group could potentially work on generating the functions necessary to determine how to print the support material at various angles. This would allow us the print an object and empirically determine what angle the printer is at due to any deviation we find. This should not be a concern to a mechanical engineering group, however, as it is beyond the scope of what an ME project does.

### 6.3.7. Changes to XY Axis Adapters

After assembling and testing the X-axis, we realized that the timing belt pulleys incased in both XY-Axis adapters were not in plane with the timing belt securement features in the 3D printed X-carriage part. Instead of the timing belt remaining parallel to the X-axis as the extruder moves back and forth, the timing belt forms a peek at the X-carriage and valleys at each of the XY-Axis adapters. This issue stemmed from mistakes made regarding the function of some of the features on the Prusa Mk2 extruder X-carriage. This is important because for the motion of the X-axis to be linear and consistent throughout its full range of motion the timing belt must be parallel. However, this should be easy to resolve. Upon further inspection it appears the timing belt should be centered between the two X-axis linear rods instead of off center. Both XY-Axis adapter parts must simply be edited to move the timing belt pulley features to the center between the X-axis rods.

## 6.4. Marlin

Marlin is an easy code format to change as there are lines that are simple to read and change the settings. Generally, the values can be changed to whatever desired value the coder wants, however the obvious implication is that certain values should not be changed to ridiculous values. For example, a default feed rate on the extruder is 25 mm/s, this value can be changed to a faster or slower feed rate by changing the code, however it should not be changed to 500 mm/s as this value is dangerous to the stepper motor, to the driver board and Arduino, and to the hotend itself. Section 6.4.1 analyzes the standard settings within the Marlin code and edits that we made to our code to run the printer.

### 6.4.1. Standard Marlin Settings and Categories

Marling firmware was created to support nearly all types of printers and therefore includes many sections and settings that are not relevant to our printer that will be only briefly discussed or skipped over entirely.

The first section of the configuration file contains settings related to the type of printer for the software is being programmed as well as the type of controller and mother boards that are being used. In our case, we used an Arduino Mega 2560 controller and a Ramps 1.4 mother board. Depending on the number of extruders and fans being used there are further settings to edit. We have one extruder and two fans and changed the settings accordingly. A filament diameter of 1.75mm was selected to match that of our extruder.

Next, we matched the thermistor that was included with our E3D-V6 hotend with the list of thermistors and specs in the configuration file. We changed the selection for thermistor 1 from 0 (none) to 5 ('5':"100K / 4.7k - ATC Semitec 104GT-2 (Used in ParCan & J-Head). Many more advanced thermal settings related to the hotend followed but they were left in their default states.

Mechanical settings followed next with end-stop settings. We elected to home the printer to X-min and Y-max so that the extruder would home to the right and up. Unfortunately, we were forced to also choose to home the Z-axis to avoid errors when compiling. It will be necessary to install an electronic switch to the Z-axis end-stop pins to be triggered manually during the homing process as there is no end to the infinite Z-axis. Next was selecting the steps per mm of travel for each axis (x, y, z, E0). These settings were calculated based on the steps per revolution of the stepper motor and the circumference of the driving surface for each motor, in most cases a pulley driver wheel. The X and Y axis motors are 4.897 steps per mm and the extruder was 12.36. Further testing was necessary to calculate the steps per mm for the Z-axis and so this was left at the value of 4000. It is worth noting that these settings are for zero micro stepping of the stepper motors and any micro stepping would require these values to be divided by the micro stepping value. Max velocity, acceleration, and jerk values were left at their suggested defaults.

Several more changes were made under the additional settings section. Preheat temperature 1 was set to 215 degrees Celsius for PLA and the fan was set to near max speed. Preheat temperature 2 was set to 240 degrees Celsius for printing PETG material and with the same fan speed. We also enabled a feature to prevent the extruder stepper motor from moving unless the hotend successfully preheated.

Finally, we set up our display and input device that consists of an LCD display, an encoder for navigation in and between menus, a cancel/emergency stop button, and a standard SD-card reader. The language for the display was set to English and the character type to Western. The user interface and available menus and options on the controller were then chosen and setup.

Under the advanced settings section we enabled dual Y-axis stepper drivers and inverted one of them just as our design calls for. Additionally, we chose 16 micro stepping and for it to only be enabled if the proper pins were connected on the ramps board. Theoretically, this will allow micro stepping to be enabled without having to adjust any of the steps per mm rates.

# 7. Conclusion

At the end of this project, we were able to construct the static system for the printer. Our design choices for specific parts, such as the motion shafts, and the belt surface are justified with analysis performed with Solidworks. Our construction process involved machining many parts to specifications as well as 3D printing numerous components. Although the Y and Z axes did not work in the design the X axis and the Extruder axis results verified the process was reliable. However, misalignment and bearing friction complications were problematic. Our design choice for the Z-axis motor system sufficed in gearing necessary to overcome the torque requirements for moving the system. The combined gear ratio, 10:1, combined with a NEMA 17 was enough to drive the system based on measured output torque. We were able to determine why some components performed less than our design specifications and developed potential solutions that a future group could implement. In addition, we offered many suggestions remedy ailments foiling some of our proof of concept design. Like our efforts, Blackbelt and Printrbot required multiple years of prototyping and ideation before they had their working prototypes. Our team has developed a proof of concept prototype with the overwhelming set of components and subsystems working within our design specifications.

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# Appendix A

Images of various machines, tools, and charts


Figure 83: Non-Ferrous Buffing Wheel for Surface Finish.

| | | Surface Feet/Minute | | | | Inches/Revolution | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Uncoated, TiN Coated, and TiAlN Coated | | | | TiCN Coated | | | |
| Material | Hardness | Uncoated | TiN Coated | TiCN Coated | TiAlN Coated | 1/8" | 1/4" | 3/8" | 1/2" | 1/8" | 1/4" | 3/8" | 1/2" |
| Low Carbon Steel | 85-125 BHN | 100 | 130 | 145 | | .004 | .0065 | .008 | .01 | .005 | .008 | .01 | .0125 |
| Medium Carbon Steel | 125-175 BHN | 95 | 125 | 140 | 175 | .0049 | .0065 | .008 | .01 | .006 | .008 | .01 | .0125 |
| High Carbon Steel | 175-225 BHN | 90 | 120 | 130 | 160 | .003 | .005 | .0065 | .008 | .0035 | .006 | .008 | .01 |
| Alloyed Steel | 200-300 BHN | 65 | 85 | 95 | 110 | .0025 | .004 | .005 | .0065 | .003 | .005 | .006 | .008 |
| Heat Treatable Steel and Forgings | 370-420 BHN | 40 | 50 | 60 | 70 | .0025 | .004 | .005 | .0065 | .003 | .005 | .006 | .008 |
| Tool Steels | <24 HRC | 60 | 80 | 90 | 110 | .003 | .005 | .0065 | .008 | .0035 | .006 | .008 | .01 |
| Tool Steels | >24 HRC | 30 | 40 | 45 | 55 | .0025 | .004 | .005 | .0065 | .003 | .005 | .006 | .008 |
| High Speed Steels | 14-30 HRC | 35 | 50 | 55 | 60 | .0025 | .004 | .005 | .0065 | .003 | .005 | .006 | .008 |
| Grey Cast Iron | 120-200 BHN | 115 | 160 | 175 | 205 | .005 | .008 | .01 | .0125 | .006 | .01 | .0125 | .0155 |
| Grey Cast Iron | <350 BHN | 90 | 120 | 135 | 165 | .005 | .008 | .01 | .0125 | .006 | .01 | .0125 | .0155 |
| Malleable Cast Iron | <300 BHN | 70 | 95 | 105 | 125 | .005 | .008 | .01 | .0125 | .006 | .01 | .0125 | .0155 |
| 300 Series Stainless Austenetic | 120-200 BHN | 60 | 80 | 90 | 10 | .003 | .005 | .006 | .0075 | .0035 | .006 | .0075 | .009 |
| 400 Series Stainless Martensitic | 200-300 BHN | 40 | 50 | 60 | 80 | .0025 | .004 | .005 | .0065 | .003 | .005 | .006 | .008 |
| Stainless - Sulpherized | <25 HRC | 50 | 70 | 75 | 90 | .003 | .005 | .006 | .0075 | .0035 | .006 | .0075 | .009 |
| PH Stainless Steel | 300-375 BHN | 30 | | 45 | 55 | .0025 | .004 | .005 | .0065 | .003 | .005 | .006 | .008 |
| Nickel Alloys | 300-375 BHN | 20 | | 30 | 45 | .0025 | .004 | .005 | .0065 | .003 | .005 | .006 | .008 |
| Wrought Aluminum | 40-100 BHN | 300 | | 450 | | .006 | .009 | .011 | .0135 | .0075 | .011 | .0135 | .0165 |
| Aluminum Cast < 10% Silicon | 200 BHN | 225 | | 275 | 350 | .005 | .006 | .009 | .011 | .006 | .009 | .011 | .0135 |
| Aluminum Cast > 10% Silicon | 200 BHN | 180 | | | 300 | .004 | .0065 | .008 | .01 | .005 | .008 | .01 | .0125 |
| Brass | 190-210 BHN | 140 | 190 | 210 | | .004 | .0065 | .008 | .01 | .005 | .008 | .01 | .0125 |
| Bronze | 150-200 BHN | 90 | | 130 | 160 | .0035 | .005 | .0075 | .009 | .004 | .0065 | .009 | .011 |
| Copper | 65-100 BHN | 125 | 145 | 175 | | .004 | .0065 | .008 | .01 | .005 | .008 | .01 | .0125 |
| Plastics | | 55 | 75 | 90 | | .0035 | .0055 | .0075 | .009 | .004 | .0065 | .009 | .011 |

Figure 84: Feeds and Speeds for Different Materials.

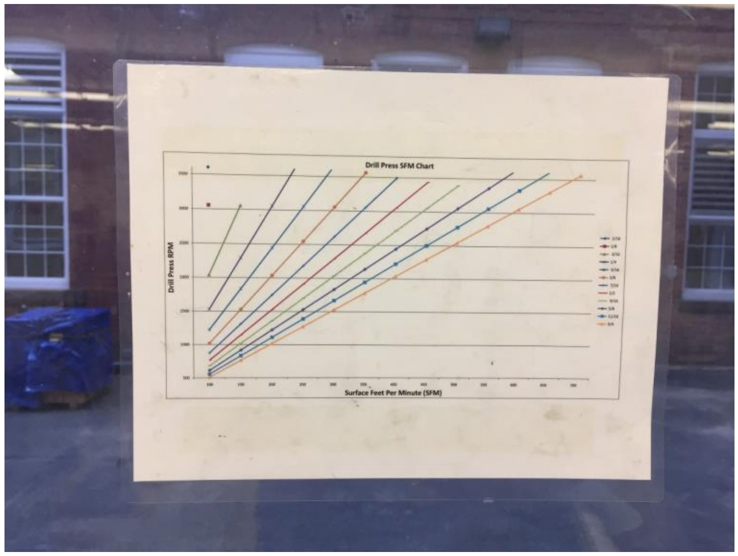


Figure 85: Drill Press RPM Based Off of SFM and Drill Bit Size.


Figure 86: Drill Press with Different RPMs based on Orientation of Levers.


Figure 87: Vertical Band Saw in Washburn Shops.

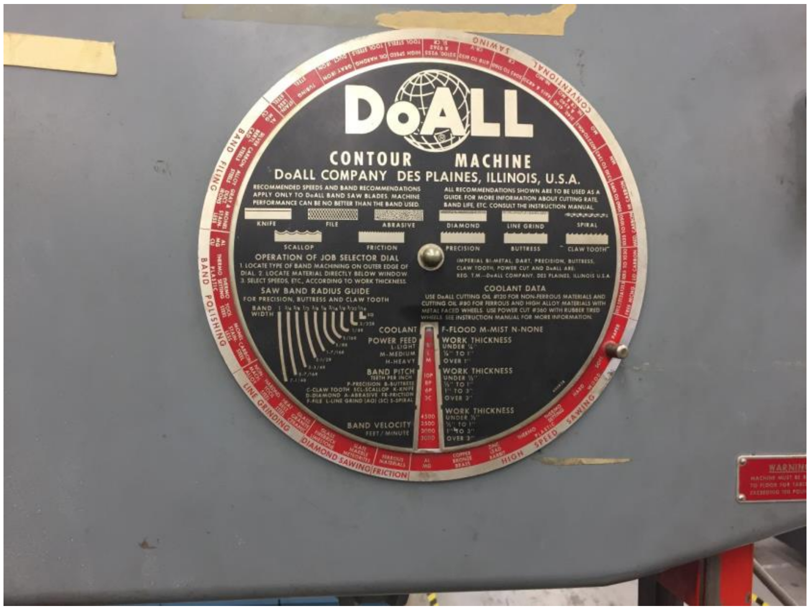


Figure 88: Band Velocity Based on Material Thickness

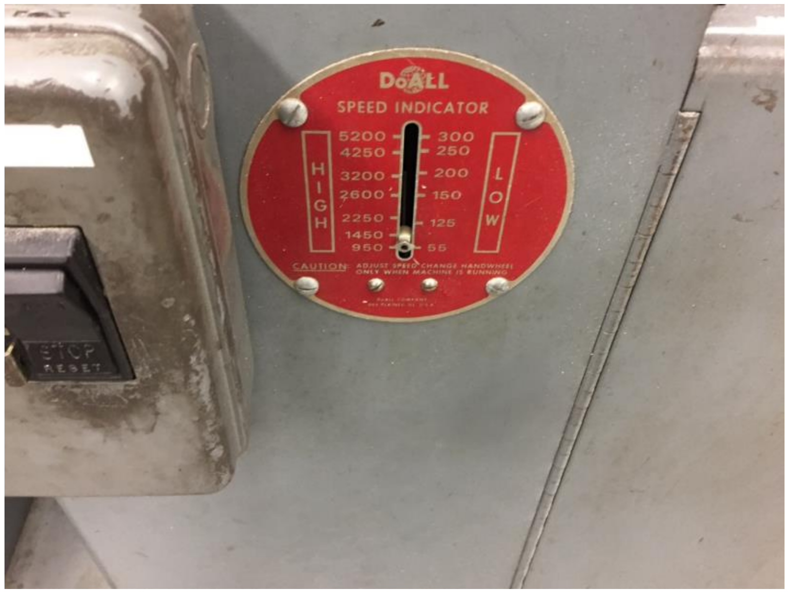


Figure 89: Band Velocity Indicator

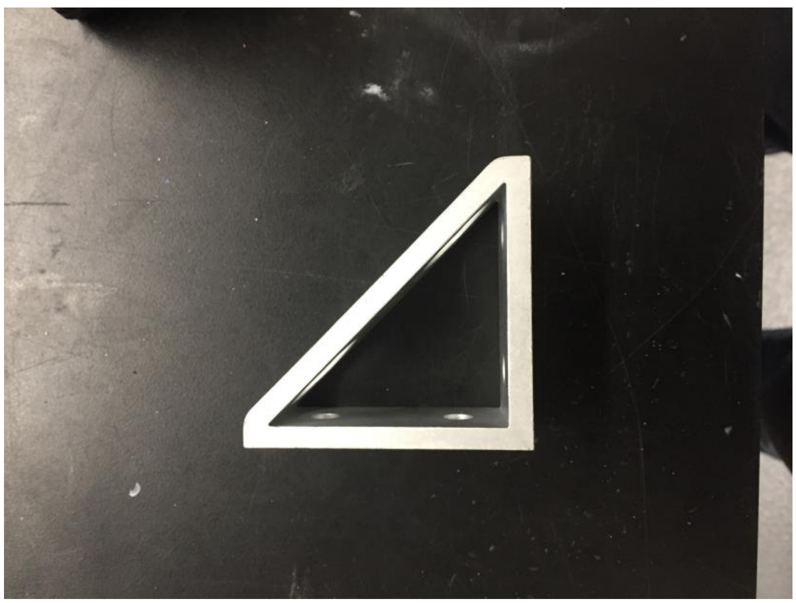

Figure 90: Original Inside Corner Brackets


Figure 91: Belt Sander in Washburn Shops.

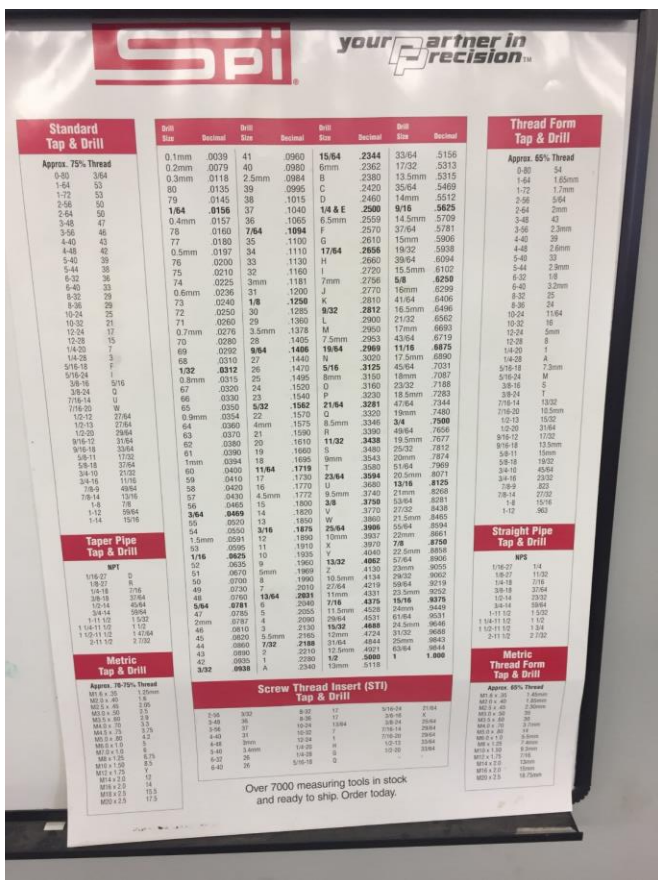


Figure 92: Drill Hole Sizes and Matching Tap Size Chart.

Figure 93: Face mill Tool for Facing Parts.

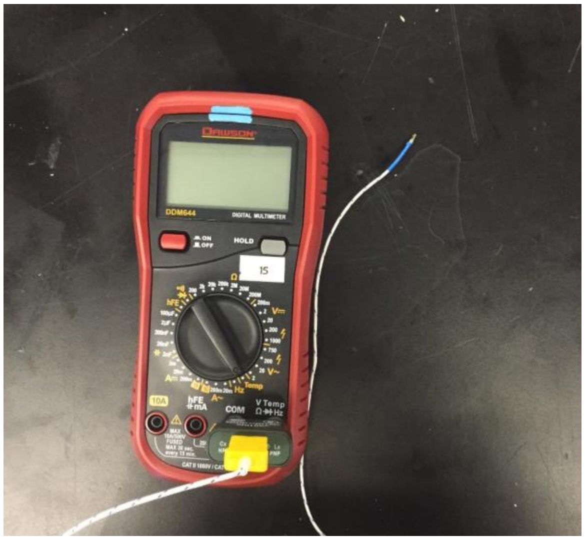


Figure 94: Thermocouple used for Thermal Measurements.

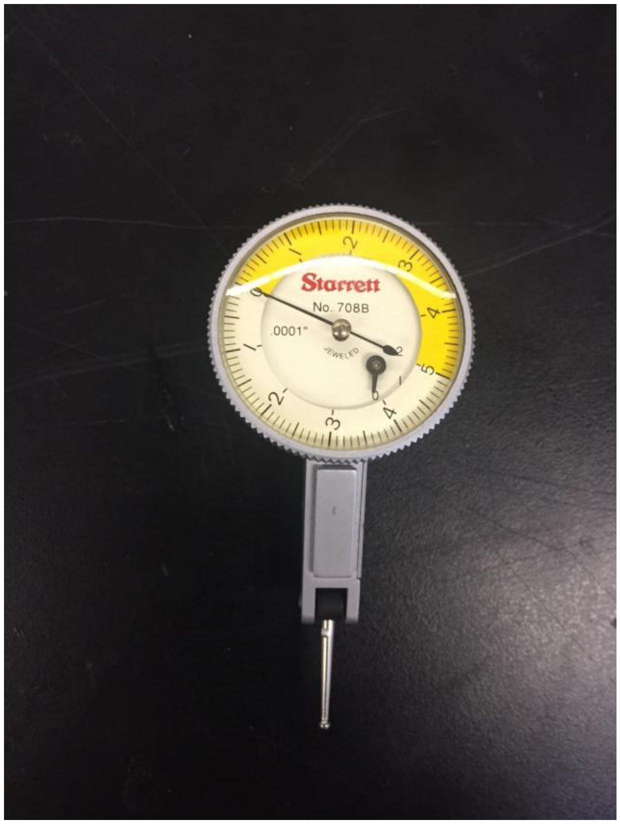


Figure 95: Dial Indicator used for Measuring Surface Roughness.

Figure 96: Torque Wrench used for Measuring Torque.

# Appendix B

Images of every unique CAD model

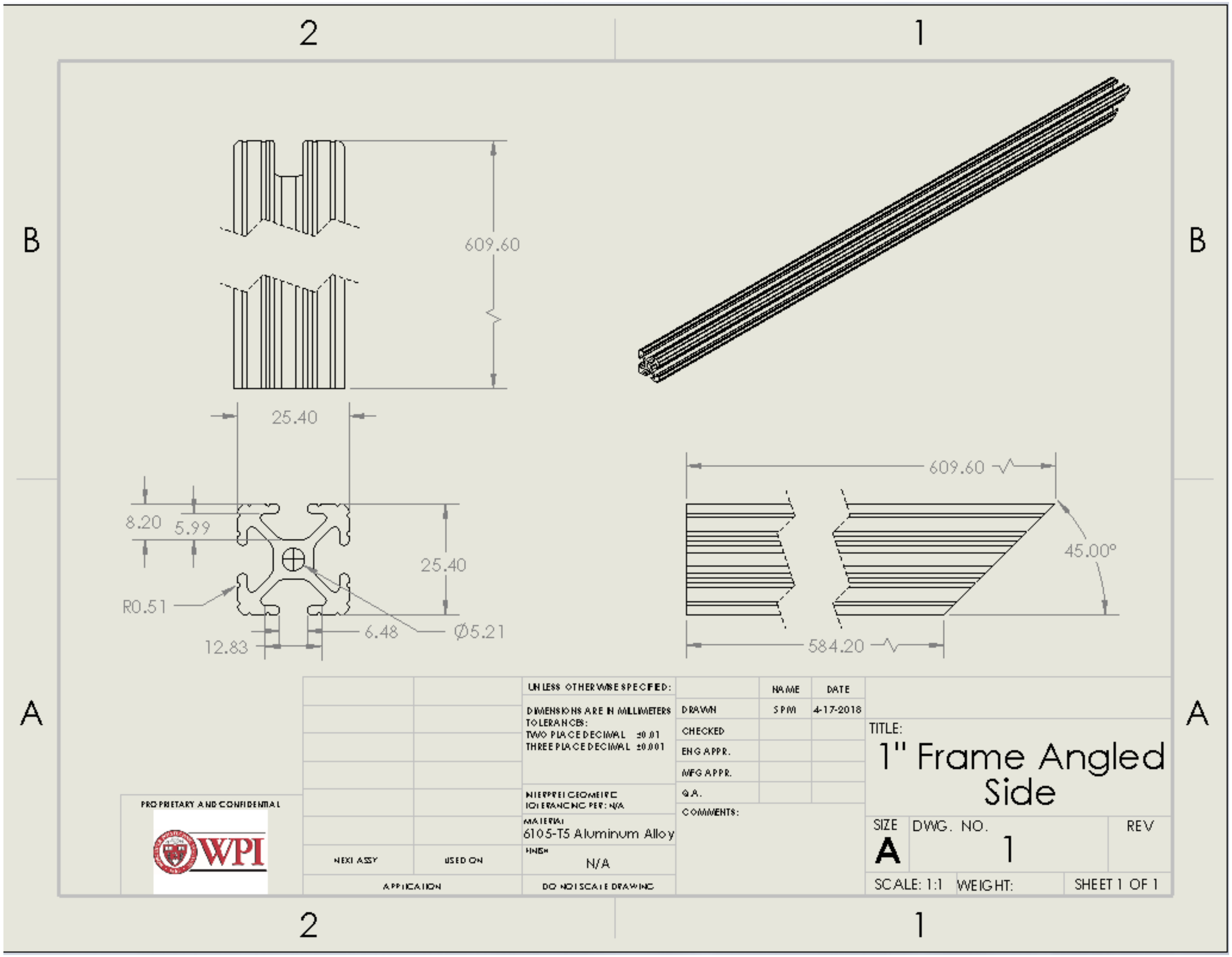


Figure 97: 1" Frame Angled Side.

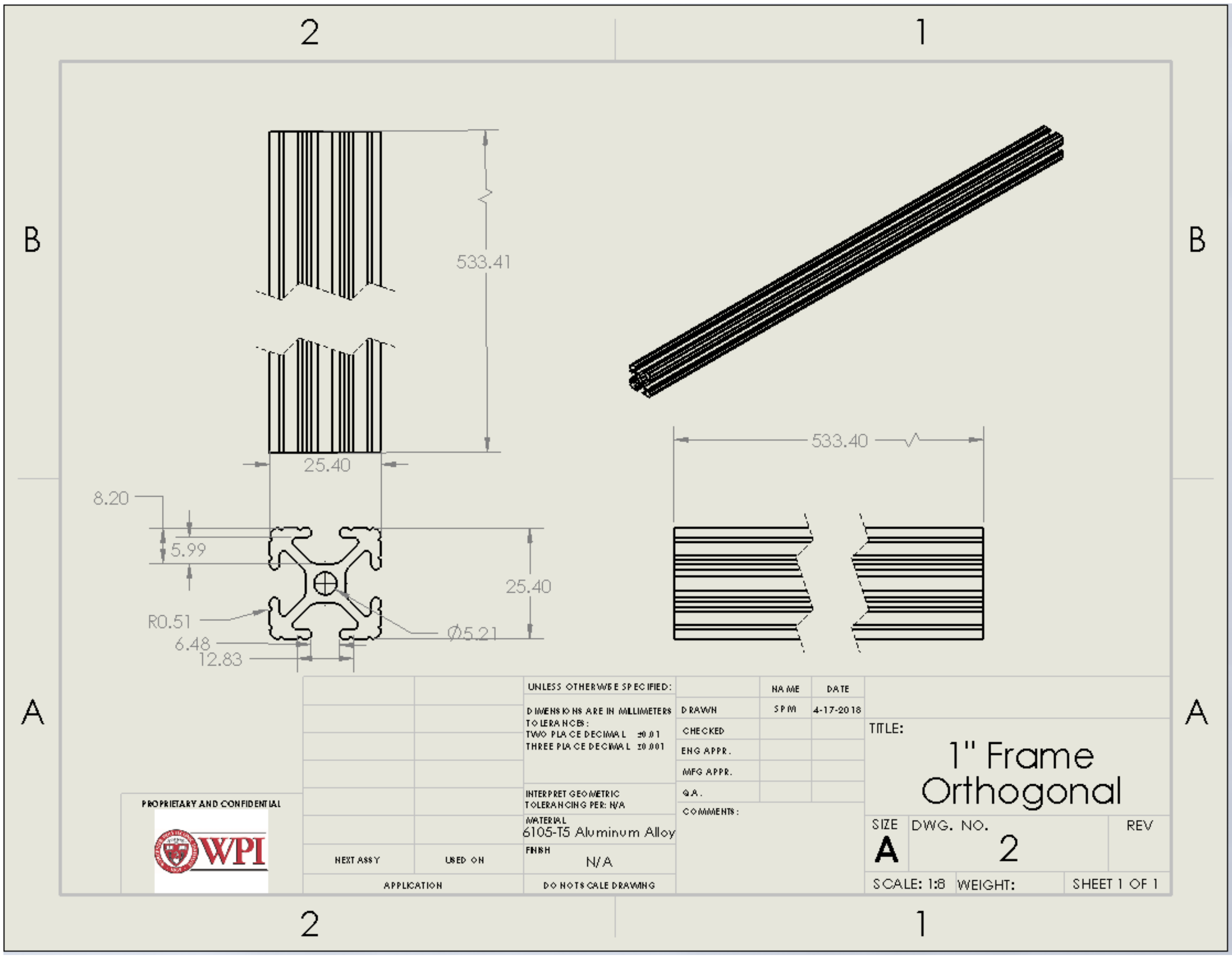


Figure 98: 1" Frame Orthogonal.

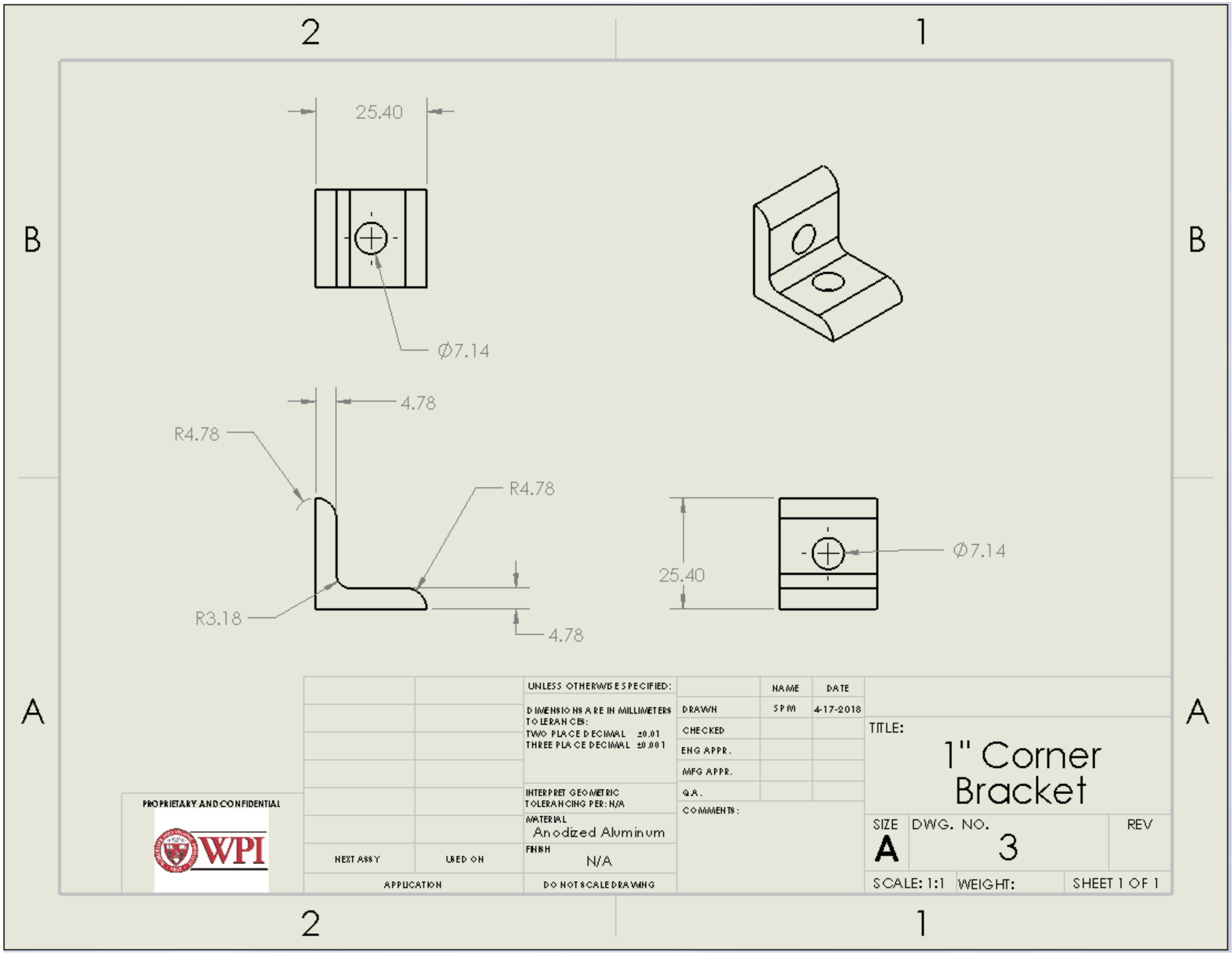


Figure 99: 1" Corner Bracket.

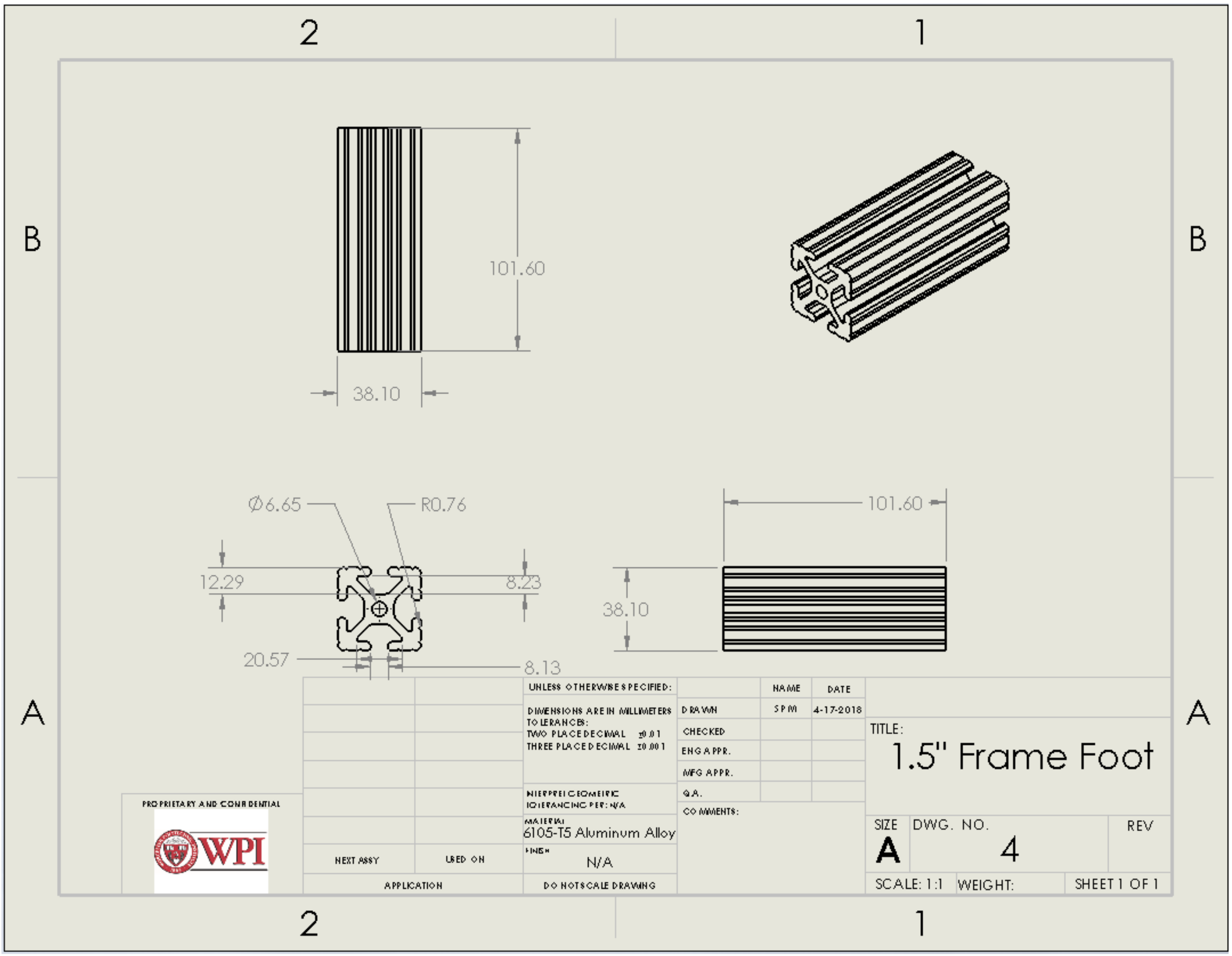


Figure 100: 1.5" Frame Foot.

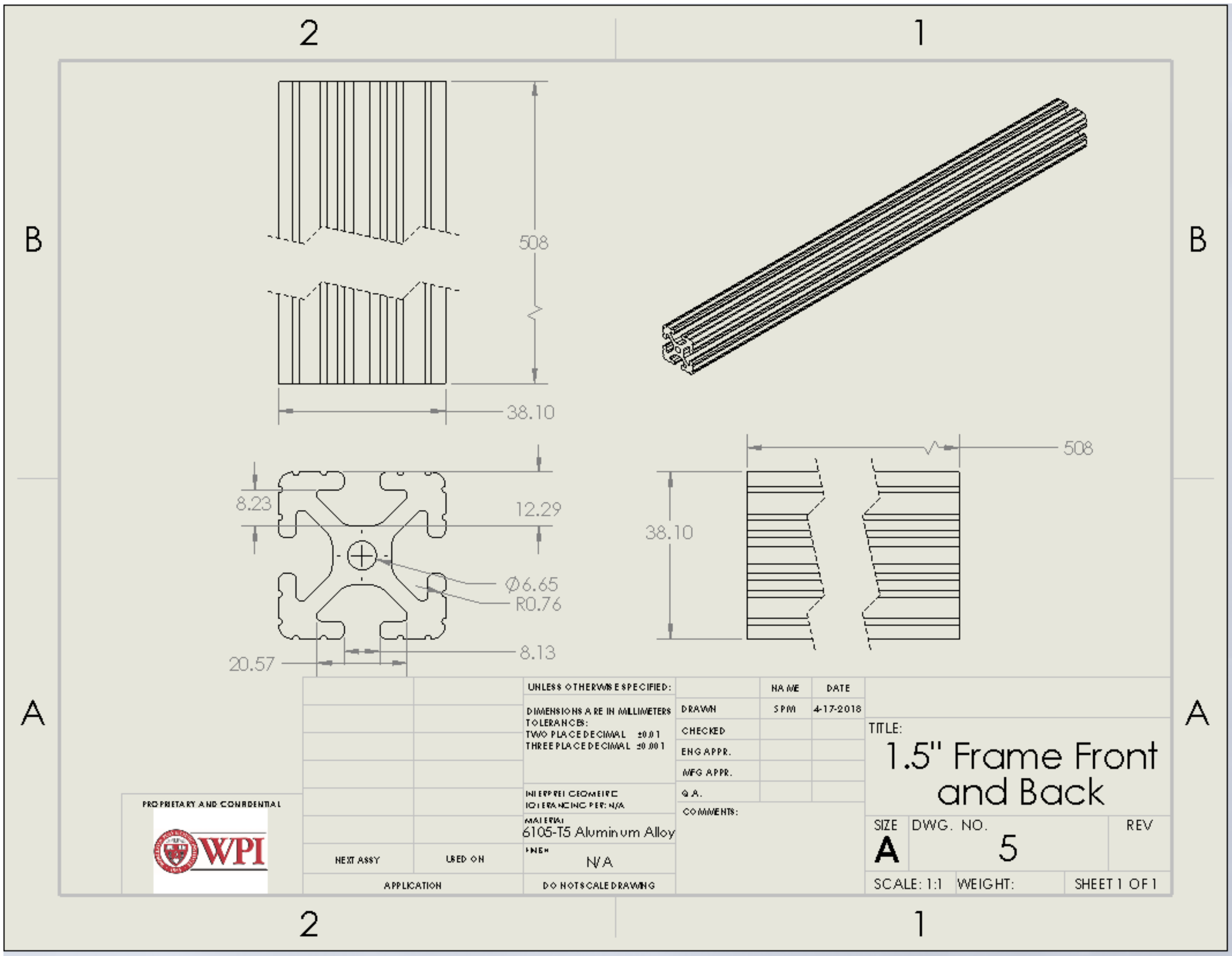


Figure 101: 1.5" Frame Front and Back.

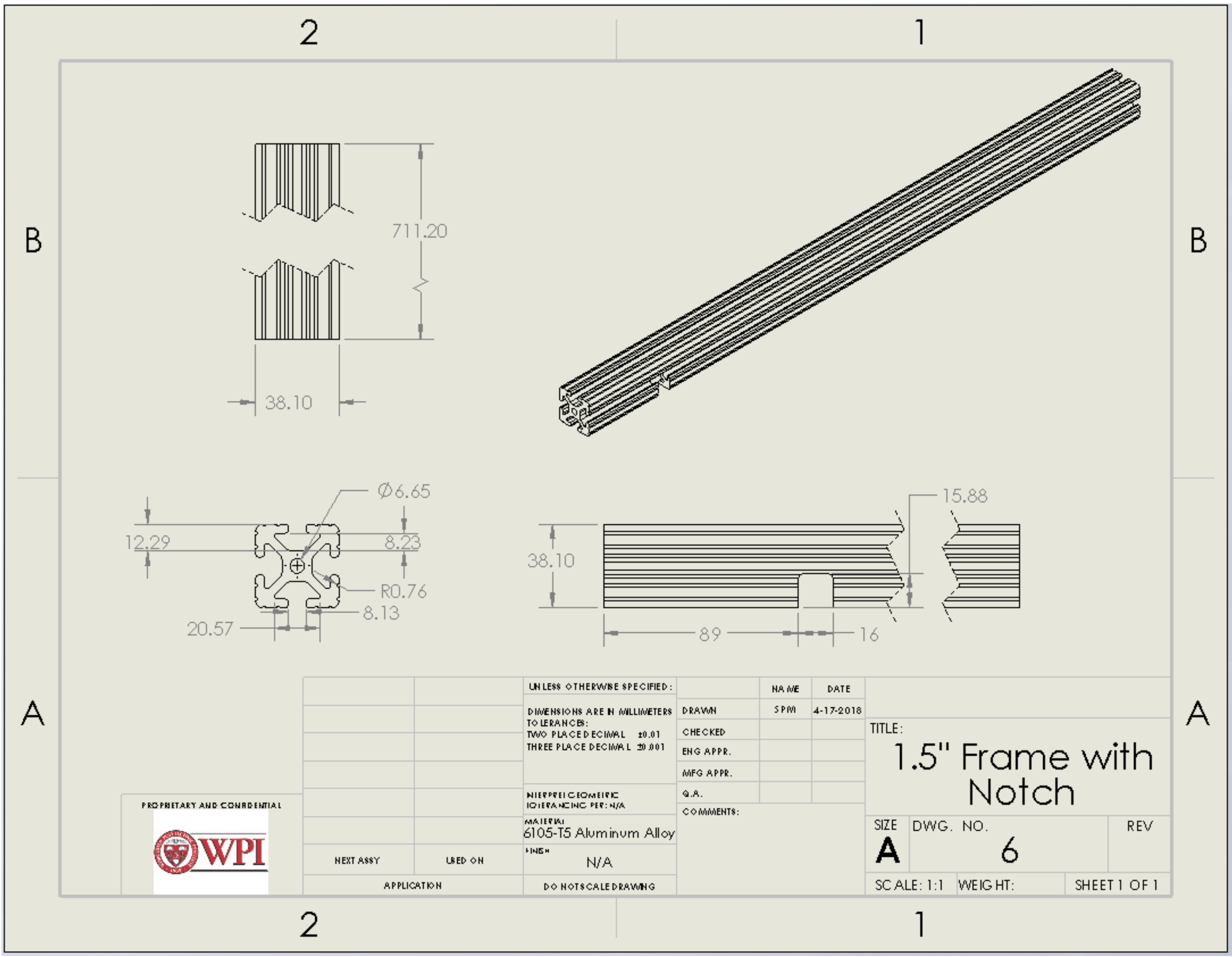


Figure 102: 1.5" Frame with Notch.

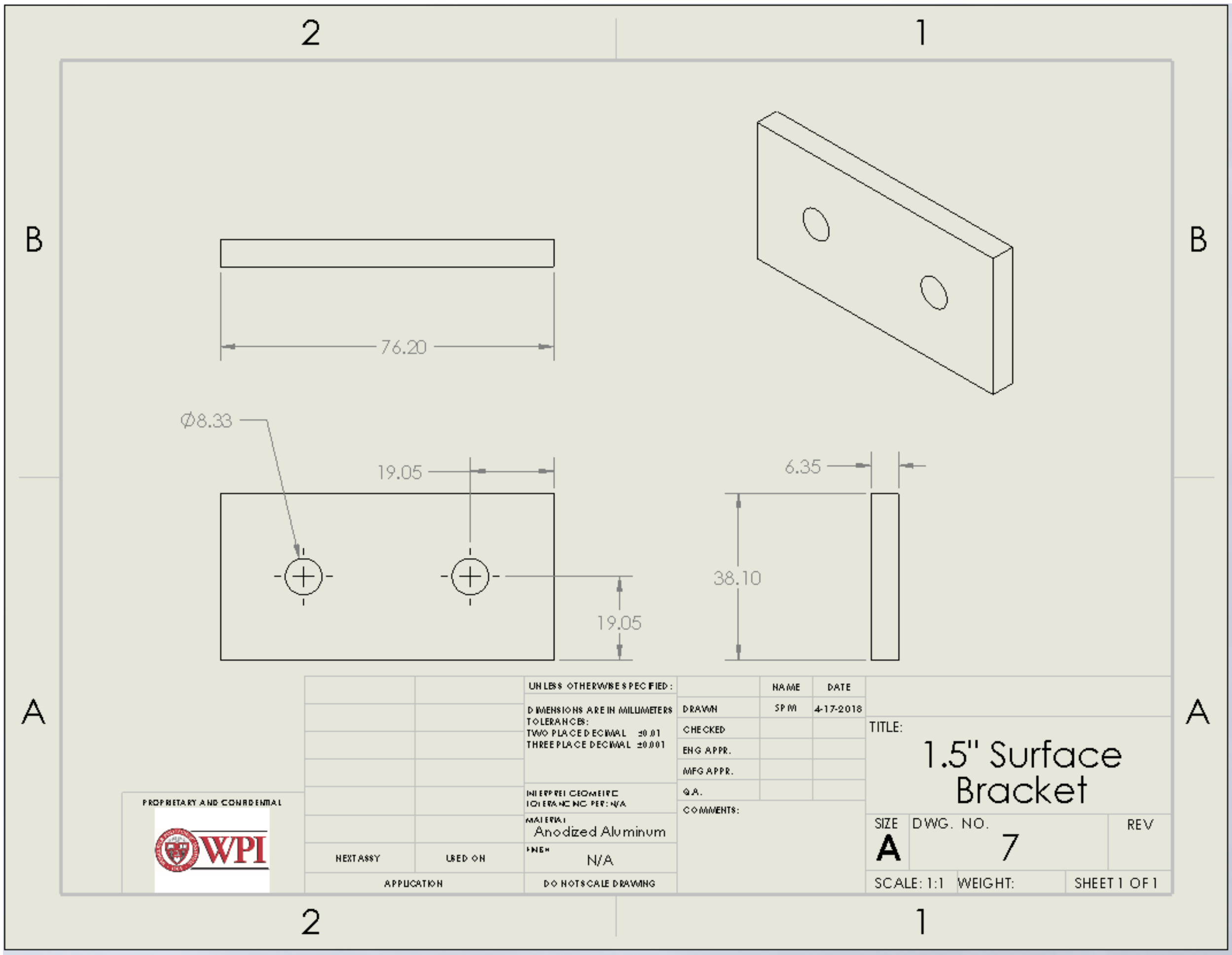


Figure 103: 1.5" Surface Bracket.

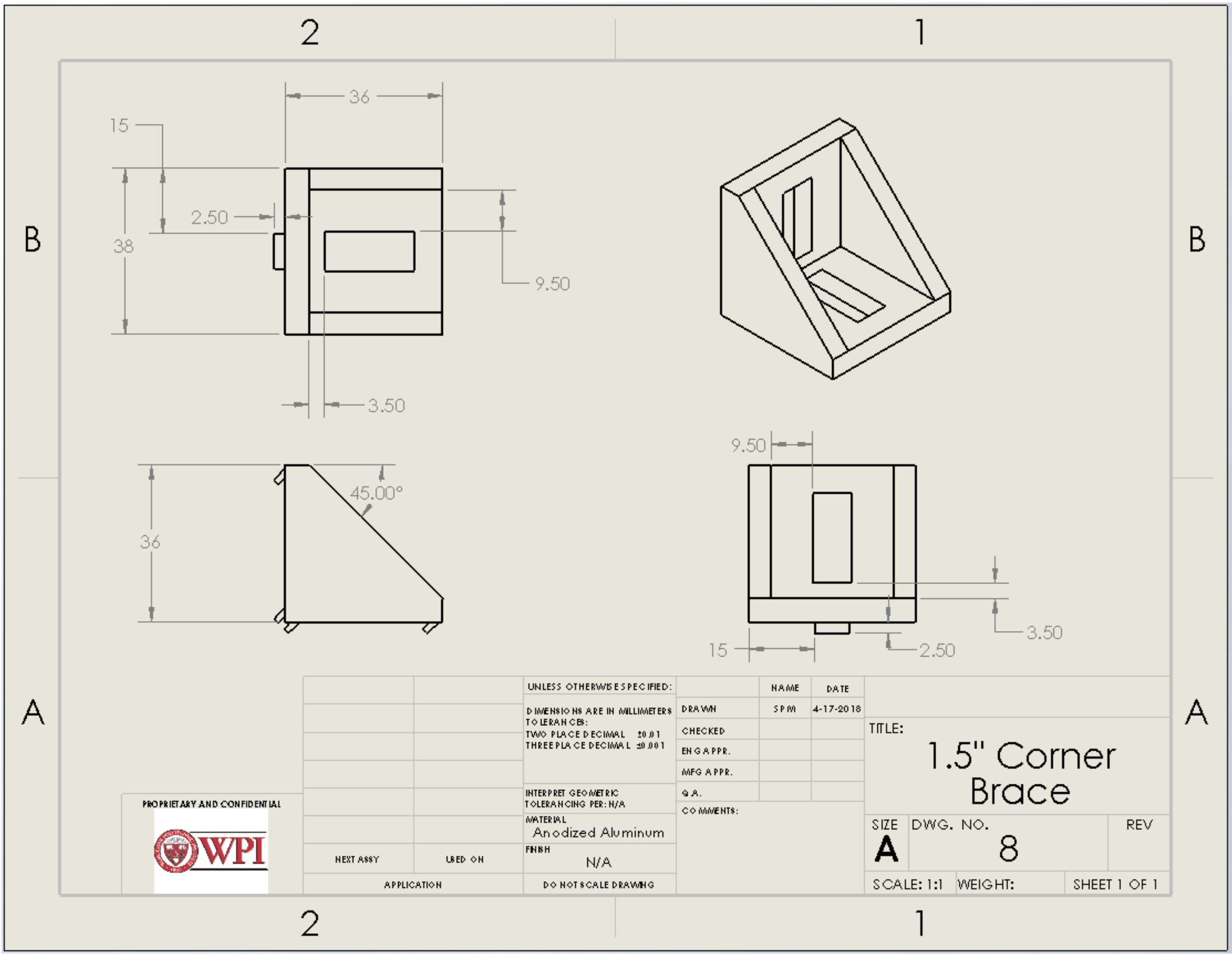


Figure 104: 1.5" Corner Brace.

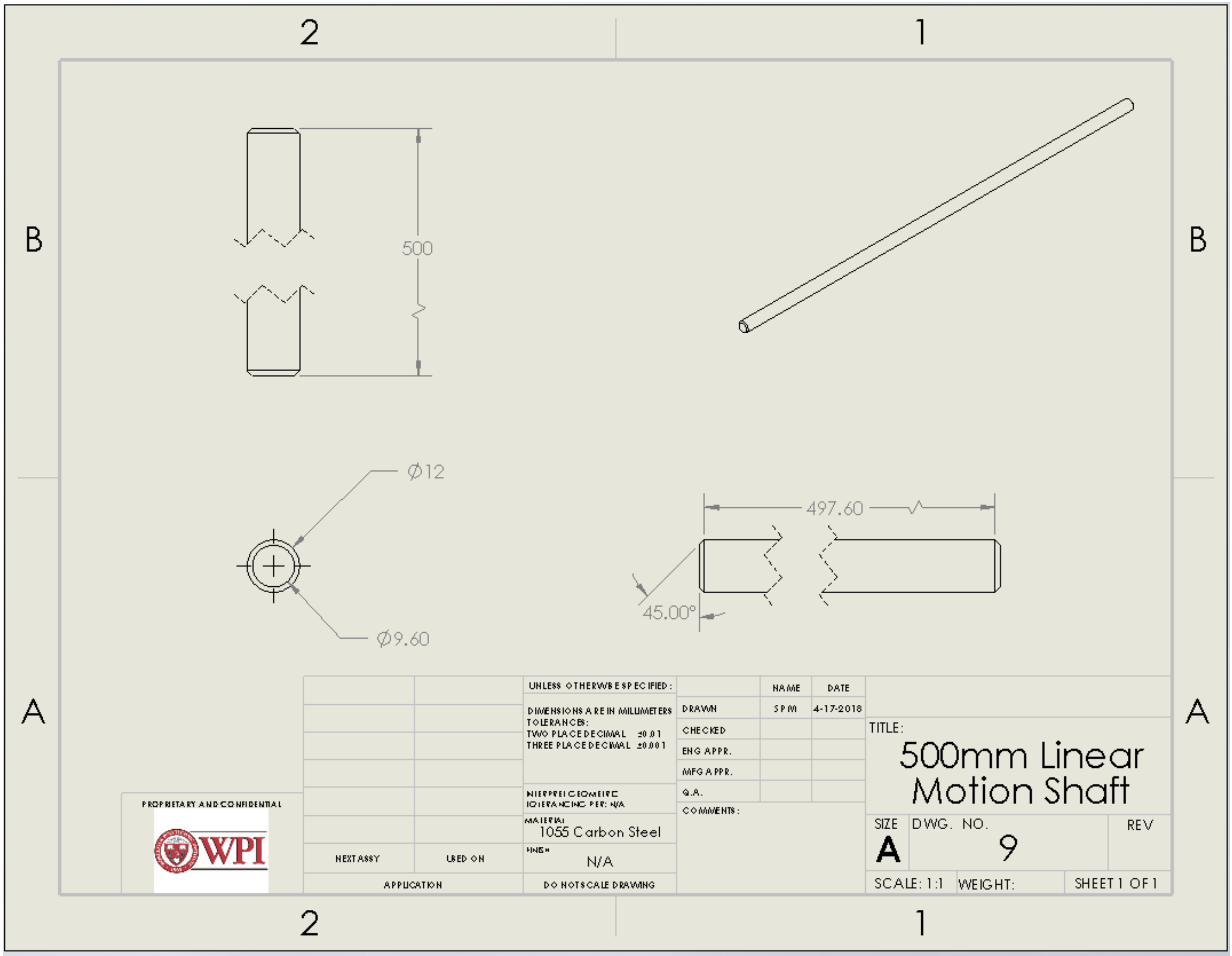


Figure 105: 500mm Linear Motion Shaft.

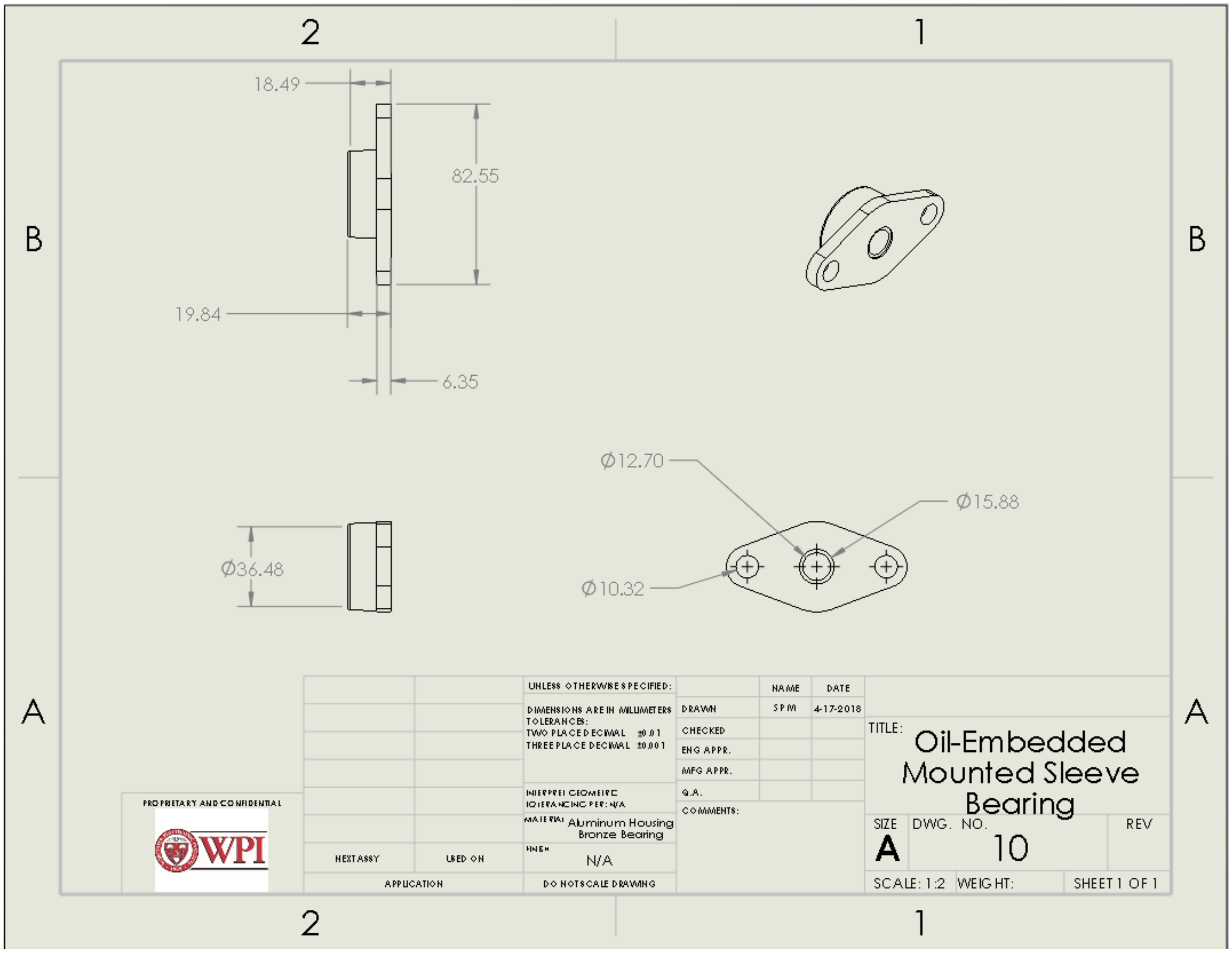


Figure 106: Oil-Embedded Mounted Sleeve Bearing.

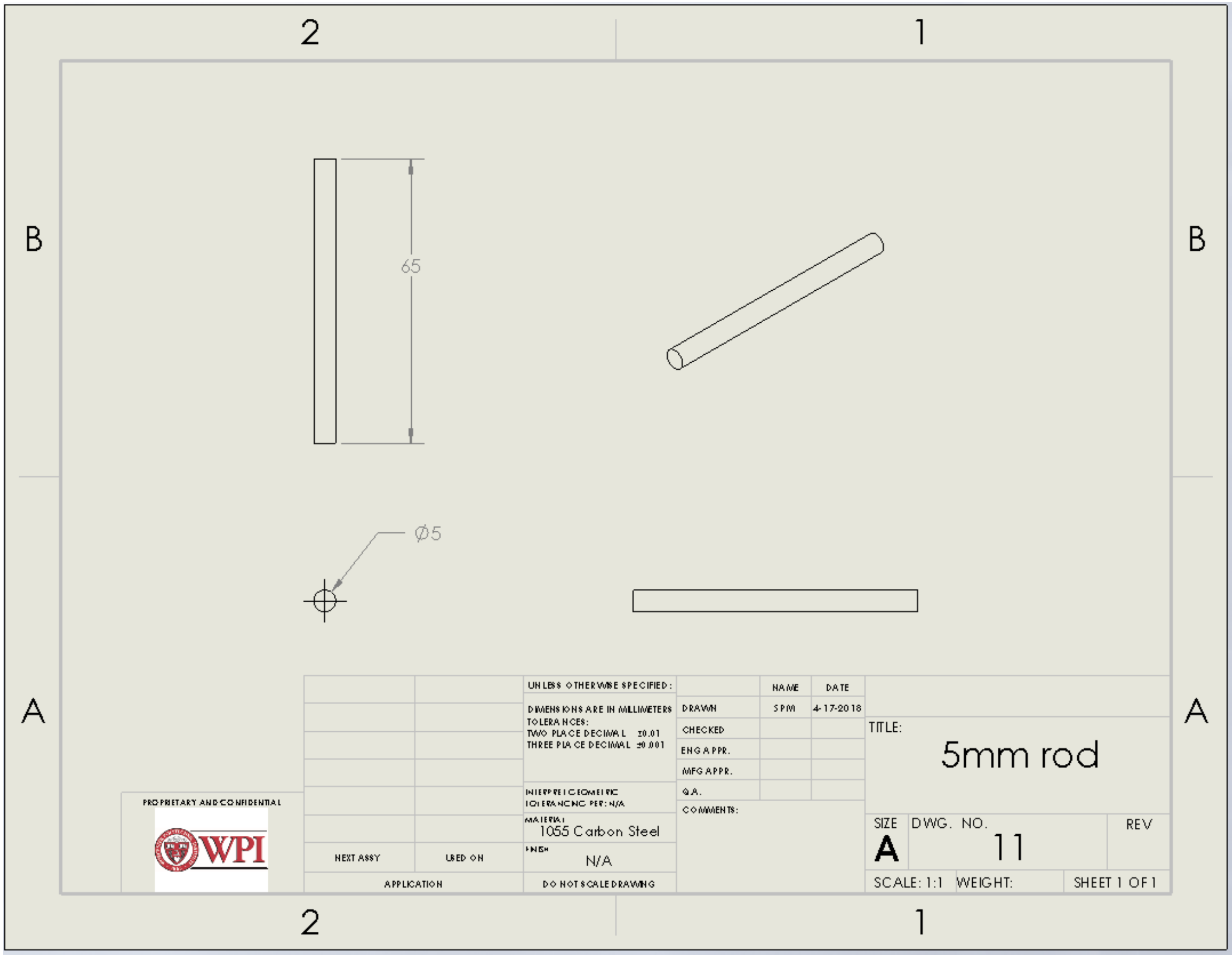


Figure 107: 5mm Rod.

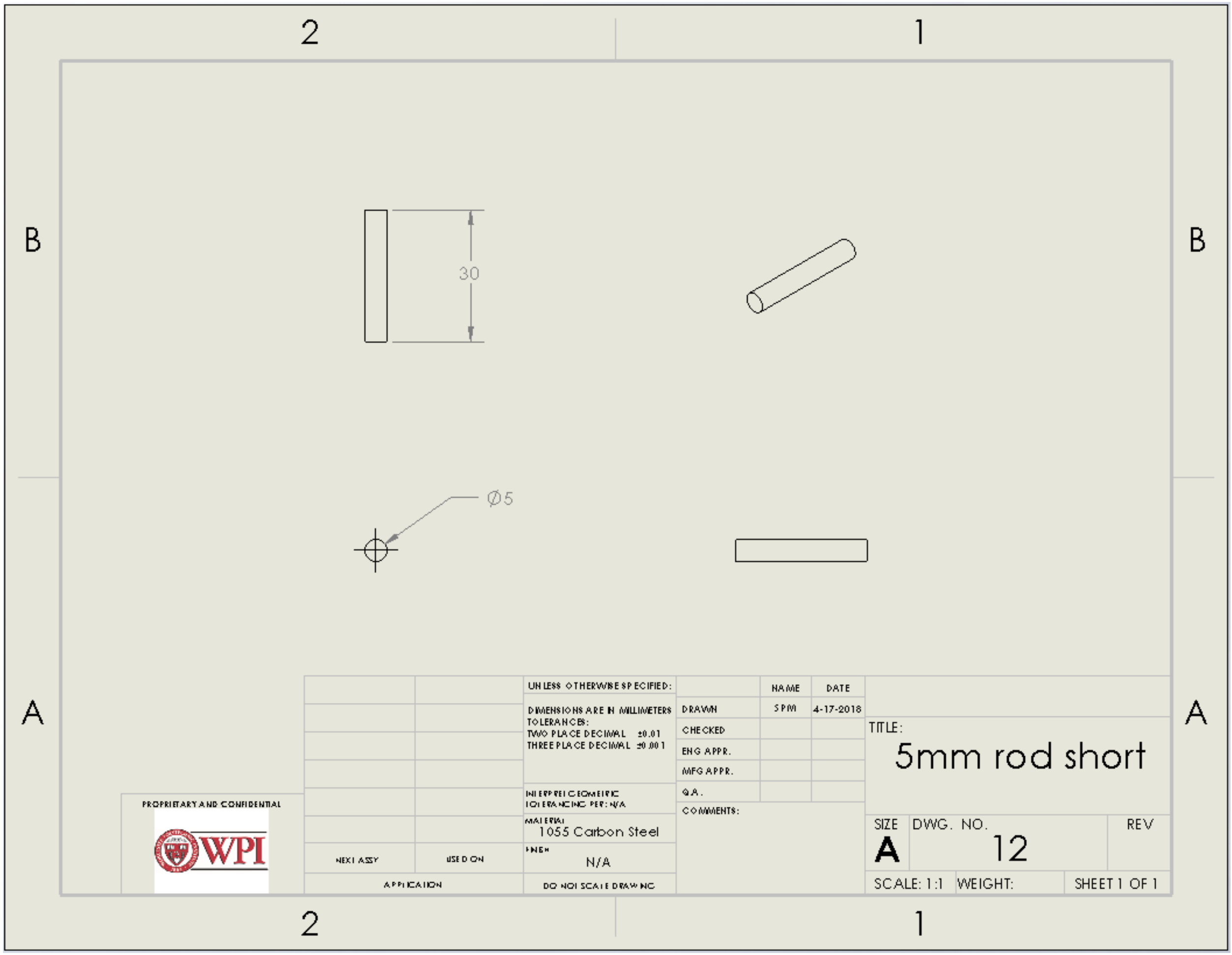


Figure 108: Short 5mm Rod.

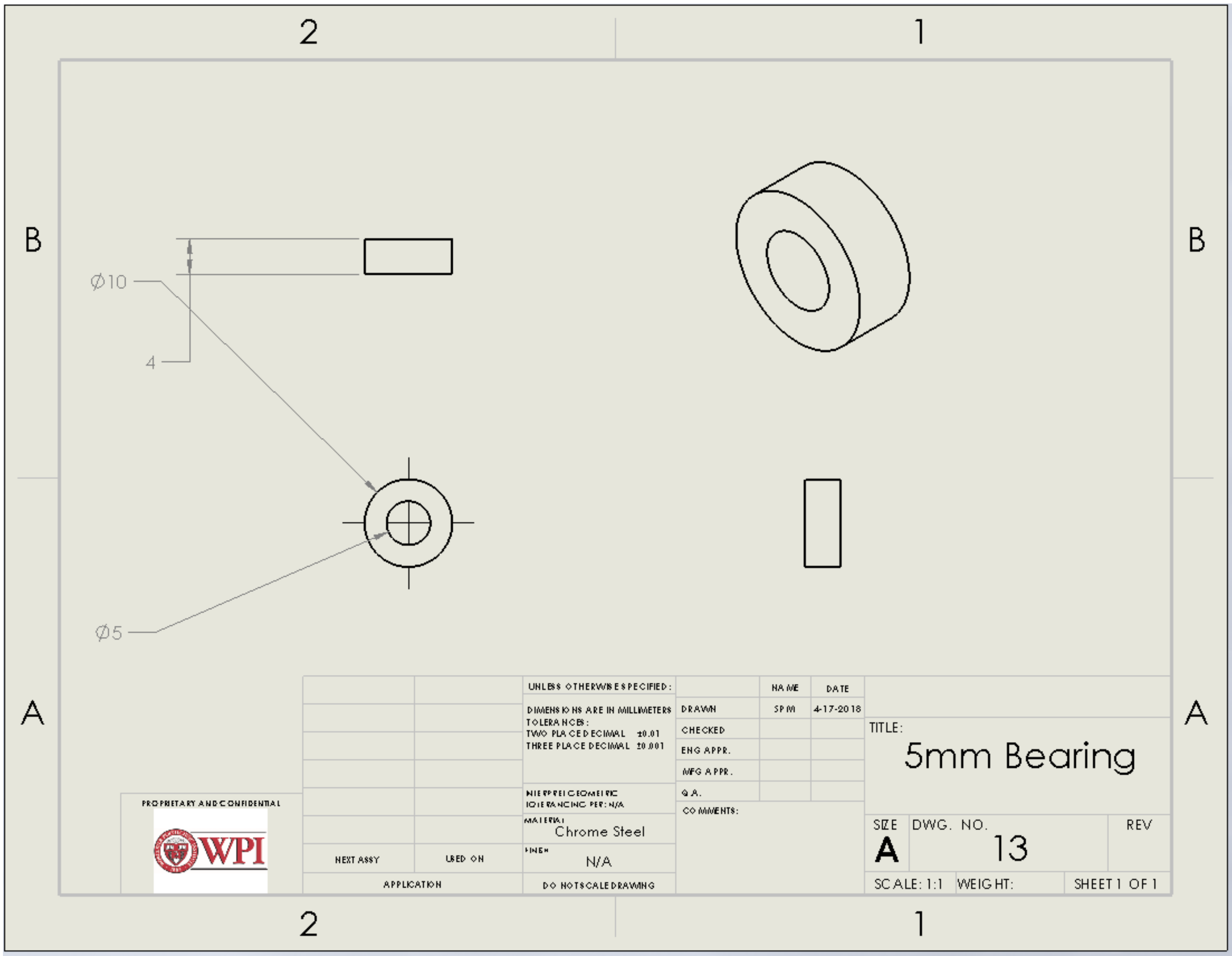


Figure 109: 5mm Bearing.

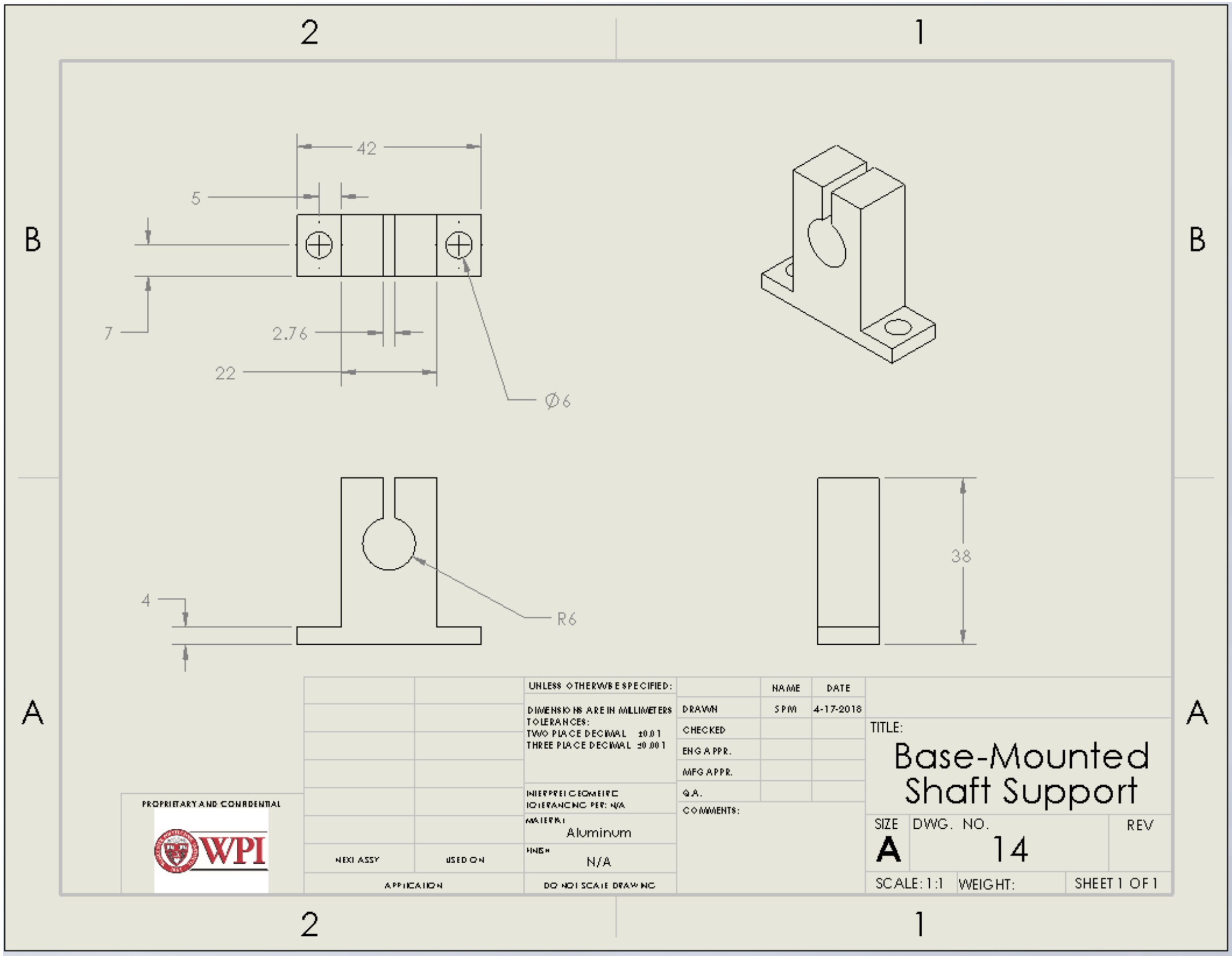


Figure 110: Base-Mounted Shaft Support.

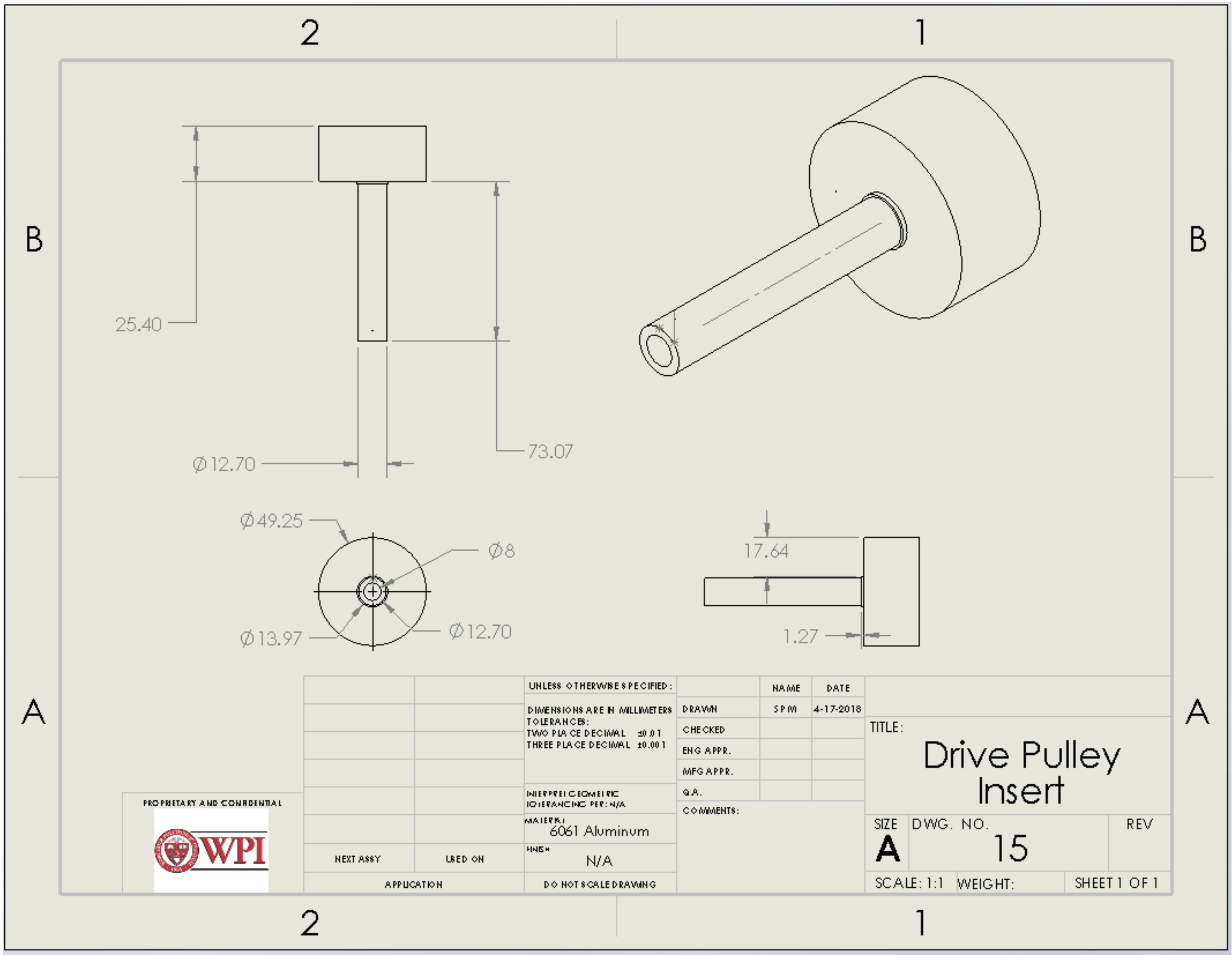


Figure 111: Drive Pulley Insert.

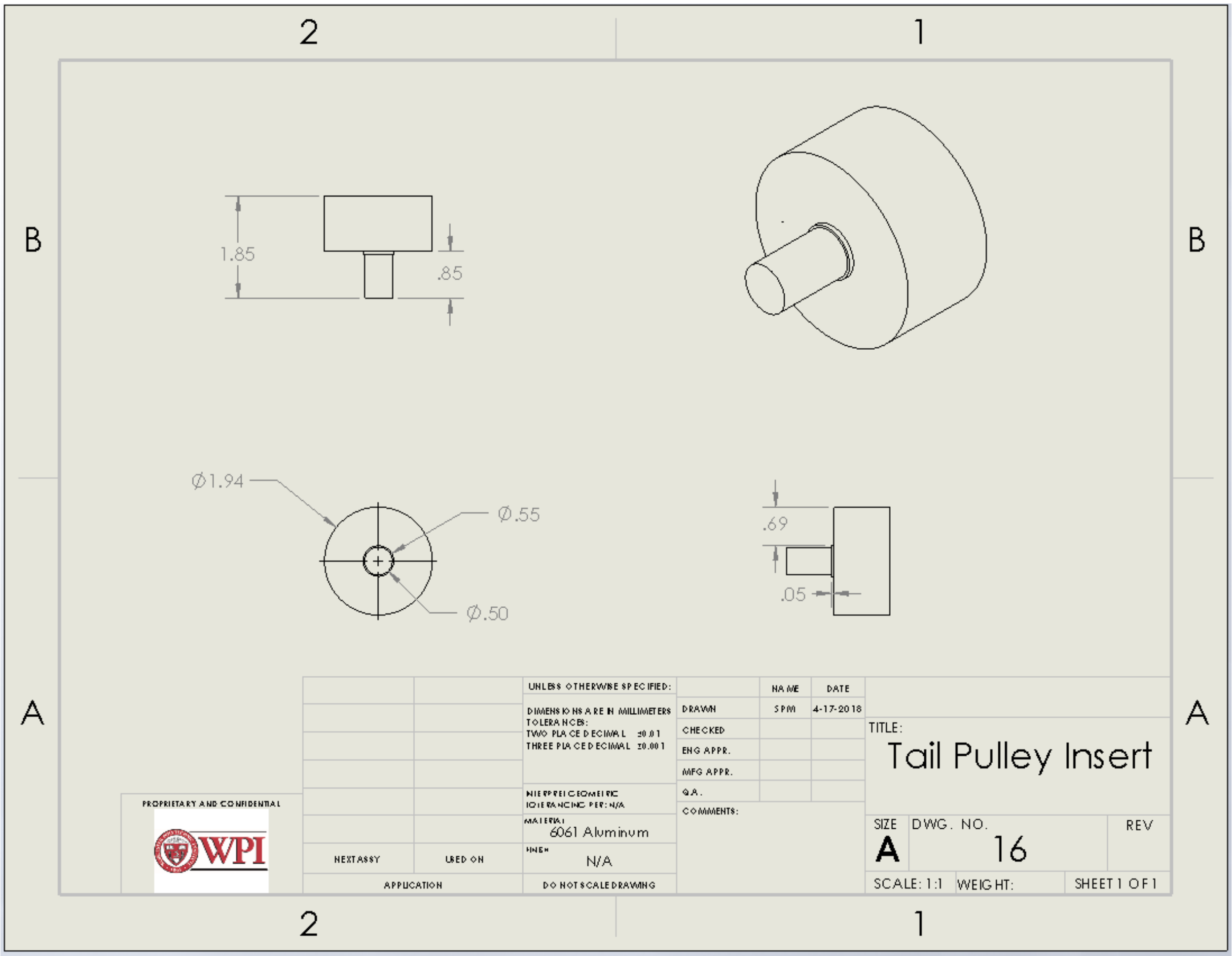


Figure 112: Tail Pulley Insert.

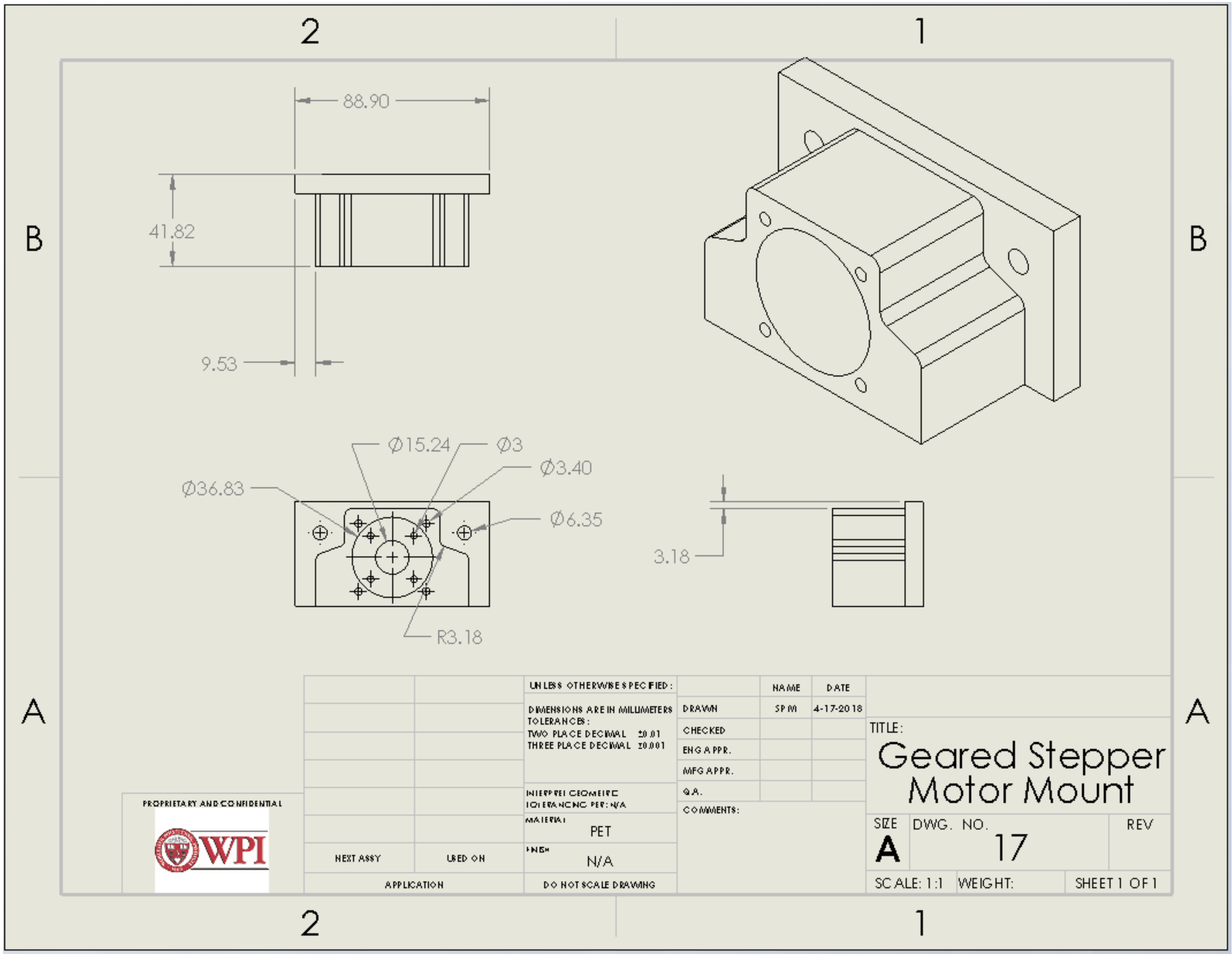


Figure 113: Geared Stepper Motor Mount.

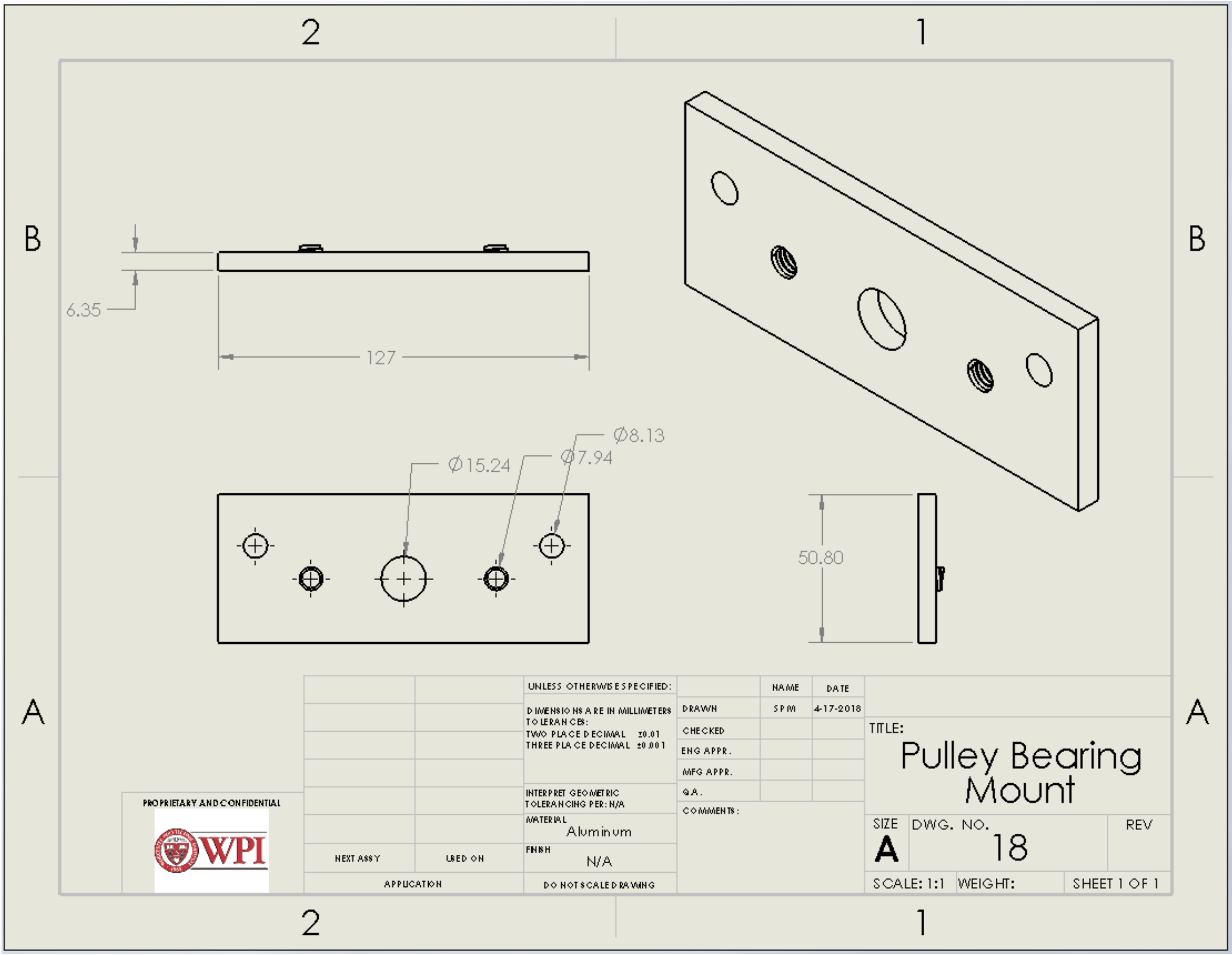


Figure 114: Pulley Bearing Mount.

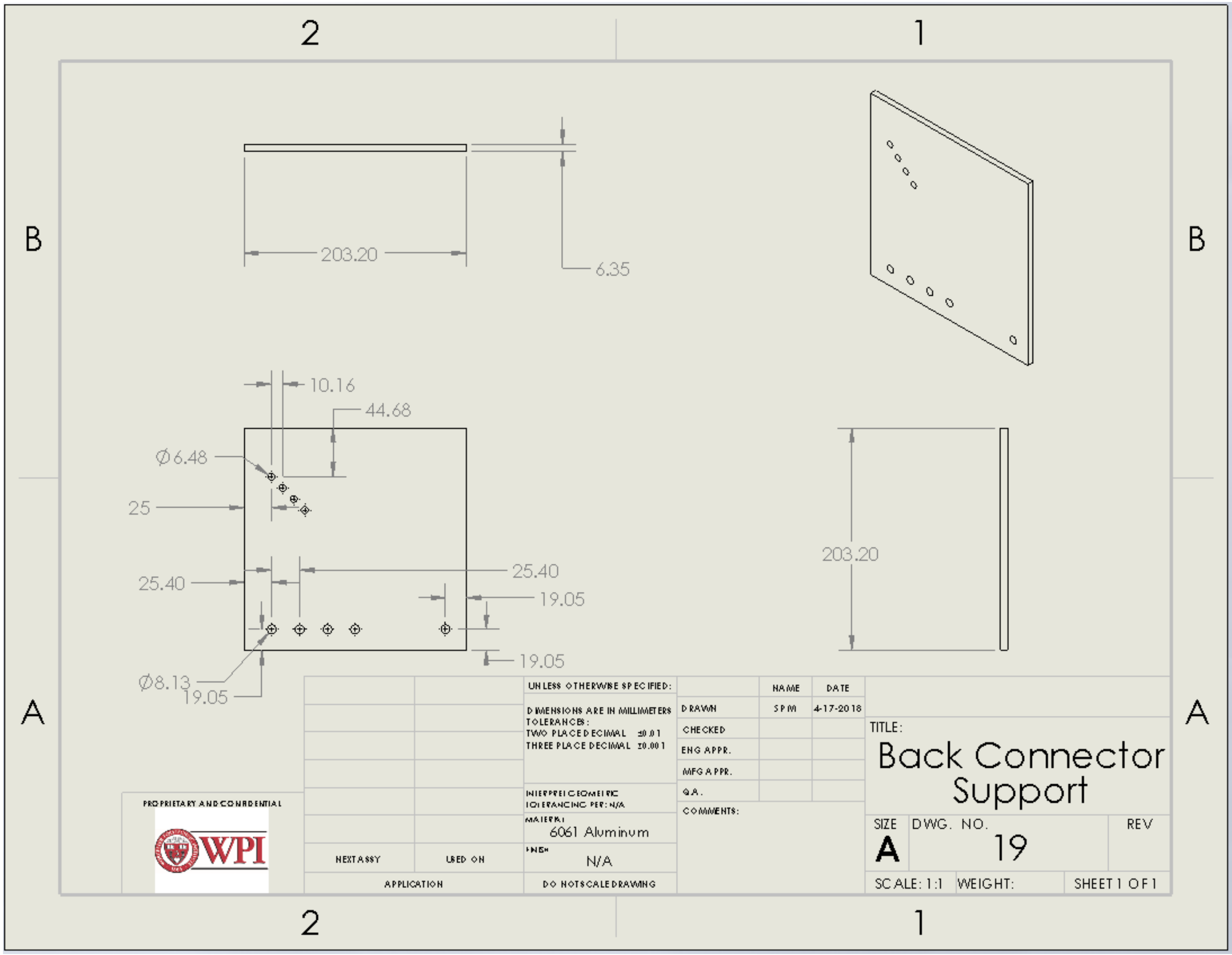


Figure 115: Back Connector Support.

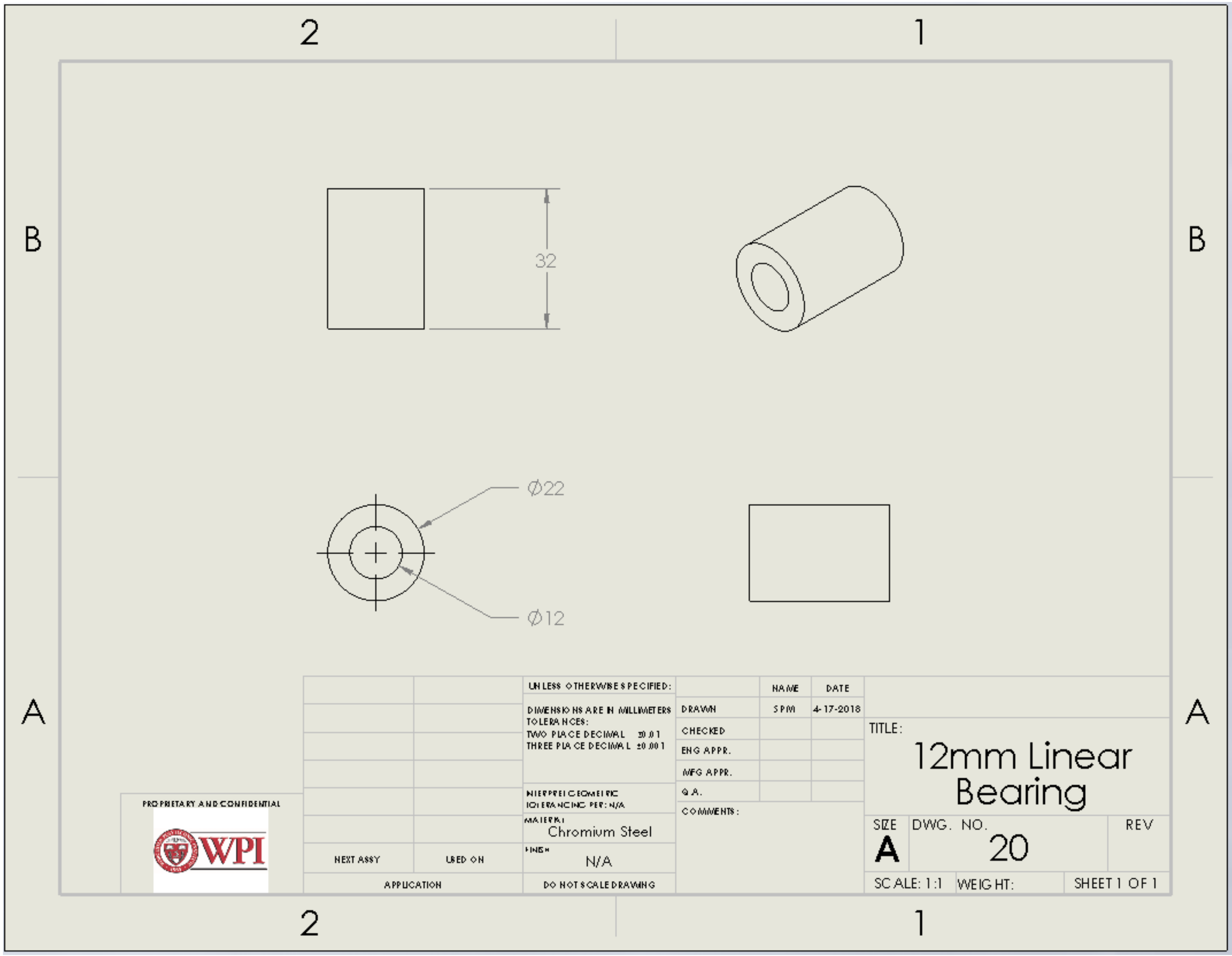


Figure 116: 12mm Linear Bearing.

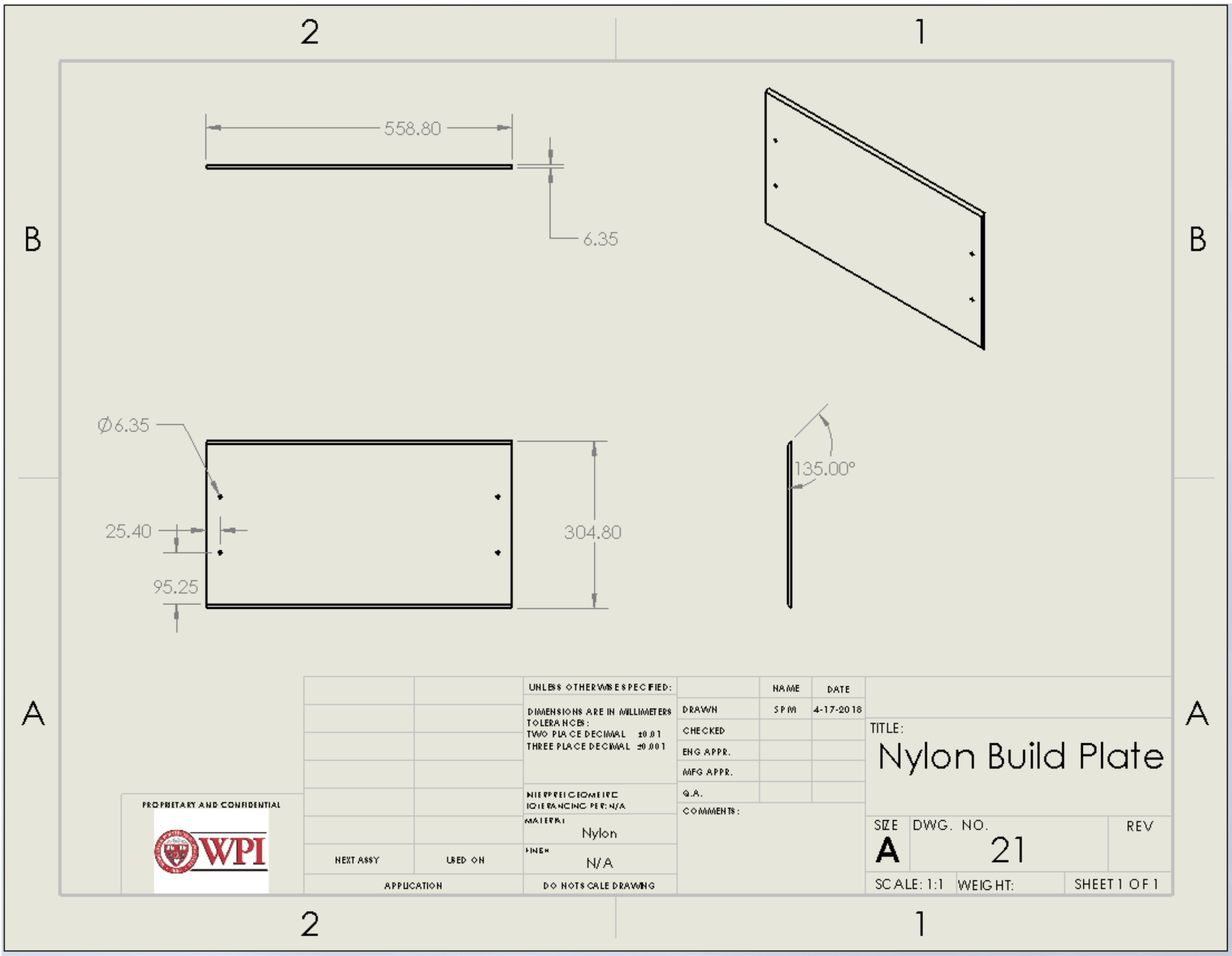


Figure 117: Nylon Build Plate.

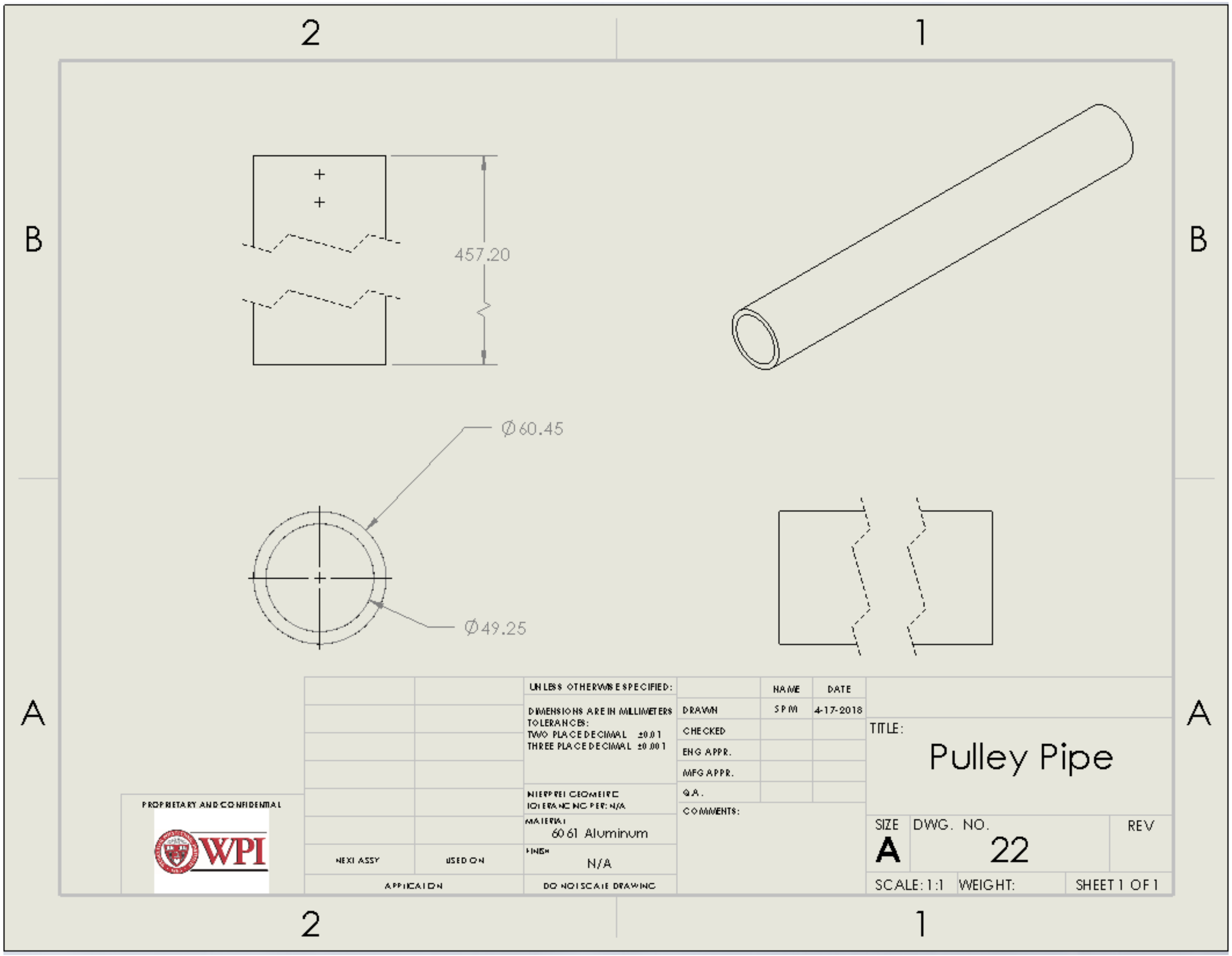


Figure 118: Pulley Pipe.

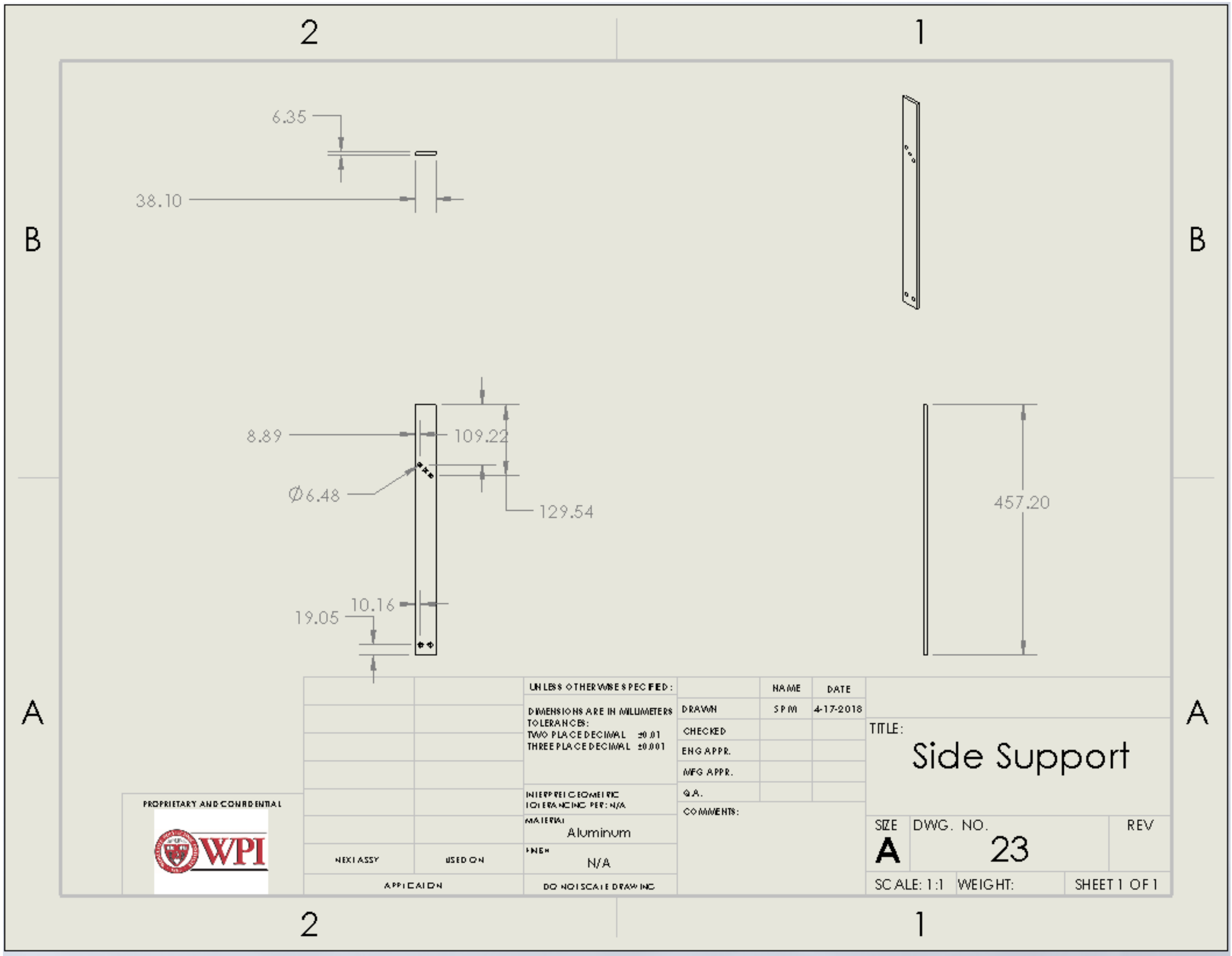


Figure 119: Side Support.

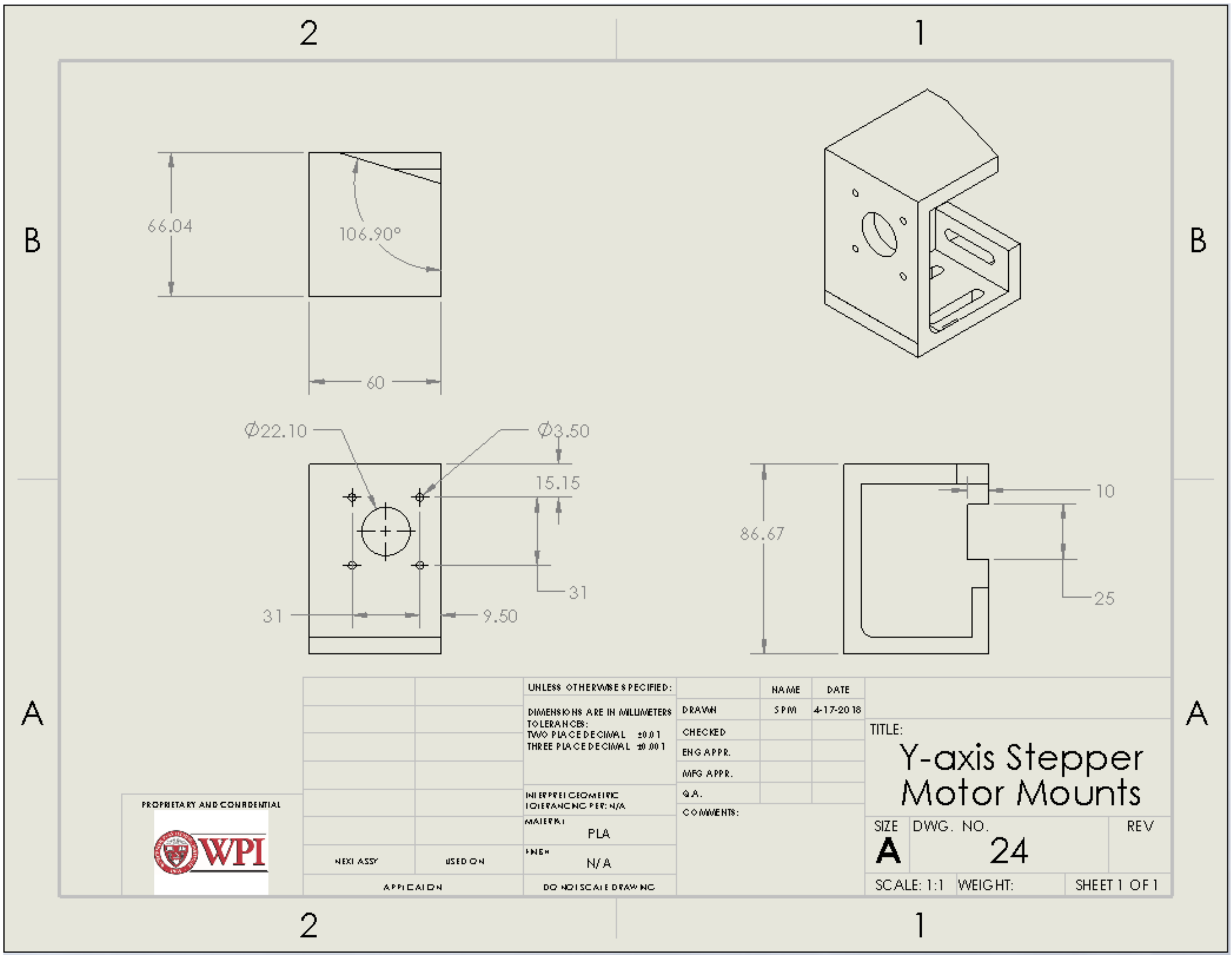


Figure 120: Y-axis Stepper Motor Mounts.

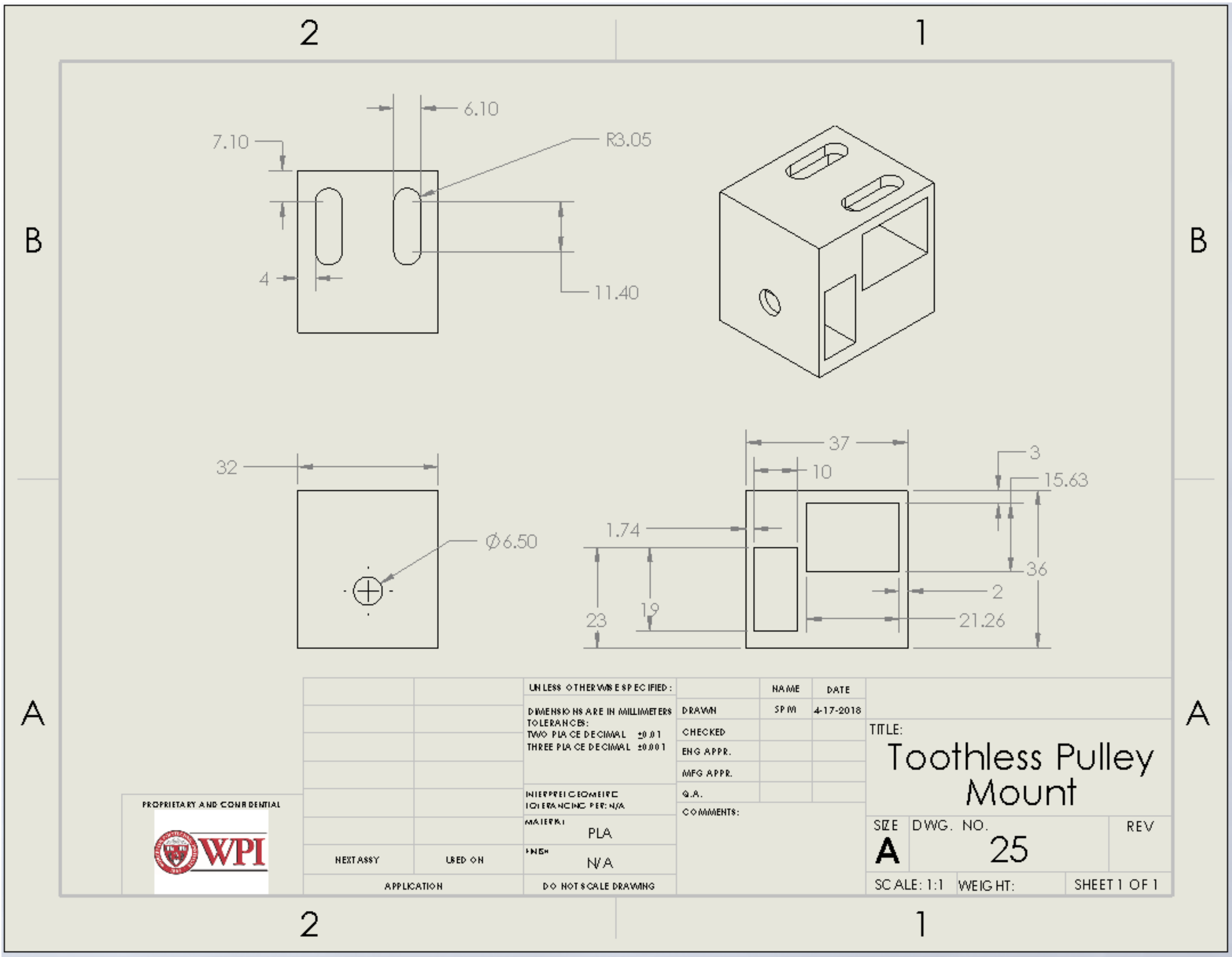


Figure 121: Toothless Pulley Mount.

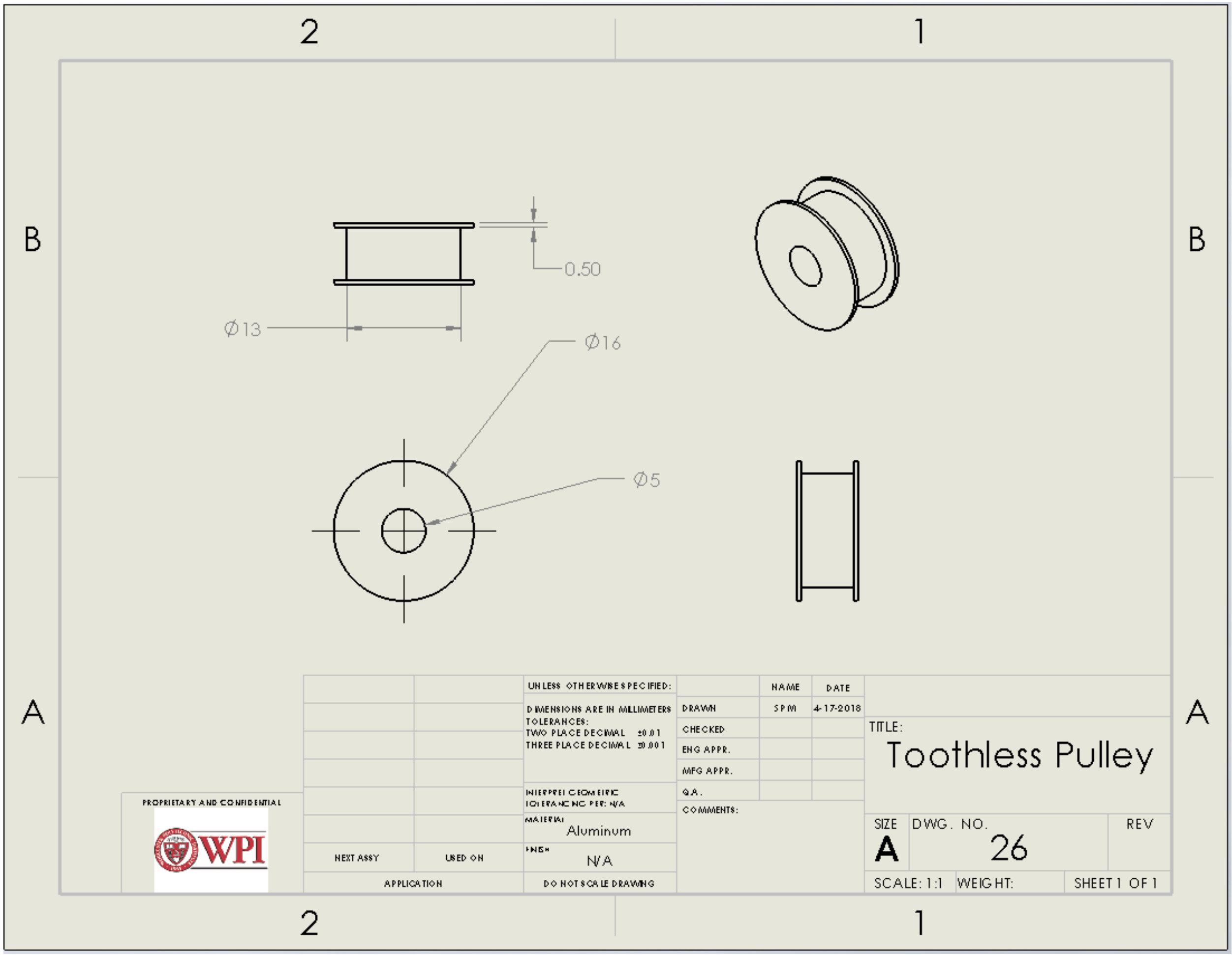


Figure 122: Toothless Pulley.

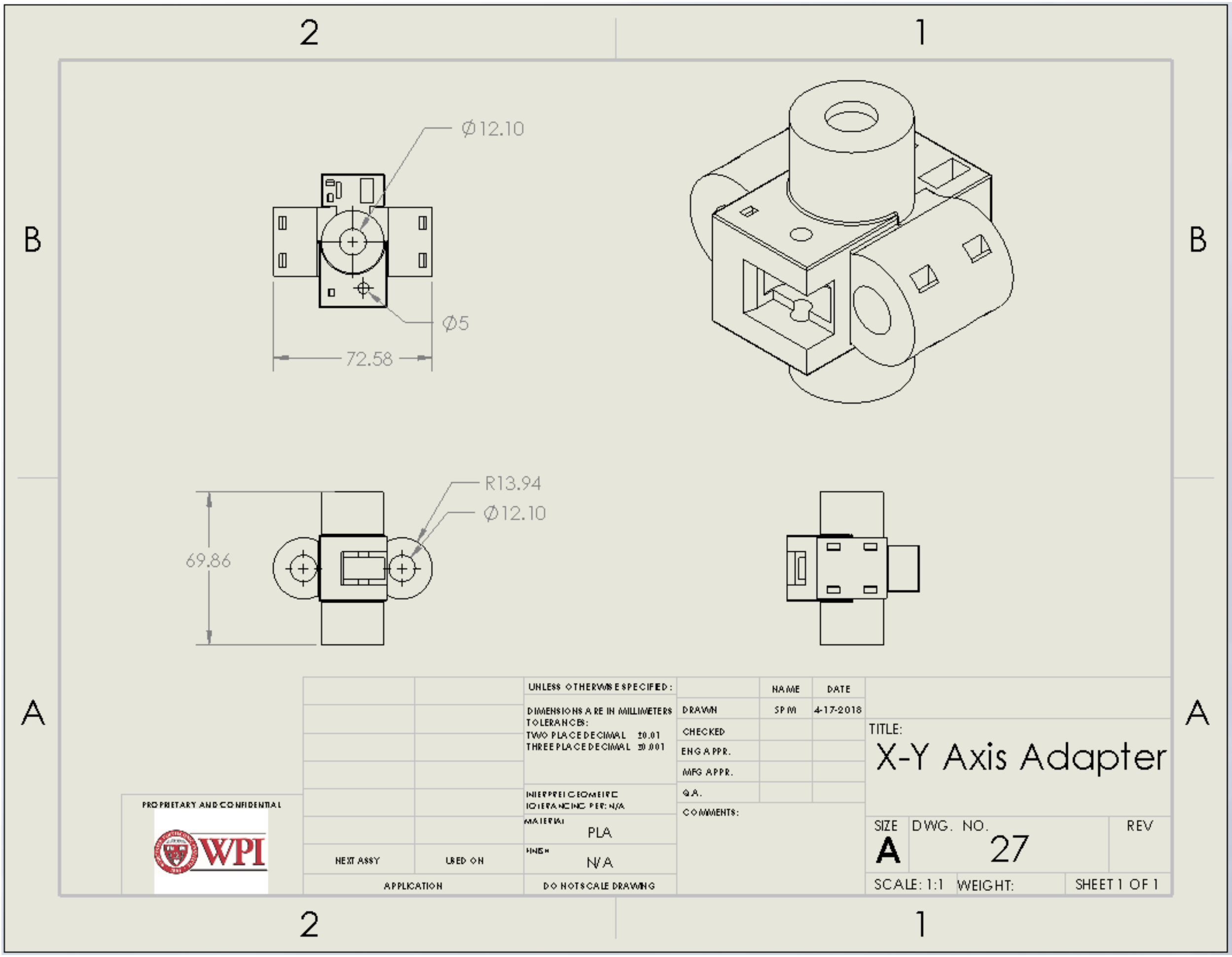


Figure 123: X-Y Axis Adapter.

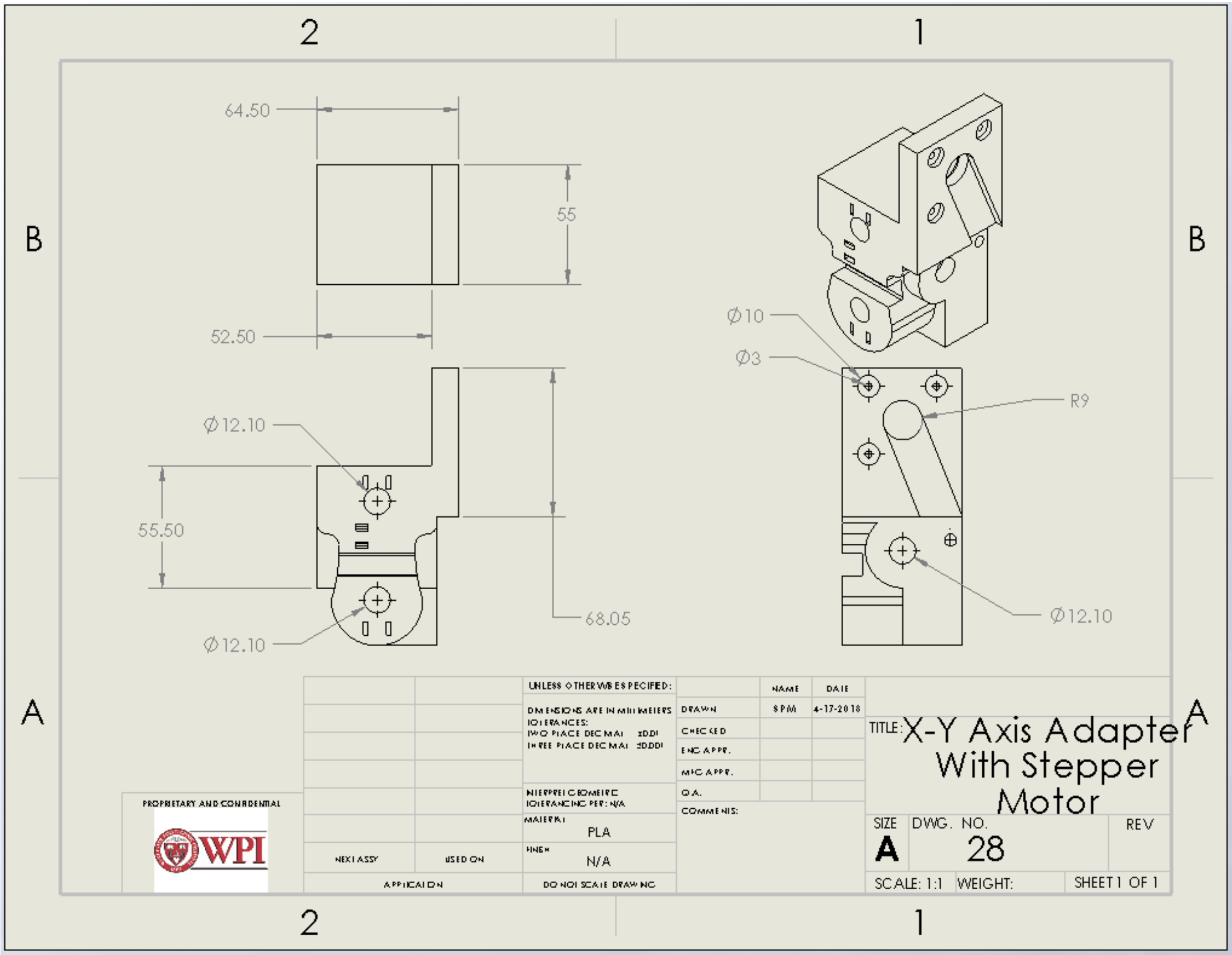


Figure 124: X-Y Axis Adapter with Stepper Motor.

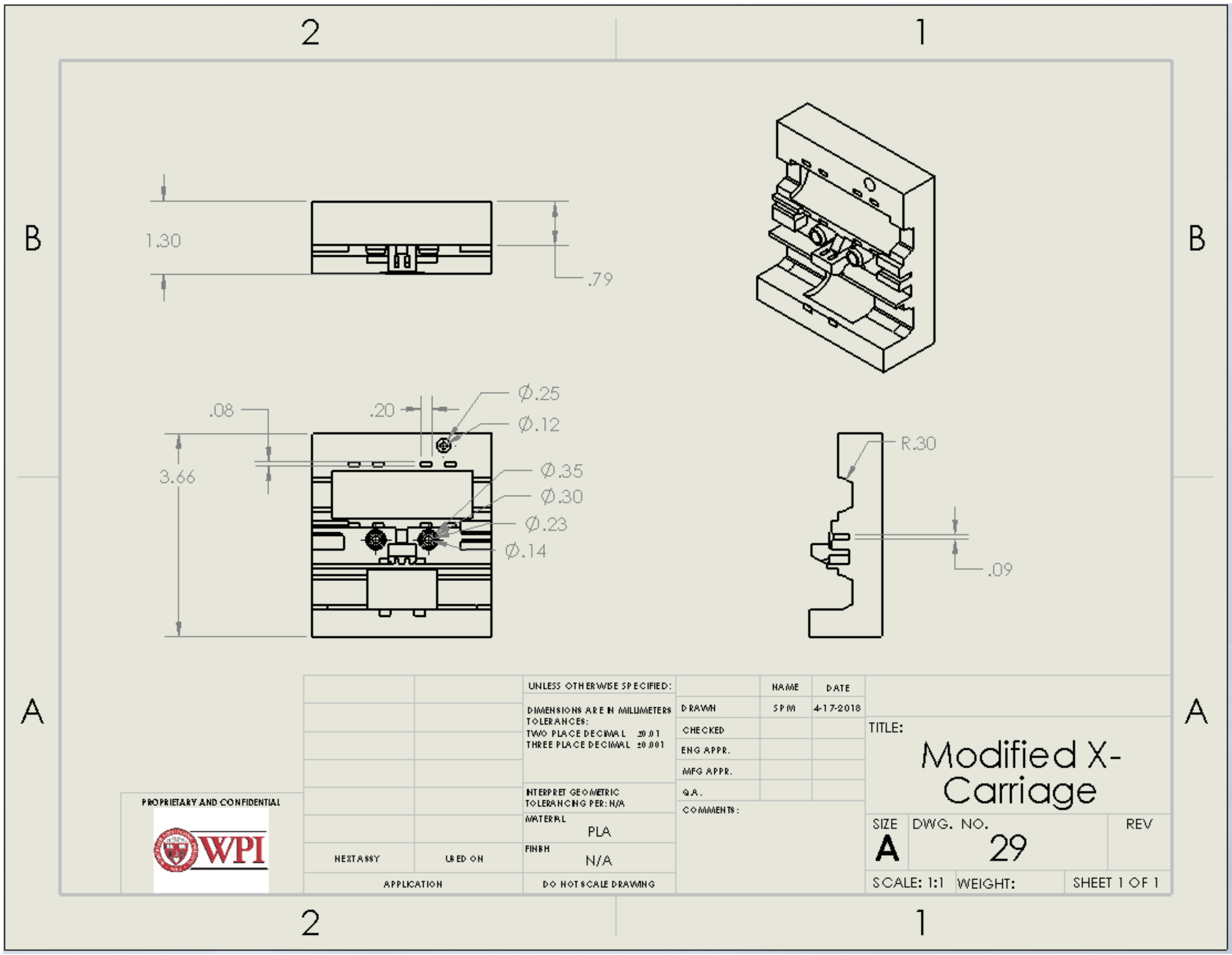


Figure 125: Modified X-Carriage.

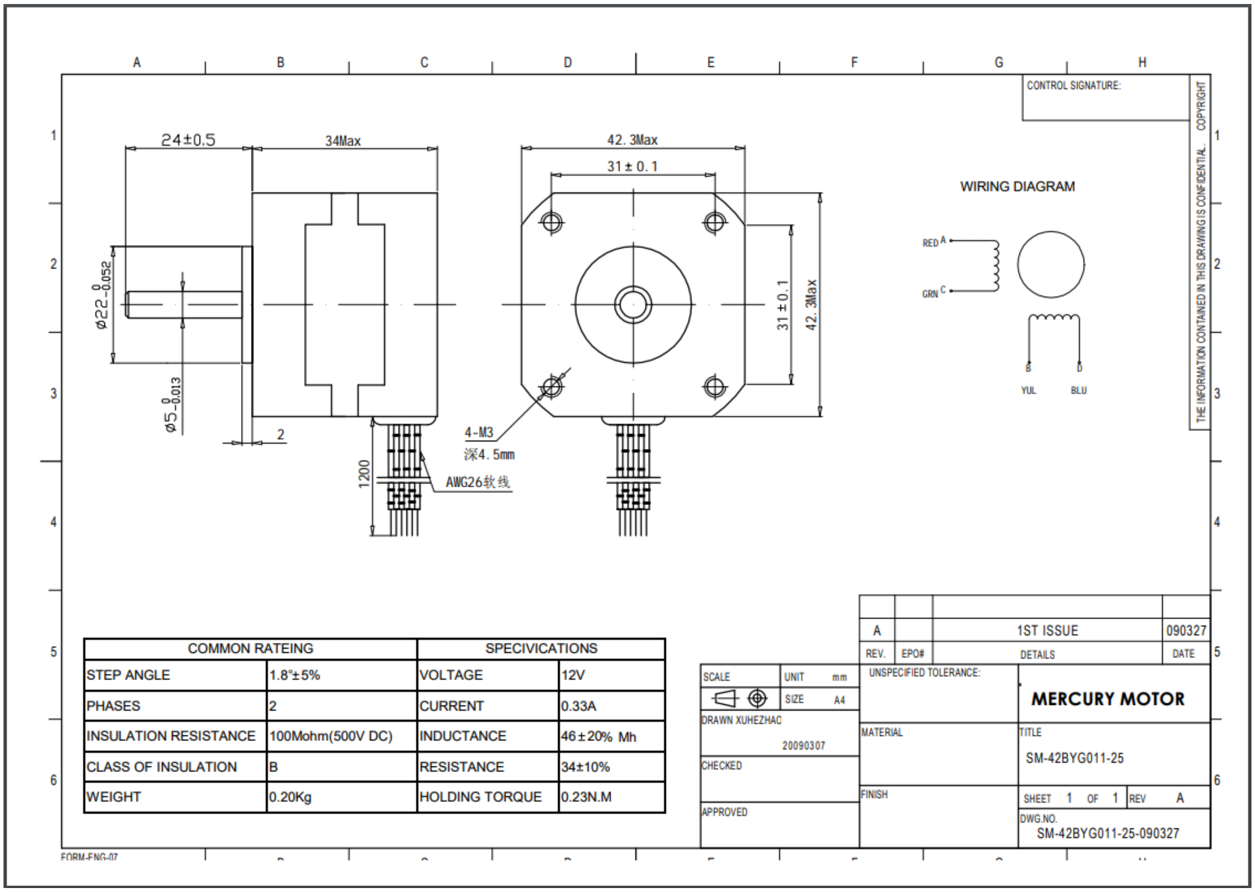


Figure 126: Nema 17 Motor *[56]*.

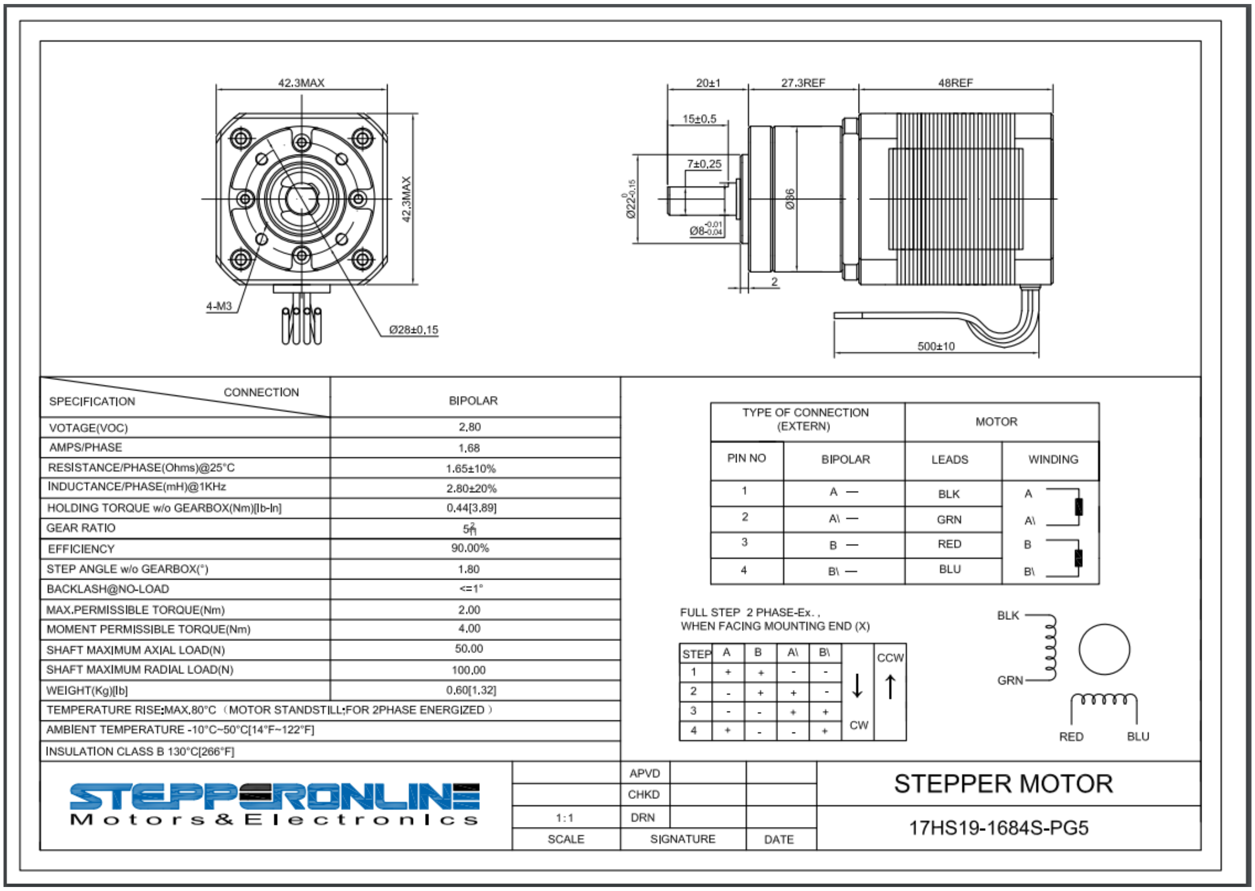


Figure 127: Geared Stepper Motor *[57]*.