
Design and Prototype of a 3D Printer

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Abstract

The following report outlines the detailed design process followed by the construction of a 3D printer prototype was conducted throughout this project. The purpose of the project was to create a 3D printer with tool changing capabilities, a high degree of resolution, and a print volume of 300x300x300mm. The final product was handed over to Stephen McMillan, at which point it was added to BCIT's fleet of rapid prototyping technologies.

The design process followed that of typical iterative engineering design methodology. Initially, the process began with rough hand sketches and conceptual design reviews, followed by solid modelling in SolidWorks, and finally the construction of a physical prototype.

Initial difficulties included finding the optimal placement of the critical components throughout the frame such as the electronics and the X, Y, and Z motion control systems. Deciding on the placement and orientation of each of the major components required the use of much foresight into the latter stages of project progression. Throughout the manufacturing process, it was found that many of the design choices required an immense amount of time in the shop due to lack of experience and high tolerances – this further extended the project length due to the vast number of custom parts created. Testing and calibration procedures had to be performed in a systematic manner due to the inherent dependency of systems between one another, requiring an extensive trial and error process to achieve the desired results. A project scope change was required to be made after the final design was agreed upon due to the tool changing components not being made commercially available, and were instead stuck in beta testing phases. The shift from this major scope change required a high degree of adaptability in order to work around the road block while still providing the proof of concept and infrastructure required to meet the initial goal.

Throughout the manufacturing process, the design of the model also changed, allowing for a significant decrease in the total time required for construction, making predominantly minor adjustments where needed. Once the manufacturing was complete, tolerance stack-up was considered and remedied through the extensive foresight of adjustable mounting options. The resulting motion control systems were executed as originally planned, with a rising and lowering Z-axis and a planar CoreXY motion system positioned at the top of the printer. Further results included the successful integration of the electronics with the aforementioned motion systems – providing the adequate power, safety, and maintenance requirements.

Through the employment of an extensive design process backed up by key resources and expertise, the revised project goals set forth during the project were successfully completed. The total cost of the project was just over \$2,300 CAD, a fraction of comparable products available on the market.

Acknowledgements

The team would like to extend their gratitude to the project sponsor, **Stephen McMillan**, who was instrumental in the completion of this project. His knowledge, expertise, and enthusiasm continually drove design iterations in new and exciting directions. Without his vast wealth of knowledge, this project would have come out in a very different form.

Another thank you must be made to **Chris Townsend**, who spent countless hours in the shop assisting the team from simple questions to hands on creation of parts. His patience and shop knowledge helped overcome many manufacturing speed bumps.

Finally, without consultation from BCIT's **Jason Brett**, the electrical system could not have been designed to the quality it is. His knowledge, resourcefulness, and patience handling many questions related to the design, assembly, testing, and troubleshooting of the system have helped expand the designer's knowledge and together develop a very professional final design. Jason's supply of everything from small fasteners, electrical components, and cables were a huge help towards completing the 3D printer on-time and to budget.

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Chapter 1: Introduction

1.1 – Problem Statement

Currently, the majority of the 3D printers available on the market are limited to a fairly low resolution, the printing of a single material, and boast an excessive cost when precision components are utilized.

This project aims to address the aforementioned problems and deliver a product that is unlike anything else currently available on the commercial market. Achieving a high print resolution requires the use of high-quality components requiring the use of precision manufacturing techniques. Furthermore, extensive calibration procedures both mechanically and electrically need to be addressed to mitigate any resolution related artifacts.

Since only being able to print using a single material greatly restricts the possibilities in an engineering design, the project must address this by providing the infrastructure for the use of multiple print heads able to print multi-material parts.

On top of having to achieve a high resolution and multi-material prints, the 3D printer produced from this project must provide a print volume that reaches or exceeds 300x300x300mm. Lastly, since the markup cost on 3D printers with these attributes is very high, the final project must be limited to a budget of ~\$2300 CAD – approximately two to four times less expensive than other commercially available products.

1.2 – Project Objectives

The deliverable of the project will be a fully functional 3D printer which is capable of hosting a tool changing system. The printer will transition into the hands of the British Columbia Institute of Technology, where it will join as a member of BCIT's rapid prototyping fleet, or continue on as a legacy project for other capstone groups to modify and improve. The key design goals are:

1. **300x300x300mm print volume**

The large print volume will allow this custom 3D printer to create objects which BCIT was previously not able to create. At the time of this project, the maximum 3D print volume BCIT's printers can fabricate is a 250x250x250mm print.

2. **Construction using high quality materials and methods**

Quality is the utmost concern when considering the design and manufacturing of this 3D printer. Due to this, the printer will be created with all components save for non-load bearing electrical guidance components created with metal materials.

3. **Capable of hosting a tool changing system**

The original goal for the project was the creation of a printer with tool changing technology using a proprietary component from E3D [1]. Unfortunately, the device was not made available as of the midway point of the project, and the scope was altered to creating a printer which could host a tool changing system, without actually being capable of changing tools itself.

4. **Delivery of a complete, functioning printer**

For the project to be considered a success, a fully functioning printer with the aforementioned requirements must be delivered to BCIT.

The printer may change form once it is handed off to BCIT; however, with the due diligence and care the project is being designed and manufactured with, it is expected to stay as a relevant product for use and learning for several years after the completion of the product.

1.3 – Scope and Boundaries

The scope of this project is the design and manufacturing of a 3D printer. As a 3D printer is a fully complete system by itself, any and all components which are necessary for the completion of the printer are to be included in the scope of the project. With that in mind, the following are some notable exclusions to the project scope:

1. **Electrical components**

Electrical components do not need to be designed by the team, and may instead be purchased from suppliers. These items include, but are not limited to, the power supply, bed heater, motors, etc.

2. **Hot end and extruder**

As with the electrical components, the hot end and extruder are not to be designed by the team. Instead, a Titan Aero extruder will be used to satisfy both these needs.

3. **Tool changing mechanism**

The initial goals for this project were to create a 3D printer with tool changing capabilities. The design and prototype of the actual tool changing system were not included in the scope of the project, and the system was instead to be purchased from a supplier. As the product never became available, this was left out from the scope.

4. **Slicing software**

The creation of the slicing software will not need to be done by the team. Instead, open source software such as Cura or Slic3r may be used.

1.4 – Project Background

BCIT currently owns several 3D printers, however this project represents an exciting new device to be used as a manufacturing tool by BCIT for capstone projects, hobbies, and more by both faculty and students. This new printer will add to the school's capabilities by being, at the time of completion, the largest printer which exists on campus. Further, the quality of the printer will be held to a very high standard, making it one which is capable of printing at an incredibly high resolution with minimal print artifacts.

Going further as a project, if/when a tool changing device is released commercially, a capstone project can be the modification of the 3D printer provided from this project to include the device – as well as the other future work related items discussed later in section 6.3 – Future Work. Upon the addition of the tool changing device to this 3D printer, it will be the only printer capable of changing tools on the BCIT campus, enabling production of intricate parts with several different materials in a single print. This opportunity is especially exciting, as it enables the production methods capable of delivering customizable materials as needed, i.e. printing with carbon reinforced material, dissolvable support material, and PLA in a single print. This will open a countless number of doors in the likes of part creation, innovative design, and other design and engineering related projects across the various programs at BCIT.

1.4.1 – Important Terminology

Some key terms which may not be common knowledge will be used many times through the following document. This section will detail the majority of these terms.

Hot End – The hot end of a 3D printer includes the heating block and 3D printer nozzle. Seen in the red circle of Figure 1 below, the hot end is where the filament melts, and is then later extruded from the nozzle of the printer. It ends at the finned section (the thermal break) where the filament is meant to be solid, allowing it to be pushed into the hot end by material further down the line.

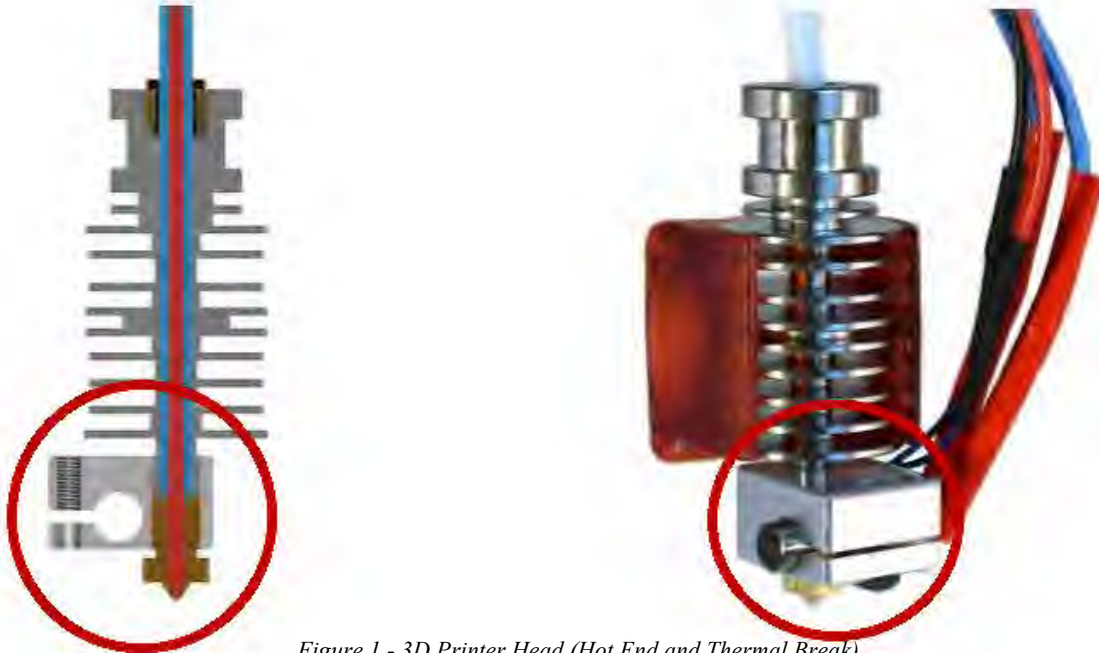


Figure 1 - 3D Printer Head (Hot End and Thermal Break)

Printer Head – The printer head is a generalized term to describe the entire setup of thermal break and hot end, as seen in Figure 1 above.

Printer Bed (AKA Build Plate) – Printer beds are the physical surface upon which a 3D printer extrudes filament upon. Several types of printer beds can be found, though they are commonly either glass or a plastic material. Other variations include flexible plates, tape covered plates, Garolite, silicon wafers.

1.4.2 – Key Project Considerations

There are numerous components which are critical to the characteristics of a 3D printer. These include, but are not limited to, the filament diameter, the motion system, the power transmission system, the frame construction, and number of extruders.

1.4.2.1 – Filament Diameter

3D printer filament is standardized to 1.75mm or 3mm diameter, with few notable exceptions (for example, the Ultimaker series using 2.85mm). There is much debate about which filament size is better or worse for different properties. A smaller filament has advantages of melting faster than a larger one; however, a larger filament may be capable of faster print speeds due to a greater heated area. While small filaments work well with smaller printer nozzles, leading to more precise prints, larger filaments work better with the extrusion of flexible filaments, as they compress less, creating less pressurization of the print nozzle and more precise filament throughput from the nozzle.

The debates over 1.75mm against 3mm filament can be found on endless forums, each having its own strengths and weaknesses. As the printer for this project is one which is not being used for one specific, specialized purpose, there is no factor which drives the requirements more towards 1.75mm or 3mm. Due to this, the printer will be designed and delivered using a 1.75mm filament, though could easily be changed over to a 3mm filament at any point after the completion of the project.

1.4.2.2 – Motion System

The motion system is used to describe how the 3D printer head and bed move in relation to each other, and to the frame. It is the most defining characteristic of a 3D printer. Several different motion systems exist, offering different strengths and weaknesses.

Polar & Scara Printers – Polar and scara printers are both very experimental and niche in nature. A polar printer has a print bed which rotates similar to a record turntable while the print head moves radially. Scara printers are characterized with a robotic arm that rotates at multiple joints, the print head being attached to the end of the arm. Both styles are not popular on the market due to high complexity. The two types of printers are shown in Figure 2 below, with the polar style being shown on the left and the scara printer being shown on the right.



Figure 2 - Polar 3D Printer (Left) and Scara 3D Printer (Right)

Delta Printers – The delta motion system (seen on the right in Figure 3 below) is one characterized by printers with three large vertical members, and a printer head suspended off of them. Translation of the printer head is accomplished by moving the support arms connecting to the printer head to the frame up or down along the vertical support members. As each of these connections move relative to one another, the printer head can translate up, down, or around the printer bed. This style of printer makes up a small portion of the market, and are more niche printers; however, they do excel at circular prints (i.e. cylindrical shapes)

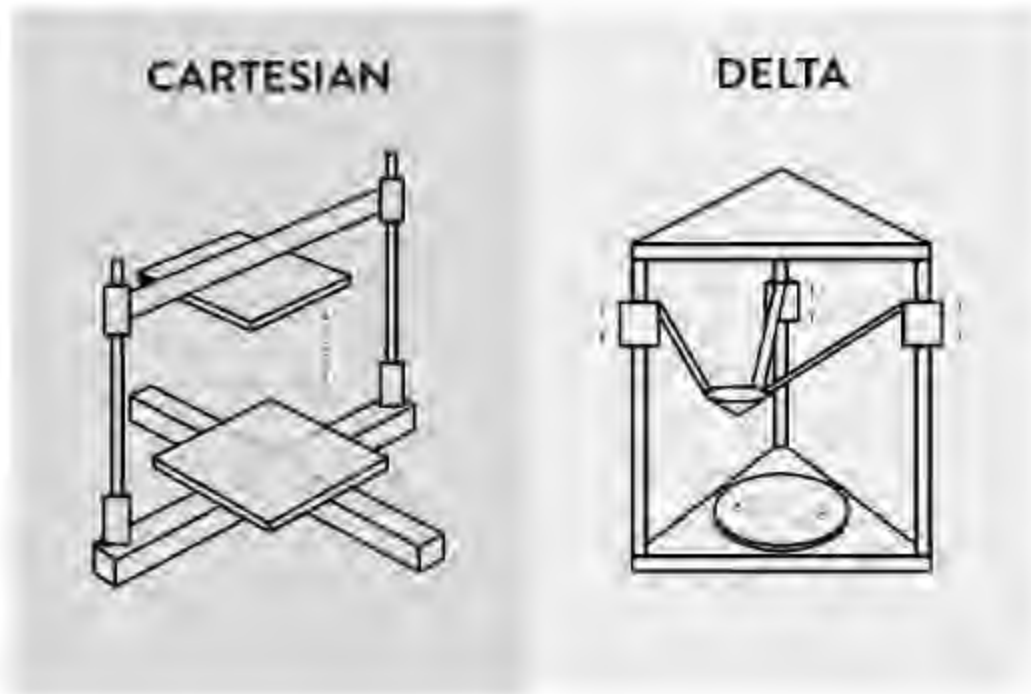


Figure 3 - Cartesian Motion vs. Delta Motion Profiles

Cartesian Printers – Cartesian printers (seen on the left in Figure 3 above) are the most common printers on the market right now, which in large part is due to their simplicity. A Cartesian printer is a generalized term used to describe a printer which is characterized by the combination of linear motions in the X, Y, and Z axes to create a final print. They host a rectangular print base, and are generally quite accurate. Numerous subsets of the Cartesian motion system exist, all of which have the printer head and bed moving in different ways relative to one another.

1.4.2.3 – Power Transmission Systems

The main power transmission types for 3D printers are threaded rods, lead screws, ball screws, and belt driven systems. It is common for designs to incorporate multiple different styles, i.e. using a belt for the horizontal plane motions, and a lead screw for the vertical axis of motion.

Threaded Rods & Lead Screws

Threaded rods are the cheapest option, and as such are also the least consistent. They have large amounts of backlash, and wobble from the rods not being manufactured to high standards. Lead screws are a step up from threaded rods, and a comparison of the two can be in Figure 4 below. Many commercially available printers use lead screws as they are more rigid than threaded rods, and are designed to be moving through a nut rather than for being fastened once like a threaded rod. The threads are much more robust on a lead screw than on a threaded rod as well.



Figure 4 - Lead Screw (Top) and Threaded Rod (Bottom)

Ball Screws

A ball screw, pictured in Figure 5, is a very precise version of the lead screw, with recirculating ball bearings flowing to minimize friction and maximize efficiency. Ball screws are more predictable, rigid, and have higher load capacities; however, they are also much more expensive than a lead screw.



Figure 5 - Ball Screw Cut-Away View

Belts

GT2 belts are a standardized timing belt style with a 2mm tooth pitch and 6mm width. Due to their standardization, many different components (i.e. tensioning clips and pulleys with various bores and teeth number) are available through many suppliers. The GT2 belts are an excellent method to transfer rotational motion from their motors into linear motion of either print heads or print beds. Belts offer smooth motion, and can be customized to fit whatever size is required; however, they do have weaknesses including belt stretching, proper tensioning, and end fixturing.

1.4.2.4 – Number of Extruders

Printers are often created with one or two extruders. A printer with only one extruder will be able to create basic prints from a single material, while one with dual extruders will be able to make more complex parts, using different materials where they are required. A dual extruder printer often uses a dissolvable support material in concert with PLA or ABS. This allows prints with large overhangs (unsupported sections) to be created with ease. The dissolvable support material is printed to build up to the overhang, which is printed with the main material (PLA or ABS). Afterwards, the completed print can be placed in water to dissolve the support.

As the number of extruders on a printer increases, the amount of complexity, functionality, and potential problems also increases. As multiple extruders are mounted to the same gantry which carries the print head, there is more mass moving while the print head traverses, meaning small features with quick direction changes will be more difficult to create.

Creating a printer which changes tools, where only a single print head is mounted on the printer head gantry at a time would allow for the quick direction changes of a single extruder, with the capabilities of a multi-extruder printer combined into one.

1.4.3 – Current Market Options

The consumer market right now does not have any commercially available printers which host a tool changing system. There is only a single supplier who is openly developing a tool changing device (not including any software or hardware, only the device itself), which is the E3D tool changer. Unfortunately, this device has yet to be made available to the public, and has instead been in a beta testing phase for over a year, only being made available to certain early adopters who are testing the device.

Several different styles and sizes of printers are commercially available with dual extruders. A dual extruder system is the closest alternative to a tool changing system, as the systems allow for two materials to be used in a single printing operation where required. A brief discussion of dual extruder systems can be found in the preceding section (1.4.2.4 – Number of Extruders).

As the 3D printer market is constantly evolving and heavily saturated with printers, many are available which boast a similar print volume (300x300x300mm) across several different price points; however, to obtain the quality of production offered by the printer created through this project (both through the unique and superior CoreXY motion system, and the linear rail guidance), no commercially available printers are available.

1.5 – Project Planning

The following sections will cover the project planning activities performed by the design team prior to the project proposal and maintained throughout the term of the project. These activities included work breakdown, project roles and responsibilities, project schedule, project budget, and an overview of the required resources to complete the project. The documents associated with these tasks can be found in Appendix B, and with them, the team was able to develop project management tools that enabled efficient management of time, budget, and resource allocation throughout this project.

1.5.1 – Project Work Breakdown

To fully understand the scope of work to be done for developing a 3D printer prototype, the project team broke down the work to be done for each phase of the project. As seen in Appendix B, a project work breakdown structure was used to visually layout the various components of each project phase. With this, more complex project phases could be broken down into a series of lower level tasks that can be easily tracked through to completion. This work breakdown identified the following five project phases:

- Concept Generation
- Mechanical/System Design
- Manufacturing and Assembly
- Calibration and Testing
- Documentation and Calibration

These phases each had individual components that sequentially led to the completion of each phase. With this, each team member could be assigned roles and responsibilities to complete these lower level tasks, as well as develop a preliminary project schedule, as shown in the following sections.

1.5.2 – Roles and Responsibilities

The roles and responsibilities of each team member were broken down as follows to allow the team members to focus on certain aspects of the project in a directed manner:

Frame & Electrical – Liam Smyth

CoreXY Motion – David-Alexander Dabic

Z-Axis Motion & Print Bed – Devon Whitter

These roles were selected based on the interests and strengths of the group members. While the project was divided up into multiple sections (listed above), the team still worked together to design, manufacture, and assemble all of these various printer systems. A more detailed breakdown of these project roles and responsibilities can be found in the RACI chart illustrated in Appendix B. This document allowed each team member to focus on design of specific system elements and specifically provided members with authority over final decisions in each of these roles.

1.5.3 – Project Schedule

The most important document used to track the team's progress over the course of this project was the Gantt chart, as found in Appendix B. This document was regularly reviewed and updated as the project advanced to ensure sufficient time was allocated for current and future activities. It also became incredibly useful for determining the priority of various concurrent tasks as the project entered its final two phases to guarantee completion by the MECH Expo.

With the Gantt chart, important project milestone dates were established to ensure short term project goals were known by all team members. These dates somewhat varied over the course of the project due to previously unknown delays, specifically in the design and manufacturing phases; however, each milestone was met within a reasonable limit and helped ensure the team could complete the many tasks set out from the beginning of the project.

These milestones began by successfully completing the proposal presentation in order to secure the project. Once secured, the following two milestones included concept selection and a design review. These milestones were crucial in optimizing the delivery of the project and making the best design and manufacturing choices possible towards the success of the project. Once the project specifics were concluded, the next milestone involved completing the manufacturing and assembly process. These four milestones culminate with the final milestone being project completion and performance at the 2019 BCIT Mech Expo.

1.5.4 – Project Budget

Initial Budget Estimate: \$2,203.93 CAD

Final Project Cost: \$2,310.27 CAD

The initial prospected budget for this project was roughly \$2,100.00 CAD, and can be found in Appendix B. This included the purchase of the majority of components, though as time went on several items which were not initially considered had been added to the project. These included specialized tools, extra belts and pulleys, and electrical components among others.

The total cost for the project was \$2,310.27 CAD. This was only slightly above the initial estimates due to the inexperience of the group regarding the requirements of a 3D printer project. As the project required an incredible numbers of fasteners, electrical components, and mechanical items, many small items had been missed during initial estimation which resulted in a slowly growing final prototype cost. Furthermore, the team had expected BCIT to have several more components available than were actually stocked.

1.5.5 – Resources Required

Several resources were required for this project, including:

Engineering Advisor

- Stephen McMillan, M.Eng, P.Eng, Manufacturing Program Head, BCIT

Workshop Advisor

- Chris Townsend

Workshop Machinery

- CNC mill
- Manual mill
- Lathe
- 3D printer
- Drill press
- Waterjet
- Laser cutter
- Powder coater
- Band saw

Funding

- Provided through BCIT

Software

- SolidWorks 2016 (3D modelling & part drawings)
- Microsoft Excel & Word
- Google Drive (file management)

BCIT was expected to provide all of these requirements, save for Google Drive for file management. The workshop on campus in the SW9 building houses all the required machining equipment. Instructors provided the expert advice required by the team, and funding was provided through BCIT for the project.

1.6 – Project Reviews

The team scheduled weekly meetings in person with sponsor and expert Stephen McMillan. During these meetings, mini-design reviews were the most important item. These periods allowed the members to come up with ideas independently, investigate, and design a system based on the design, then present and evaluate the designs with the group. The mini reviews were invaluable times for the team, as almost every system designed by the team was augmented and optimized in one way or another during these times.

A formal critical design review was hosted on February 20th, 2019. This period allowed the team to present their current design to other engineering students and BCIT faculty, and receive feedback. The process proved successful in garnering important feedback regarding the design of the printer. The results of the formal design review did not bring any outstanding issues to light, and it was valuable for confirming the current design of the team.

1.7 – End of Life Plan

Upon completion of this project, the produced 3D printer has been handed over to BCIT instructor and program head Stephen McMillan. From this point in time, the printer may either join BCIT's Mechanical Engineering rapid prototyping machines, or may be further developed through additional capstone projects. Future work which may be done to the printer as either a capstone project, or as hobby/optimization work can be found in Section 6.3 – Future Work.

Chapter 2: Detailed Description of the Current Status

2.1 – Current Status

At the onset of this project, the goal was to create a high-end 3D printer that could rival the quality of other top-of-the-line consumer printers on the market today, such as the Ultimaker 3, the Formlabs Form 2, or the Zortax M300. The design objective for this printer was for it to have a 300x300x300mm print volume and to be capable of tool changing using multiple extruder heads for multiple filaments. The printer was to be created exclusively from high quality materials where structure or motion was concerned (i.e. no 3D printed braces) to ensure the highest quality printer possible. This initial goal for tool-changing was removed due to the tool changing system initially specified for the project not being made commercially available by the supplier (E3D).

A revision of the project was created, which was to create the same 3D printer in terms of size and quality, but instead being capable of hosting a tool changing mechanism rather than actually having one. These goals have been met by the team, who spent the better part of 8 months designing, manufacturing, assembling, and calibrating the 3D printer seen in Figure 6 below.

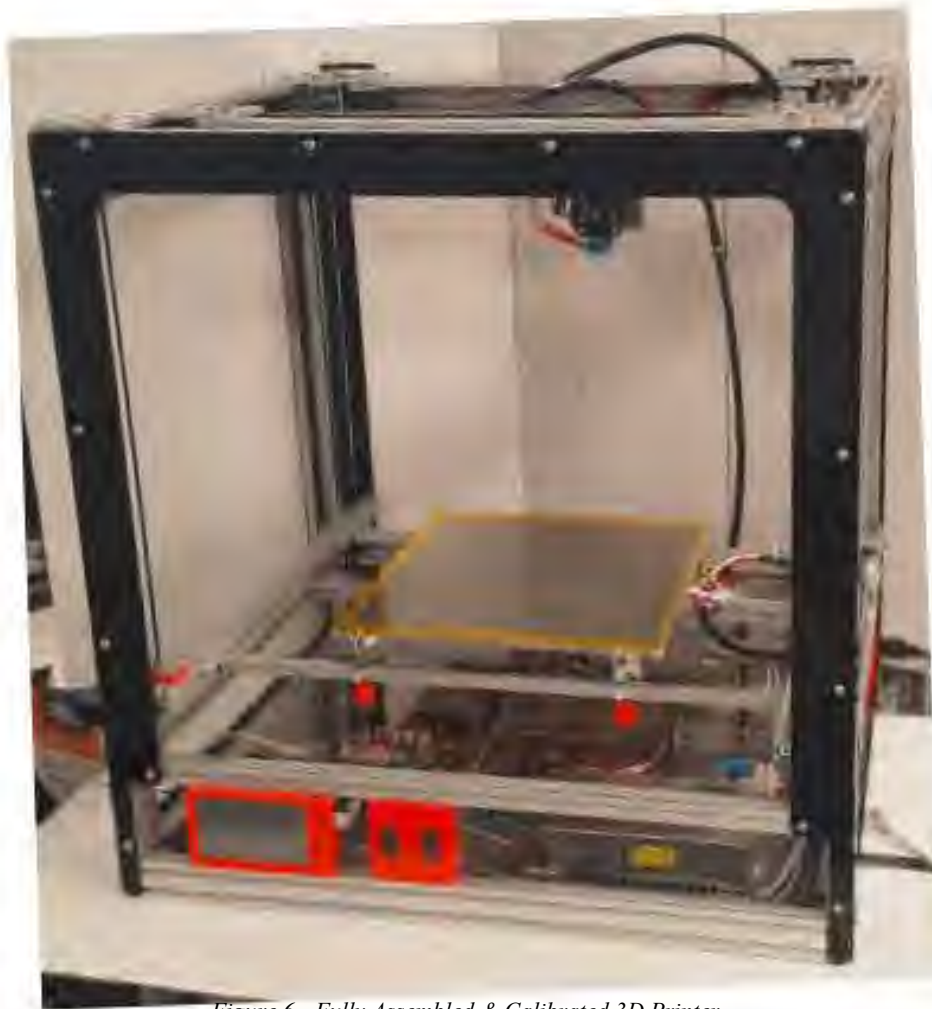


Figure 6 - Fully Assembled & Calibrated 3D Printer

Two months were spent in the research phase of this project, where the team did a detailed investigation into 3D printers, finding out the intimate workings of the devices. From here, the team had several lengthy discussions with the project sponsor, Stephen McMillan, and major decisions were finalized regarding the motion system (CoreXY), the power transmission system (belts), and the printer frame material (aluminum T-slot extrusion).

After completion of the research phase, the team moved into the design phase. The design phase was a constantly evolving and ongoing process, where many concepts were generated and discussed before the selection of final design details. The team met weekly with project sponsor Stephen McMillan, often hosting mini design reviews to discuss the new ideas brought forward for subsystems. A detailed description of the design phase can be found in Section 5.1 – Design Results.

Moving beyond the design phase was the manufacturing phase. Numerous machines including the waterjet, CNC mill, drill press, powder coater, and 3D printers were used to create the over 100 custom components required for this prototype. The manufacturing phase was incredibly time consuming due to the high number of custom components to be made of which several had to be made to quite high tolerances. The subsequent assembly phase went relatively smoothly; however, many small manufacturing issues and oversights were found and had to be corrected quickly. A more detailed account of the manufacturing and assembly can be found in section 5.2 – Prototype Manufacturing Results.

After completion of the manufacturing, assembly, and wiring phases, the team began calibration and testing of the 3D printer. This process involved accurately tensioning down belts, squaring up frame, bed carriage, and printer gantry members, and adjusting limit switches to the appropriate locations for homing the printer head. Testing was centered around ensuring electrical components functioned and could all seamlessly communicate to the controller.

As of the submission report, the **current status** of the 3D Printer is as follows:

- frame members manufactured and assembled;
- motion systems (XY & Z axes) manufactured and assembled ;
- electrical system wired and thoroughly tested;
- printer gantry level and belt tensioning calibration completed;
- initial printer testing underway.

The design goals achieved by this project at this time are as follow:

- a 300x300x300mm print volume;
- high quality materials used for manufacturing motion and structural components;
- speed Demon LM76 Linear rail guidance;
- steel kinematic coupling bed mount;
- CoreXY motion system.

The future work to be completed for this project is detailed in section 6.3 – Future Work.

Chapter 3: Theoretical Background

The theoretical background for this project will be broken into the following main sections:

1. Z-Axis of motion
2. Printer bed
3. XY Axes of motion
4. Frame & structural considerations
5. Electrical system

In these sections, in-depth details will be outlined for the various design decisions which were required to develop each major system on the printer. These sections will investigate possible methods to accomplish the design goal in order to establish a strong theoretical base for the decision at hand. This will be elaborated upon to discuss the reasons behind the final design decision, including implementation onto the final prototype.

3.1 – Z-Axis of Motion

3.1.1 – Power Transmission

The power transmission system selected for the Z-axis of motion was a belt driven system. Strengths inherent to a belt driven system include the elimination of gear lash from a threaded rod, lead screw or ball screw system. Additionally, this system offers smooth power transmission, relatively simple modification of the travel lengths, and cheap, standardized, off-the-shelf components. This method was also selected because the project sponsor had an interest in using a belt driven Z-Axis as a novel solution to a system which is commonly accomplished through a lead screw.

The printer was designed to use GT2 belt components. Mentioned earlier, these pieces are standardized off the shelf components which are widely available from several distributors in various open and closed loop lengths. The properties of the components (i.e. belt tensile strength) are well documented from their common use, and many 3D solid models are available through websites such as Grabcad.com. They offer a 2mm tooth pitch, and are 6mm wide.

The belt routing was an interesting portion of the design as using a single, central drive shaft from the Z-Axis motor means that the two vertical belt spans rotate in opposite directions. This means that one of the belt clamps must attach to the outermost span of the belts, and the opposing side must attach to the innermost span of the belts. To get around this, the vertical belt spans are clamped using different belt clamp designs, where one is made with a slot to allow for a belt run to pass through unimpeded (seen in Figure 7 below).



Figure 7 - Vertical Span Belt Clamps

3.1.2 – Belt Stretching

Belt stretching under tension was an inherent issue with a belt driven system which the team had to consider. This was especially important due to the large print volume capabilities of the printer. Due to the 300x300x300mm print volume, a solid print could potentially weigh just under thirty-four kilograms, plus the weight of the Z-Axis carriage and printer bed itself. Rounded off, the upper weight limit on a print is considered to be forty kilograms.

Based on research into GT2 belts, it was determined that a belt would stretch under one millimeter with a 100 newton force applied to it [2]. Due to the massive size of the printer, four lifting points on the Z-Axis bed carriage were designed, meaning that the upper load limit before significant belt stretching occurs is **800N**.

$$\text{Density of PLA:} \quad 1250 \left(\frac{kg}{m^3} \right)$$

$$\text{Maximum print volume:} \quad .3m * .3m * .3m = .027m^3$$

$$\text{Maximum print weight:} \quad .027m^3 * 1250 \frac{kg}{m^3} = 33.75kg$$

$$\text{Conversion to Newtons:} \quad 40kg * 9.81 = 392.4N$$

**Weight rounded to 40kg with bed and Z-Axis components*

$$\text{Factor of safety:} \quad SF = \frac{800 N}{392.4 N} = 2.04$$

3.1.3 – Belt Tensioning

A major concern when using a belt transmission is tensioning. If the belts are not appropriately tensioned, the system could be off balance, over, or under tensioned. Under tensioning would lead to slipping of the pulleys, and no movement of the printer bed, while over tensioning could place high stresses on the bearing surfaces and impede motion. If the belts are unevenly tensioned, the stresses on the system would not be uniform, which may lead to deflection of critically aligned components from the belt stress.

All of the issues associated with improperly tensioned belts meant that belt tensioning was one of the key concerns with the system. All belts were given ample room to be tensioned by using the slotted design of the aluminum extrude. Through this, belts could be fitted onto pulleys easily, then tensioned into the appropriate position and tightened down snugly.

The engine mounts in particular were a critical area for belt tensioning, as that is where the power for the Z-Axis originates. A problem here would mean no motion whatsoever. To ensure that there was ample amount of travel for belt tensioning, setscrews were placed in the bottom of the motor mounts to allow the belts to be tensioned precisely before being locked in place by two screws to the frame, as seen in Figure 8 below. The slots were made quite large to accommodate the potentially large travel required to properly tension the belts.



Figure 8 - Adjustable Z-axis Motor Position Using Set Screws

3.1.4 – Motion Guidance

A traditional 3D printer setup uses a cylindrical rod for motion guidance. This is due to their compact size, simple design, availability and low cost. The problems found with a cylindrical rod system include:

1. friction from plastic bushings sliding along the rod (as is common in many commercially available printers)
2. unresolved rotational degree of freedom requiring at least two rods to guide motion
3. the complex housing geometries required to constrain a cylindrical bushing

Instead of using a cylindrical rod setup, the team opted for LM76 Speed Demon linear rails, seen in Figure 9 below. These rails were chosen instead of several other similar rails due to their aluminum construction. As noted in the 3.4 – Frame and Structural Considerations section, the frame is constructed exclusively from aluminum T-slot rails. By selecting an aluminum linear rail, the printer's frame and motion guidance components will thermally expand at a uniform rate, leading to more precise prints over a wide range of temperature fluctuations.

Further to the thermal considerations, linear rails boast a much smoother and more controlled motion than cylindrical rods. The carts house three adjustably eccentric bearings (seen on the right half of Figure 9 below) which slide on the rails; adjusting the eccentricity allows users to select how much preload the carts have to motion. Finally, the bearings inherently impart a much more controllable amount of friction on the motion of the printer compared to a plastic bushing.



Figure 9 - LM76 Speed Demon rail & carts. Left shows the cart on a rail. Right shows the underside of a cart.

A total of five spans of linear rails are used in the printer. Two for the Z-axis, as they are only guidance and not load bearing, meaning the bed is not a cantilevered system. Two more mount along the Y-axis to hold the cross member of the X-axis, where the final linear rail is mounted. All appropriate degrees of freedom are removed in this manner. The rails are located inside the envelope of the 3D printer, which led to a slightly larger frame overall, but a much more contained and tidy looking final product with fewer exterior moving parts to be accidentally bumped by users.

3.1.5 – Self Locking of Z-Axis

A traditional leadscrew 3D printer setup is one which the leadscrew is self locking. This means the Z-axis motor is unloaded for the majority of the printing time, and in the event of power being cut to the system, the bed will not drop suddenly (posing potential danger to users and to the printer).

Though using a belt driven system, self locking was addressed by the team through the use of a 200:1 gearing ratio off the motor. A motor and planetary gearbox combination were selected by the team with a gearing ratio of 100:1, and a final step down of 2:1 was implemented off the drive shaft using GT2 pulleys, yielding a final gear reduction of 200:1. The result of these gearing ratios is a holding torque of 7,890Ncm at the output shaft of the planetary gearbox, meaning the motor should be able to hold significantly higher loads than are expected without requiring constant current that would quickly wear out the motor through excessive power draw.

Another alternative which was entertained by the team was a combination of motor with a worm gearbox. This combination would have also achieved the goal of self locking, though was not chosen by the group due to the additional components, and geometry of the motor/gearbox combination.

3.1.6 – Linear Travel Per Motor Step

Another important aspect to consider when determining the motor and gearing ratio was the linear distance to motor step relationship. If this ratio is not considered, then roundoff errors may occur; for instance, if a desired layer thickness of .175mm is selected, and the resolution is .03mm/step, it will be impossible to accurately hit the desired setpoint of .175mm, seen in the calculation below.

$$\frac{.175mm}{.03 \left(\frac{mm}{step} \right)} = 5.833333333 \text{ steps}$$

Roundoff error accumulated in a scenario where the desired layer thickness does not fall in line with the linear travel per motor step, leading to printing deficiencies. As mentioned previously in section 3.1.5 – Self Locking of Z-Axis, the gearing ratio of 200:1 was important not only for holding torque (which is greatly above the expected loads the shaft will expect) but also because of the linear travel per step. As the Z-Axis motor selected is a nema17 with .018 degrees per step (after gear reduction), when combined with the further 2:1 gearing ratio and the pulley diameters there is a .001mm of linear motion per step.

$$C = \pi * D$$

$$Pitch \ Diameter = \frac{C}{\pi} = \frac{NP}{\pi}$$

$$Pitch \ Radius = \frac{NP}{2\pi}$$

*N = number of teeth (20), P = pitch (2mm)

$$1 \ Step * \left(\frac{1.8deg}{step} \right) * \left(\frac{1deg_{out}}{100deg_{in}} \right) * \left(\frac{2\pi \ rad}{360 \ deg} \right) * \left(\frac{NP}{2\pi} \right) * \left(\frac{1}{2} \right) = .001mm$$

Accomplishing this linear travel per step is important, as it allows for numerous different layer thicknesses to be accomplished without getting roundoff from the motor.

As the typical 3D printer layer thickness is much larger than .001mm (generally ~.1mm and up), a 50:1 planetary gearbox may be used with a larger motor to attain the same results. The holding torque would need to be investigated to ensure that it would remain above the load from the printer bed and print itself. This would yield a .002mm per step, meaning the printer Z-axis would be capable of twice the speed while still maintaining the ability to accurately produced desired layer thicknesses. The increased speed was not considered to be a priority, as during a print the Z-axis moves minimally compared to the X and Y axes, meaning it will not greatly impact the overall speed of printing.

3.2 – Printer Bed

The printer bed selected was purchased from a vendor as a pre-made part from 713Maker.com. The bed itself is slightly oversize to allow the 300mmx300mm usable print area required, and features a bed heater to promote first layer adhesion. The bed itself is created from a single piece of milled mic 6 aluminum, with magnets set into the surface. These magnets allow for a separate, flexible steel top layer to adhere to the print bed, enabling users to remove the top layer and pop a completed print off by flexing the material instead of attempting to pry a finished off the print bed, potentially damaging the print and the bed. The printer bed itself is loosely held in place using bent sheet metal retaining clips. Had the bed been fastened tightly to printer bed carriage, the kinematic coupling discussed in section 3.2.2 – Kinematic Coupling would not have been able to function as required. Seen in Figure 10 below, the printer bed has a layer of Kapton tape to prevent wear on the base, or flexible bed, and promote heat transfer between the two.

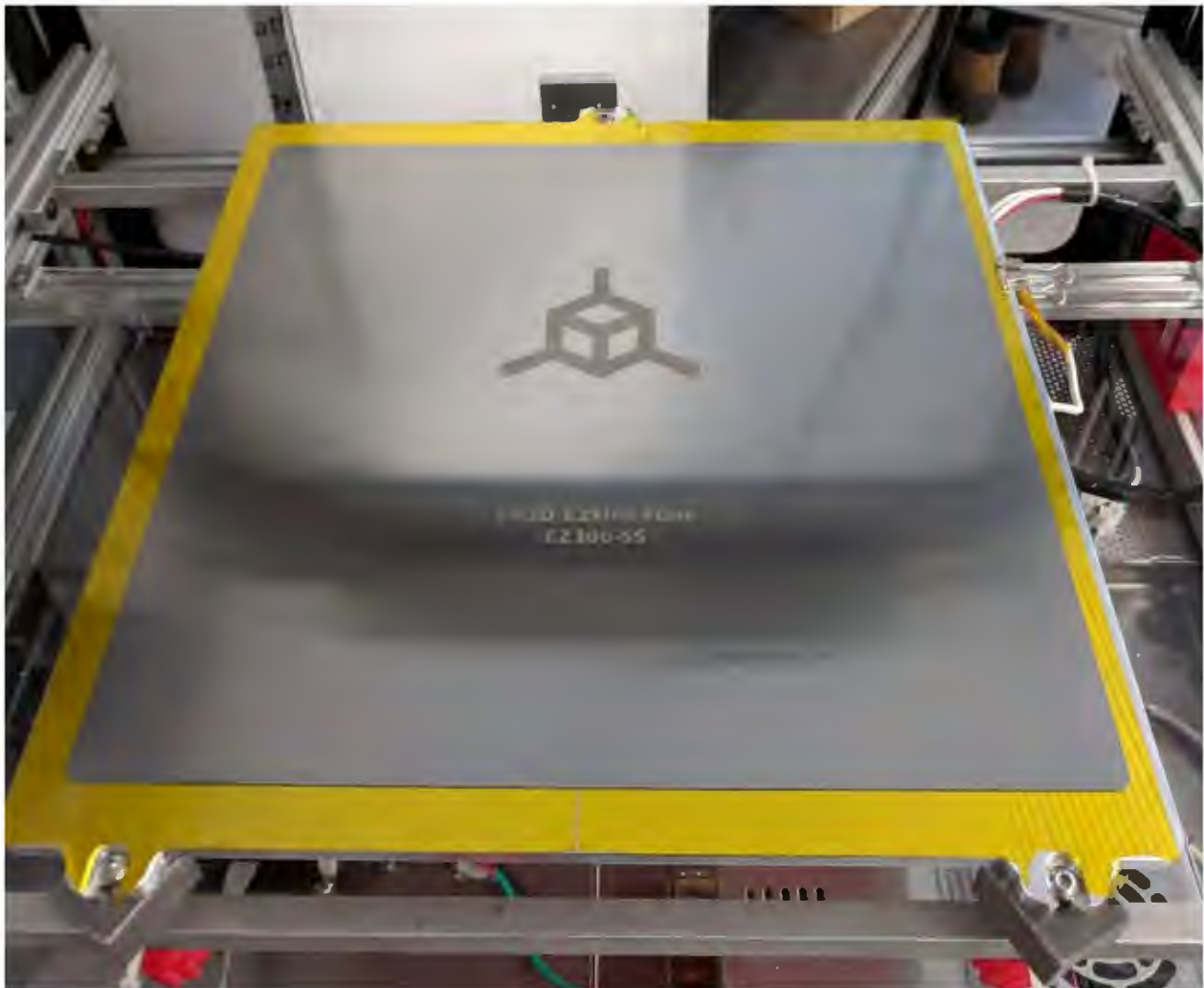


Figure 10 - Printer Bed Top View

3.2.1 – Bed Leveling

Leveling of a printer bed is paramount to ensuring a good final print. If the bed is high or low, the nozzle may run into the bed (damaging the nozzle and/or the bed), or fail to achieve adhesion of the filament on the printer bed. A three-point leveling system was implemented into the printer design, allowing for ease of bed leveling (as opposed to a four-point leveling system). The bed itself is supported by a kinematic coupling atop two cross rails spanning a rectangular printer-bed carriage. Leveling is accomplished by raising or lowering the kinematic coupling balls by means of a handle below the printer carriage. The leveling bolts cut into nylon bolts, which effectively lock the bed level unless it is changed by a user.

The ‘level’ of a printer bed is a term which covers three topics:

1. the height of the bed in relation to the printer nozzle
2. the perpendicularity of the printer bed with the printer nozzle axis
3. the warping of the printer bed

The first and second items in the list are the ones which are adjustable by calibration, as outlined in the 3D Printer User’s Guide (Appendix F). The final item on the list, warping of the printer bed, is a completely separate issue which is addressed by build quality of the printer bed, and mounting. The combination of a kinematic coupling and a high quality printer bed such as the one implemented in this project ensure that the warping of the print bed is as minimal as possible.

A four-point leveling system may have also achieved the same goal. They are a more stable system, though are much more difficult to calibrate the bed level of correctly, leading to the decision of a three-point.

3.2.2 – Kinematic Coupling

Mentioned briefly in section 3.2 – Printer Bed, a kinematic coupling is employed in the printer. The advantage of using a kinematic coupling is that it allows the bed to thermally expand or contract during a print without locking it in a defined place. Instead, the bed is allowed to expand horizontally, instead of being fixed in defined places and warping during heating. While the bed will not expand significantly during a print, the kinematic coupling will allow any expansion required to occur without causing defects in the final print. Figure 11 below shows two of the three kinematic coupling mounts as designed in SolidWorks.

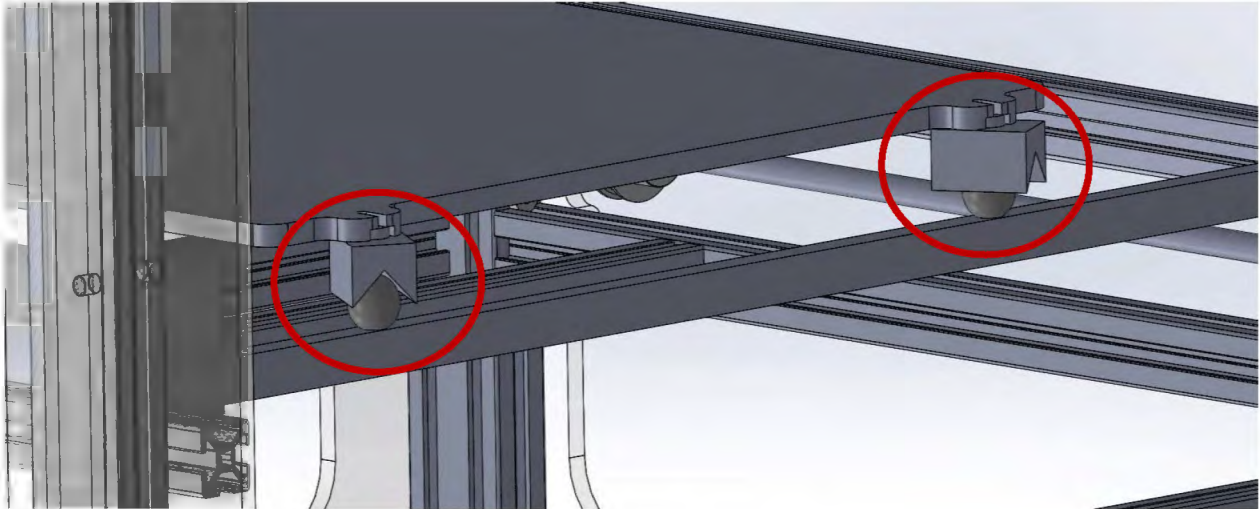


Figure 11 - SolidWorks Model of Kinematic Coupling



The coupling was created using three inverted steel v-shaped blocks (“v-blocks”) sitting on top of steel balls, one such setup can be seen in Figure 12 to the left. Each ball has two points of contact with the v-blocks, and can slide across them as needed during thermal expansion or retraction of the plate. The kinematic coupling is one of the few areas where aluminum was not exclusively used in the construction of the printer due to steel being much harder than aluminum, and not deforming during the relative motion between parts over a long period of time.

Figure 12 - Created Kinematic Coupling Blocks

3.3 – XY Motion System

3.3.1 – Motion Control

A CoreXY motion system controls both the X and Y motion through two motors that work in tandem. As both motors rotate the same direction the print head moves left and right in the x direction, and if the two motors rotate in opposite directions, the print head moves up and down in the Y direction. The advantages a CoreXY system is that there are no motors on the gantry allowing for faster speeds and a higher accuracy due to the system having less inertia.

Furthermore, the tension created in the belts during horizontal motion generates a net torque balance, rectifying the potential for deflection about the print head. A CoreXY vector diagram showing this effect is presented in Figure 13 below. Figure 14 and 15 (Figure 15 is on the following page) show the belt loops used for both the left and right motors of the printer.

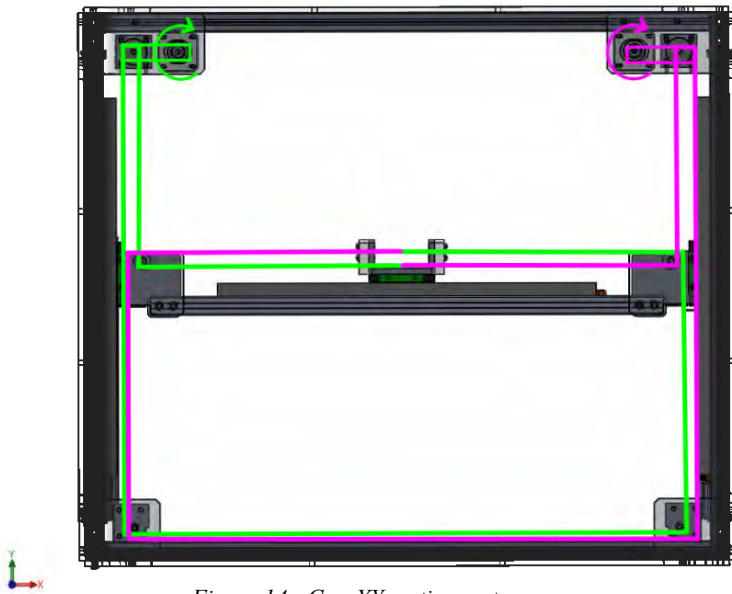


Figure 14 - CoreXY motion system

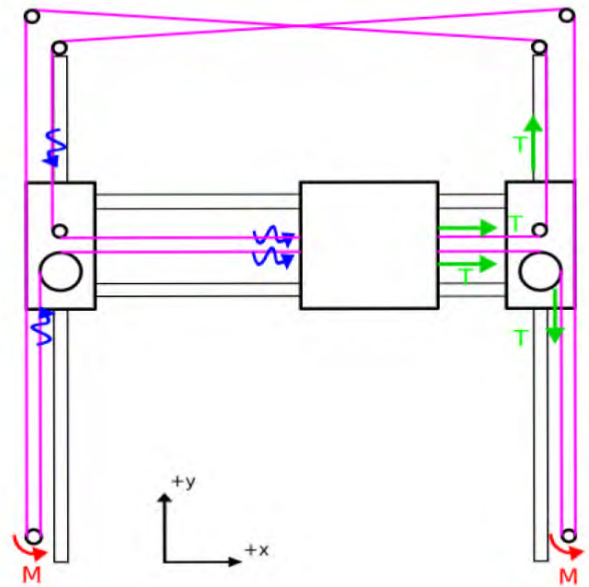


Figure 13 - CoreXY Force Vectors

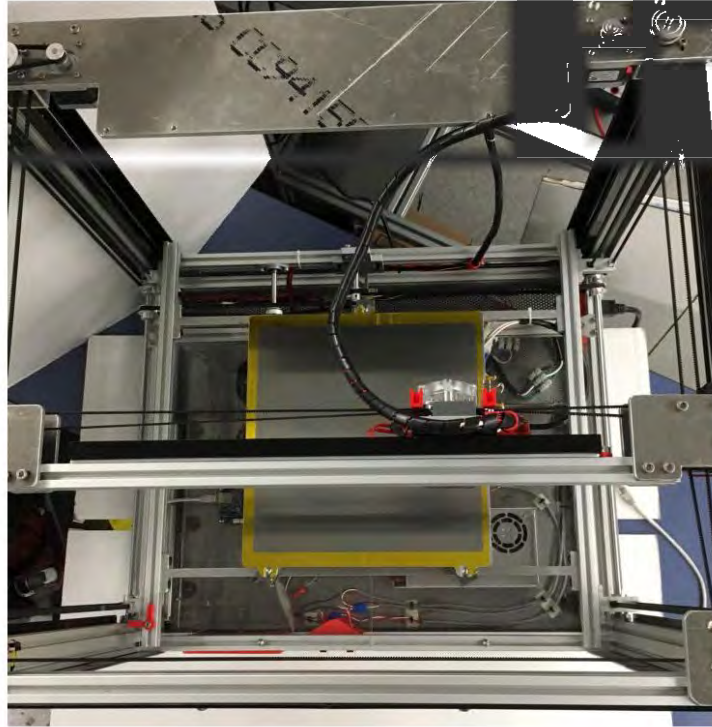


Figure 15 - Top view of physical CoreXY system

3.3.2 – Drive System Adjustments and Specifications

A gear reduction system was added to be able to increase the resolution of the print. Circled in red in Figure 16 (on the following page) is a 20-36 gear tooth ratio, with an initial stepper motor resolution of $1.8^\circ/\text{step}$. The gear reduction accomplishes a resolution of $1^\circ/\text{step}$. This resolution corresponds to a linear resolution of $0.105\text{mm}/\text{step}$ using 12mm diameter pulleys.

Motor resolution with 20/36 tooth gear reduction:

$$\text{resolution} = \left(\frac{20}{36}\right) * 1.8^\circ = 1^\circ/\text{step}$$

Linear resolution of 12mm diameter pulley:

$$\text{resolution} = \frac{12\pi}{360} = 0.105\text{mm}/\text{step}$$

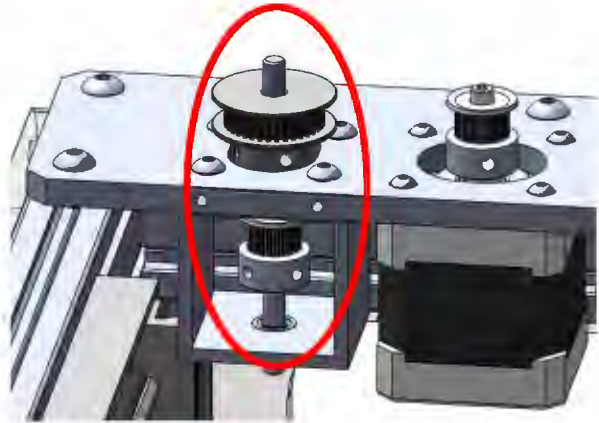


Figure 16 - Gear reduction system



Figure 17 - Slots used for belt tensioning

Figure 17 above illustrates the slots cut into the motor mounting plate to allow for belt tensioning. Since both rows of belts must be equally tensioned to allow for precise motion control, the team will dedicate much of their attention to ensure the proper adjustments are made. The fully assembled version on the printer prototype is shown in Figure 18 below, including the properly tensioned belts.



Figure 18 - Physical tensioning system view

3.2.3 – Mounting Features

The plates used to sandwich the gantry were waterjet from aluminum and accommodate the required pulleys used for the belt routing. Figure 19 below illustrates how the carriage plates also provide surfaces for the mounting of an alignment block used during the assembly process to ensure squareness to the linear rail. The carriage was mounted to the linear rails by drilling and tapping into top of the carts. The SolidWorks model and final manufactured versions are shown in Figure 20 and 21 below.

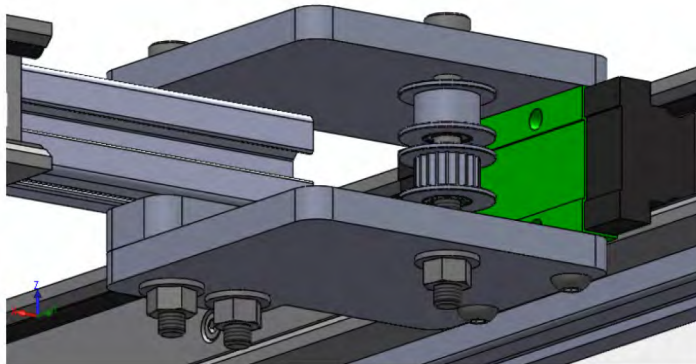


Figure 20 - Carriage mounting plates

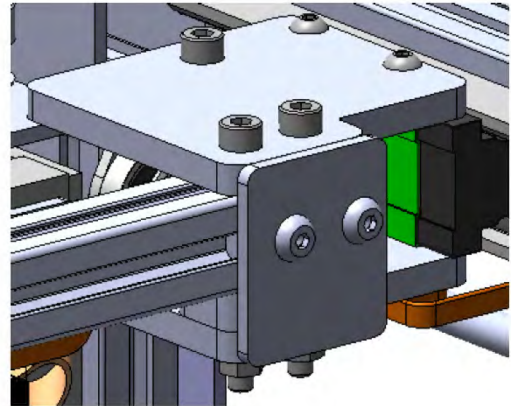


Figure 19 - Alignment feature



Figure 21 - Carriage mounting plates system

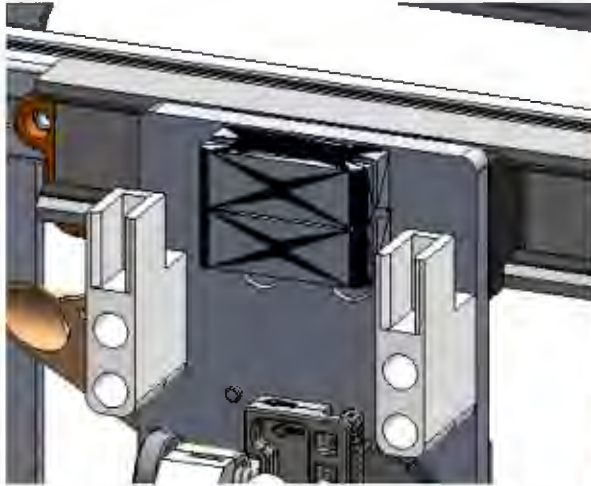


Figure 22 - Belt clamping blocks

Figures 22 and 23 illustrate how the belt clamps were used to place and tension the belts about the print head. Both blocks contain an open face where the belt can be slid in with the proper adjustment. During the assembly process the blocks will be mounted face to face to prevent the belts from falling out under tension.



Figure 23 - Fully assembled printhead

3.2.4 – Tool Locating Validation

As mentioned in earlier sections, the product to be used for tool changing was stuck in the beta-phase during the completion of this project. With that being said, the infrastructure to allow for tool changing was still incorporated, this includes tool locating features, a plate designed to clutch multiple tool heads, and the accompanying software and electronic components required.

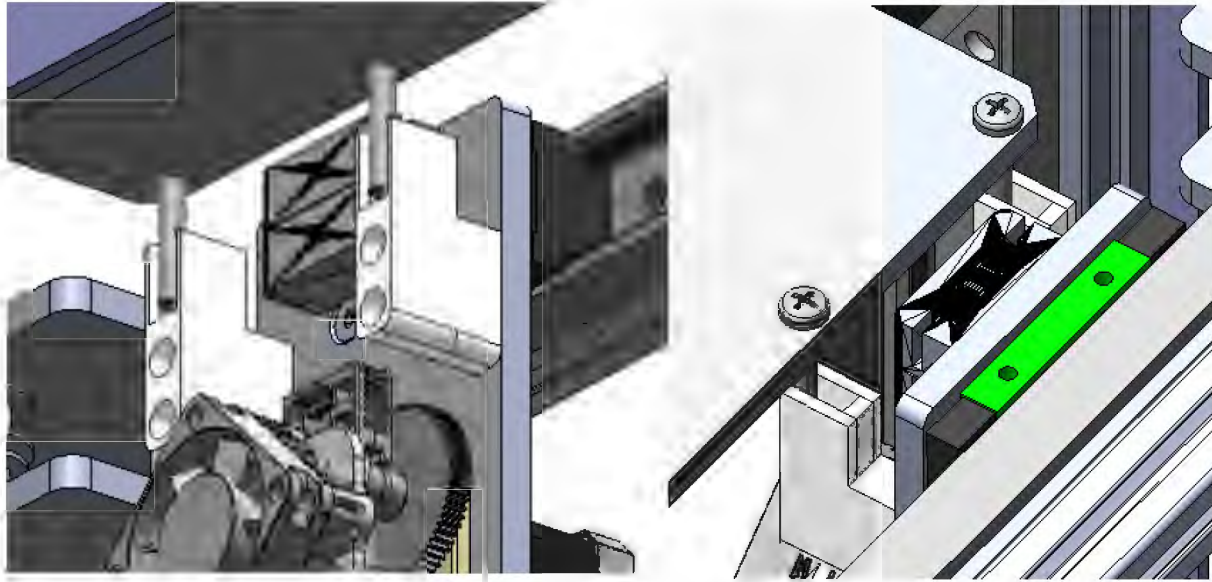


Figure 24 - Tool locating (side and top view)

Several locating pins are placed along the top plate to allow for the docking of multiple print heads. Currently, there is enough room for four separate heads to be mounted on the top plate. The locating brackets were 3D printed and mount via the spacer plate through a threaded connection, shown above in Figure 24. Once the kinematic coupling used for tool changing becomes available, the mechanism will need to be coupled to the spacer plate to allow for the swapping of multiple print heads – where tool location is currently being accomplished.

3.4 – Frame and Structural Considerations

The foundation of a good 3D printer depends not only on its motion systems, but the quality of its frame. Here, it is of significant importance for the frame to be square, have excellent stiffness, and ease of modularity for mounting of the printer's numerous components.

3.4.1 – Frame Members

To tackle these design requirements, aluminum T-slot extrusion was specified for all of the frame members. The stiffness and low weight of the aluminum extrusion, as well as its ease of mounting using commonly available T-nuts, made it the ideal solution for the printer prototype. Several iterations of the final design, shown below in Figure 25, were considered; however, this nearly cubic design was selected for its simplicity in assembly and ability to house all the required printer systems. The frame is split into two sections with the larger printing bay above separated from the electronics bay below by the smaller aluminum extrude members. This design allowed for the system components to be mounted within the frame in its entirety, including the ability for ease of access to the electronics below.

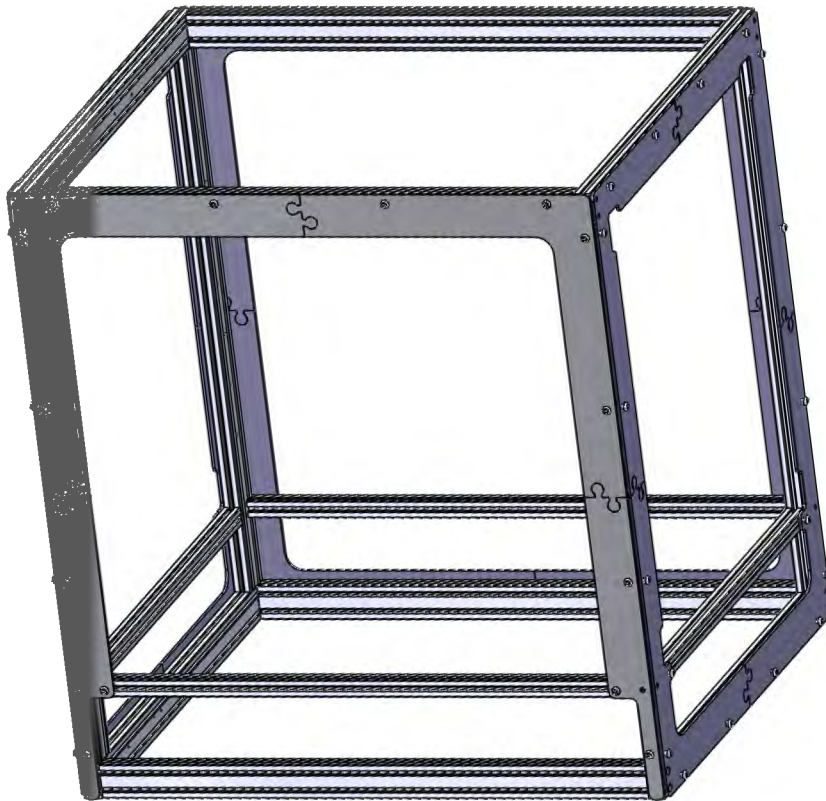


Figure 25 - Final Frame Design for CoreXY 3D Printer

For CoreXY and similar Cartesian printers to be effective, its motion components must be mounted square to the frame and to one another. Using linear rails, as discussed in previous sections, introduces a unique requirement for all faces that mount these rails to be extremely square to one another. Without this, the rails would tend to bind, adding resistance to the linear translation in each axis, and the potential for jerky motion and artifact-ridden prints.

To accomplish this, the frame members were all cut to-length and machined using BCIT's Haas CNC milling station with the help of the project sponsor and manufacturing guru, Stephen McMillan. The manufacturing process for each frame member was quite similar, where each was mounted into the machine using precision aligned vices. A live stop was used to locate each piece at which point the machine could mill each to length, and drill, tap, and counterbore any required holes. The precision offered by this manufacturing approach allowed for every frame member to be quite square and thus when assembled, square to one another to very low tolerances. Their assembly was accomplished using flanged buttonhead fasteners along the T-slot extrusion to securely mount each member.

3.4.2 – Frame Gusset Skirts

The frame's stiffness requirement introduced another level of complexity to the design. Initially, it was thought that small gussets in each of the corners could meet the required rigidity of the system; however, this method also introduced the need for multiple gussets in each corner of the machine which would have been impractical.

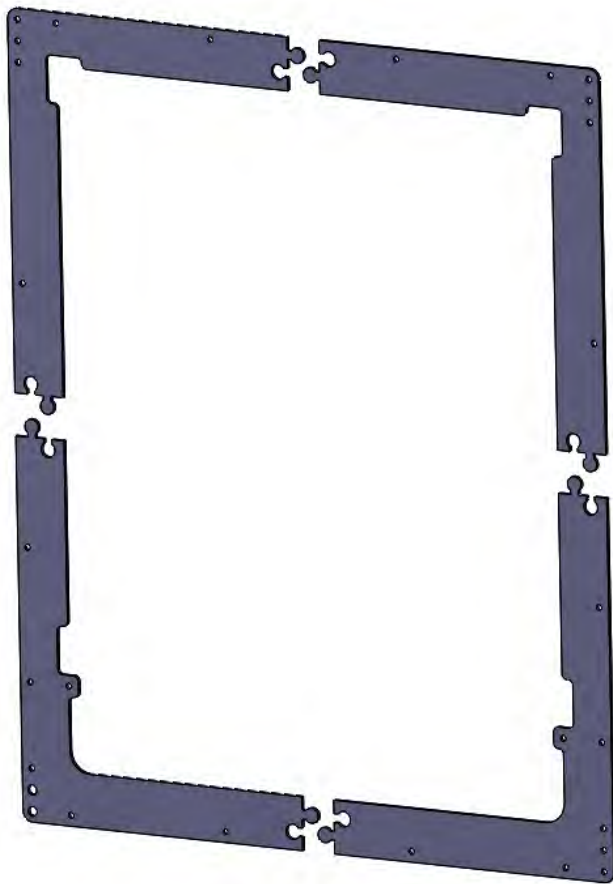


Figure 26 - Frame Gusset Skirt Exploded View of Puzzle Sections

Instead, gusset skirts were designed to join each face of the machine and improve the frame's lateral stiffness at each vertice. These skirts were initially designed to be made of 1/4" acrylic sheet; however, as pointed out by our project sponsor, acrylic is both expensive and prone to cracking under point loads. To avoid these issues, the skirts were redesigned using 1/8" aluminum sheet. Because of their size of about 26" x 26", these skirts also needed to be split in each of their corners to allow for their manufacture on BCIT's water jet cutting machine. Each skirt was thus made up of four parts and joined using a jigsaw pattern as cut out on the water jet machine. This pattern is illustrated in Figure 26, to the left. Once assembled, the skirts offered the added benefit of providing a frame on each face of the machine upon which acrylic could be mounted to fully enclose the printer; however, full enclosure of the printer was considered outside the scope of this project and should be considered in section 6.3 – Future Work.

3.5 – Electrical System

The printer's electrical system required several design considerations to guarantee the machine's reliability over its usable life. These considerations included accessibility for assembly, testing, and maintenance; component selection; circuit design for the various electrical system elements; neat wire routing for ease of assembly and troubleshooting while giving the prototype a professional appearance; and electrical safety features to protect the user and system from the high voltage supply to the printer.

3.5.1 – Electrical Access Tray

The main mechanical design component of the electrical bay is the electrical tray, shown below in Figure 27. In placing the electronics in the bottom of the printer, these components become easily accessible for any user needs. By contrast, the electronics of other 3D printers are often mounted at the backside or above the printing bay. These designs offer better spatial efficiency than mounting at the base of the machine, but increase the complexity of mounting individual system components. This was seen to be undesirable during the initial design of the frame, resulting in the electrical tray seen on the printer prototype.

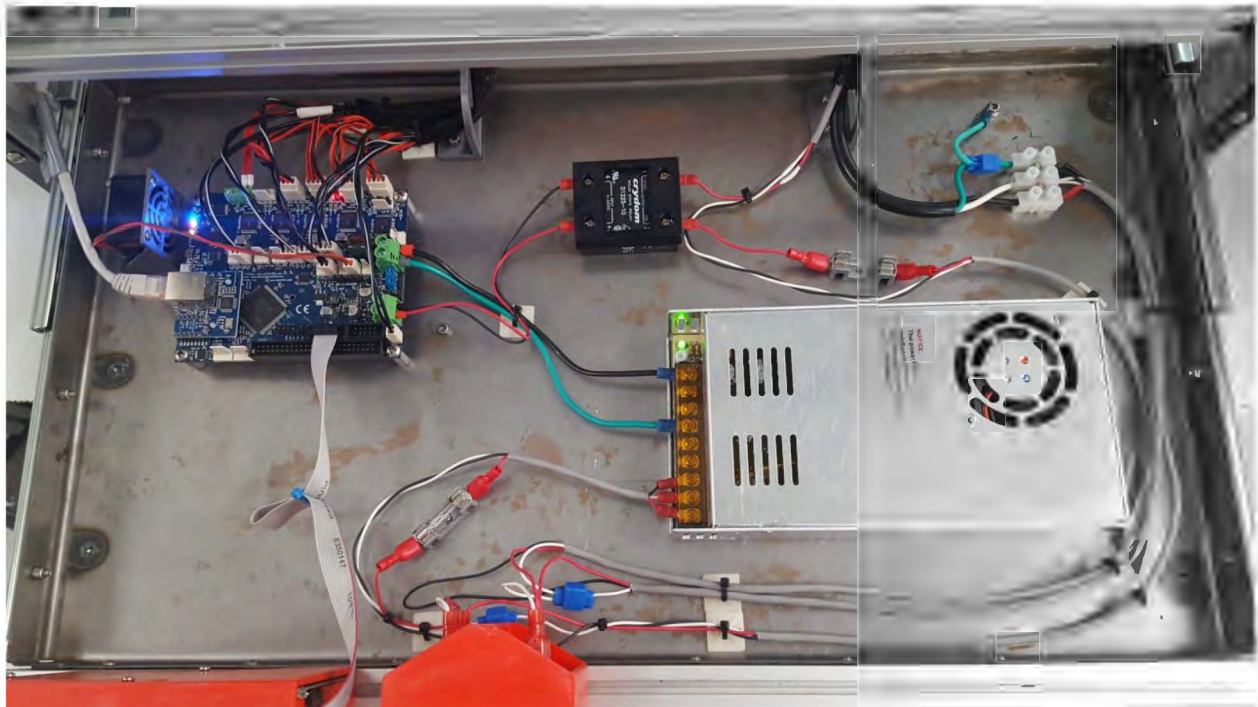


Figure 27 - Overhead View of Assembled Electrical Access Tray

The electrical access tray was designed to be manufactured from sheet steel. The design was intended to be mounted on two drawer slides attached to the inside of the frame that allow the tray to be easily opened and accessed during assembly and maintenance. The tray mounts all the main electrical components including the controller, power supply, fuses, switches, and LCD control panel mounted at the front of the machine.

The planar layout of the tray is advantageous for many reasons. Firstly, it increases ease of access to the printer components for assembly and testing of the electrical system. It also allows for the AC and DC circuits to be easily routed away from one another – the importance of this will be discussed later sections. Finally, the space offered by this layout allows for sufficient clearance between electrical components necessary for thermal management, which is especially important for the high current wires of the power circuit.

3.5.2 – Printer Controller and Hot End Selection

The requirements for the 3D printer, as determined from the outset of the project, required the ability of the printer to be expandable for tool-changing, including the addition of several extruders. To determine an effective control platform for the machine, the team consulted with the project sponsor to find a controller which would offer the required expandability as well as ease of user interfacing.

From these discussions, it was determined the Duet Ethernet controller would be used. The Duet 2.0 controllers offer a significant increase in computational power from standard RAMPS platforms. These other printer platforms rely upon Marlin open source configuration software which is incredibly complicated and has resulted in inconsistent prints that may freeze at any time, as found by other users online [3]. The Duet 2.0 series controllers use proprietary configuration software, Duet Web Control, which enhance the user experience in terms of configuration and access during printing. Rather than configuring tedious G-Code files, the Web Control offers the ability for the user to configure the board using the online RepRap Configurator Firmware tool, to generate configuration files and upload them remotely. This is advantageous not only for configuration, but also during printing where the user can remotely upload slicer files (as generated by software such as Ultimaker Cura) rather than over USB or SD cards [3]. These two web development tools are discussed in further detail in the User’s Guide found in Appendix F. Finally, these boards offer the ability to expand up to seven extruders with the Duet Expansion Board which effectively met the project requirement [4].

The Duet 2.0 series boards offer either Wi-Fi or Ethernet control for user access during printing. Either control method allows for a user to easily access the printer from the network and control the printer remotely. After some investigation, the Duet Ethernet board, pictured to the right in Figure 28, was selected because of its higher reliability from the hardwired network connection.



Figure 28 - Duet 2 Ethernet Controller

The Duet Ethernet (and Duet Wi-Fi) board also can be easily attached to a user-friendly LCD touchscreen display, the Duet PanelDue, from which the user can easily start prints and calibrate the machine using on-board macros. The display was then mounted in a 3D-printed case as found through the GrabCAD community. Figure 29 shows the PanelDue LCD and its 3D printed case, as mounted at the front of the 3D printer.



Figure 29 - Duet PanelDue 4.3" Touchscreen Monitor in 3D Printed Case

Finally, a hot-end was selected for the printer, pictured in Figure 30 below. Using the project sponsor's vast knowledge and experience in 3D-printing technology, the Titan Aero hot end was chosen for the printer. The Titan Aero's design rivaled that of other hot ends available on the market, including high quality manufactured components that allowed for ease of assembly and consistent filament extrusion. A 1.75mm filament diameter was chosen for this extruder, as discussed in Section 1.4.2.1. Although the printer is to be expanded for several hot-ends, the scope of this project was limited to one hot end to limit the final costs of the machine.

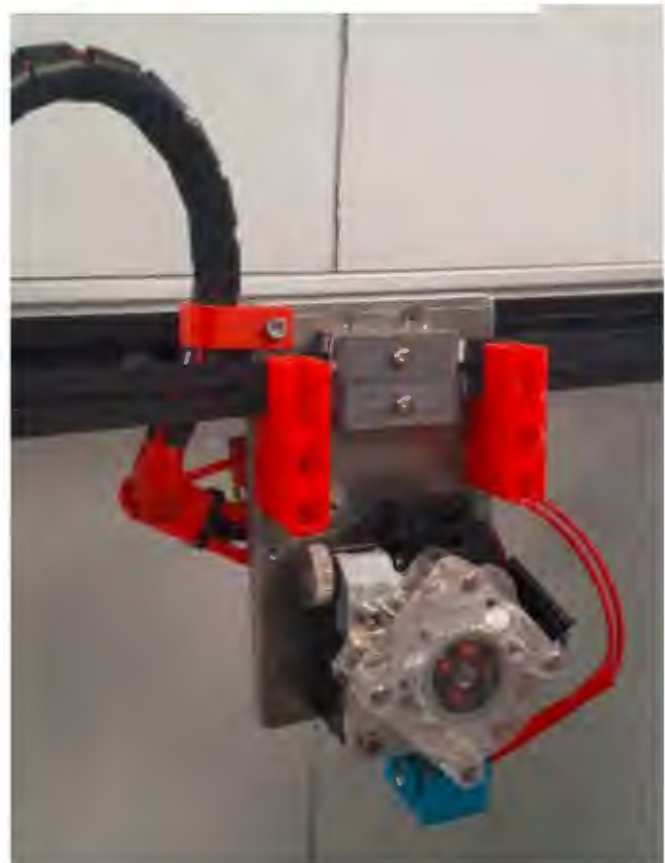


Figure 30 - Assembled Titan Aero Hot End with Mounting Plate

3.5.3 – Electrical System Design

The printer's electrical circuit design required several large design decisions to determine components that would result in a high quality 3D printer. These included considerations for the power supply, bed heater, and controller circuits that together would contribute to a highly functional machine. The electrical schematic is shown in Appendix E which includes layout for the following circuits, as well as specification of its components.

3.5.3.1 – Power Circuit Design

To begin designing the printer's power circuit, a supply voltage needed to be selected. The Duet Ethernet offers models for either 12V or 24V supplies and after little deliberation, the 24V supply was selected. Using a higher supply voltage offers several advantages.

First of all, it allows for smaller wires in the system because of reduced current demands of the board which is exceptionally important when it comes to wiring the system, as discussed in section 3.4.4. The 24V supply also offers higher motor speeds, something the team found highly desirable towards reaching the goal of developing a high quality 3D printer. The stepper motor drivers on-board the Duet controller function using current chopping to control motor speed. At higher potentials, the individual motor's magnetic fields can be saturated at much faster rates resulting in higher motor speeds and greater motor torque. The high supply voltage offers the additional advantage of offering much faster heating and higher possible temperatures for the bed and hot end heaters [5]. Understanding these advantages, a 400W, 24V power supply was selected as shown below in Figure 31.



Figure 31 - S-400-24 Power Supply Installed in Prototype

To design the circuit used for the power supply, careful consideration had to be made due to the danger of using a 120VAC wall source. For safety and ease of connection, an IEC320 C14 connector was used at the back of the printer. The connector and its wiring into the machine are illustrated in Figure 32 (to the right), which clearly shows its ease of user access for connection while preventing curious fingers from reaching the dangerous wall supply voltage inside. These connectors are often found on desktop computer power supplies with the added advantage of having an easily disconnected



Figure 32 - IEC 320 Input Cable and Connector on Back Right-side of Printer

power cable. From this, the wall source could easily be distributed along the inside of the printer to the power supply through a fuse and a switchable fuse used as power switch. These circuit protection features will be discussed in further detail in Section 3.4.5.

3.5.3.2 – Bed Heater Circuit Design

For reliable 3D printing, bed heaters are required for most materials available on the market. The Duet Ethernet controller comes with on-board connections for the bed supply; however, at 24V the bed heating routine would have become quite tedious waiting for the large aluminum printer bed to be heated to a consistent temperature.

To avoid these delays, a highly desirable feature includes using a 120VAC bed heater. A Keenovo 750W, 120VAC silicone bed heater was selected to meet this goal, pictured mounted on the printer's aluminum bed in Figure 33 to the right. The stick-on heating pad comes with built in wiring for both the bed



Figure 33 - 750W Silicone Bed Heater
Glued to Underside of Print Bed

heater, as well as an integrated 100k NTC thermistor at the center of the pad. To power this circuit, special considerations needed to be made for the controller's use of PID control to maintain a consistent bed temperature. From the 120VAC supply distributed into the frame and through another switchable fuse and in-line fuse, a solid state relay was used. A Crydom D1225 was selected to control the flow of current to the bed heater using the Duet's bed temperature outputs as DC control inputs. The 25A solid state relay was selected under recommendation from Duet's online guide to be at least four times the bed heater current [6]. This safety factor is used to avoid burning out the relay and requiring the addition of an expensive heatsink and cooling system. From this device, the board can easily control the bed temperature in conjunction with the embedded thermistor.

A final important feature in the design of the bed heater circuit is the use of a thermal cutoff fuse in-line with one of the bed heater's power cables. Solid state relay devices, if they are to fail, will fail open, allowing for rapid uncontrolled heating of the bed [7]. To mitigate this issue, a one-time use thermal fuses, specified at a cut-off temperature of 184°C, was soldered into to the circuit and clipped to the side of the heated bed using a binder clip. This temperature was deemed sufficient for printing most 3D printing materials and their required bed temperatures. The fuse is wrapped in 5 mil Kapton tape because its body is electrically live during use, as clearly shown in Figure 34 to the right.

Although in the event of failure, re-soldering the fuse is quite difficult (a heat-sink is required to avoid burning out the fuse), this feature is incredibly important to avoid starting devastating electrical fires in the case of component failure and the subsequent issues that brings on.

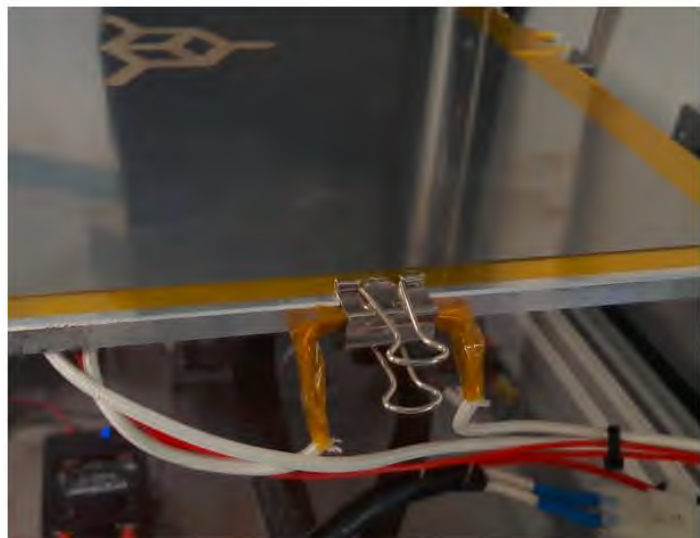


Figure 34 - Thermal Cut-Off Fuse Clipped to Side of Print Bed

3.5.3.3 – Control Circuit Design

The remaining circuit design was more cut-and-dry than the previous two sections. The DC components of the 3D printer include motors, limit switches, fans, the hot end heater and fans, and the controller cooling fan.

The 24V power supply enters directly to the Duet controller. No in-line fuses were necessary here because of the on-board 15A automotive fuse used on the controller. From the controller, all necessary DC connections could be made to the aforementioned components. The fully wired controller is shown in Figure 35 on the following page, which displays the many connections on the controller board. An important feature when implementing this circuit, as pointed out by BCIT's Jason Brett, involved consideration when wiring the motors near to the limit switches. His advice was to twist the motor wires to minimize the EMI effects of the phase shifting during stepper motor operation which can falsely trigger the limit switch if the effects are too great.

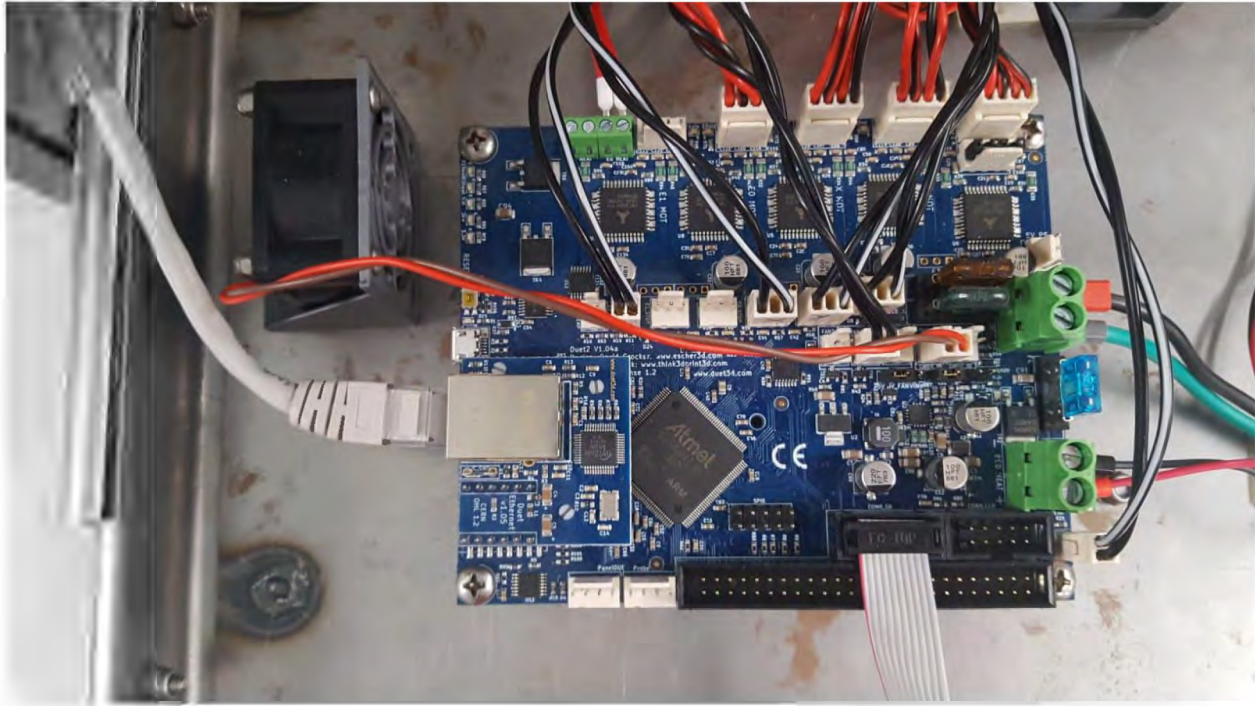


Figure 35 - Duet Ethernet Controller Installed and Fully Wired on Prototype

3.5.4 – Cable Sizing and Routing

With the circuit design completed, implementing the electronics required careful consideration for wire sizing to avoid overheating of the cables. Throughout this design process, the American Wire Gauge (AWG) sizing chart was consulted to adequately size wires for chassis wiring based upon their current draw [8].

3.5.4.1 – AC Circuits

At the system input, the machine was calculated to draw 12.55A during normal operation. This total current draw is a combination of the power supply and the bed heater's total draw. The power supply, as found per its data sheet, draws up to 6.3A when operating at 120VAC input voltage. The bed heater was calculated to draw up to 6.25A for powering the 750W bed heater. These two currents were then used to size the fuses and switches discussed in Section 3.4.5.

To size cables for the AC circuit, until the junction, 14GA cable was selected – capable of handling up to 32A – to ensure a high factor of safety for these high current cables. The individual power and bed heater circuits were chosen to use 18GA/3 Conductor wire which also includes a factor of safety of 3.5 for cable sizing.

A benefit to using high voltage powering through half of the electrical system is the lower required wire gauge to power many components. This helped significantly during wiring during which both AC circuits could be run next to one another without spatial concerns. A significant concern during the mechanical design of the machine's AC and DC system was their proximity to one another. Because of the high frequency AC wires, EMI could possibly impact the signals being sent to the motors, limit switches, and sensors. To avoid having to use more expensive 3-conductor shielded wire, the electrical layout was chosen to keep both circuits separate – the AC circuits on the right and the DC circuit on the left when facing the printer. Although the risk was not high, the effect could have been highly frustrating during the testing and troubleshooting phase, thus all precautions were taken. The split electrical bay is shown in Figure 36 below, where both the DC circuits (left) and AC circuits (right) are highlighted.

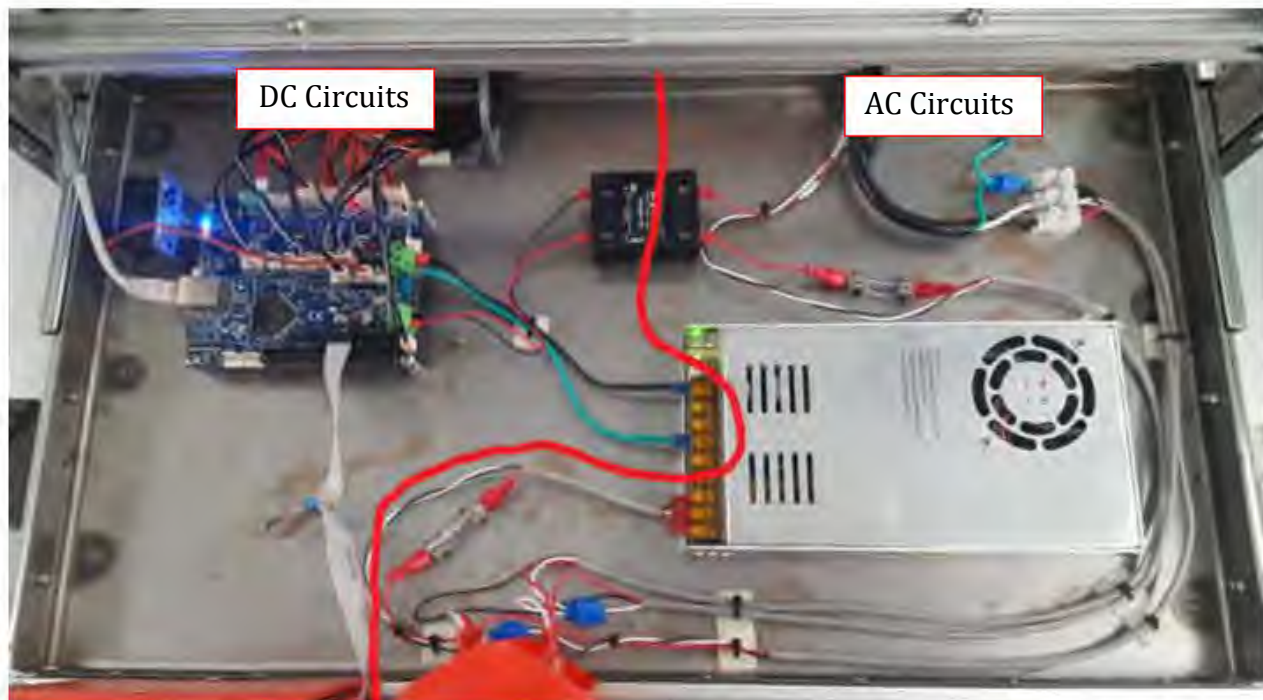


Figure 36 - Overhead View of AC and DC Circuits

3.5.4.2 – DC Circuit

The DC circuits run at much lower voltages and currents than the powering circuits. Many of the associated components operate at a signal voltage of 3.3V with low current draw. The limit switches and sensors operate at very low current draws; however, the stepper motors can draw up to 2.4A from the Duet Ethernet motor drivers, and more should external drivers be used [9]. To allow for this forwards compatibility, the motor wires were sized to be 22GA, allowing for current draws up to 7A (well above what is actually required for the NEMA 17 motors on board.) For simplicity during measuring and installation of the cables, all system wires were specified to be 22GA. The Duet controller itself can draw up to 15A (as limited by the on-board fuse) so 14GA wire was added to power the unit. Another special consideration was for the solid state relay's DC input cables which can draw up to 18A from the Duet's bed heater supply [6].

Because a resistive heater isn't attached, the actual power draw of the solid state relay is much lower, thus 18GA wires were chosen.

Cable routing for the DC circuit required special consideration from the outset of the project because of the high volume of low voltage cables to be run all over the machine. The use of T-slot extrusion frame members provided the benefit of being able to run cables within the T-slot, behind all surface mounted components. For all hot end connections and the X-axis limit switch, cables were run up the backside of the bed to the XY motor mounting plate. From here, the cables were strung across to the hot end using nylon cable wrapping to provide support across the span, as shown by the picture in Figure 37. With the addition of more extruders, their hot end cables would also be run up the backside of the machine where there is ample clearance for cable routing.

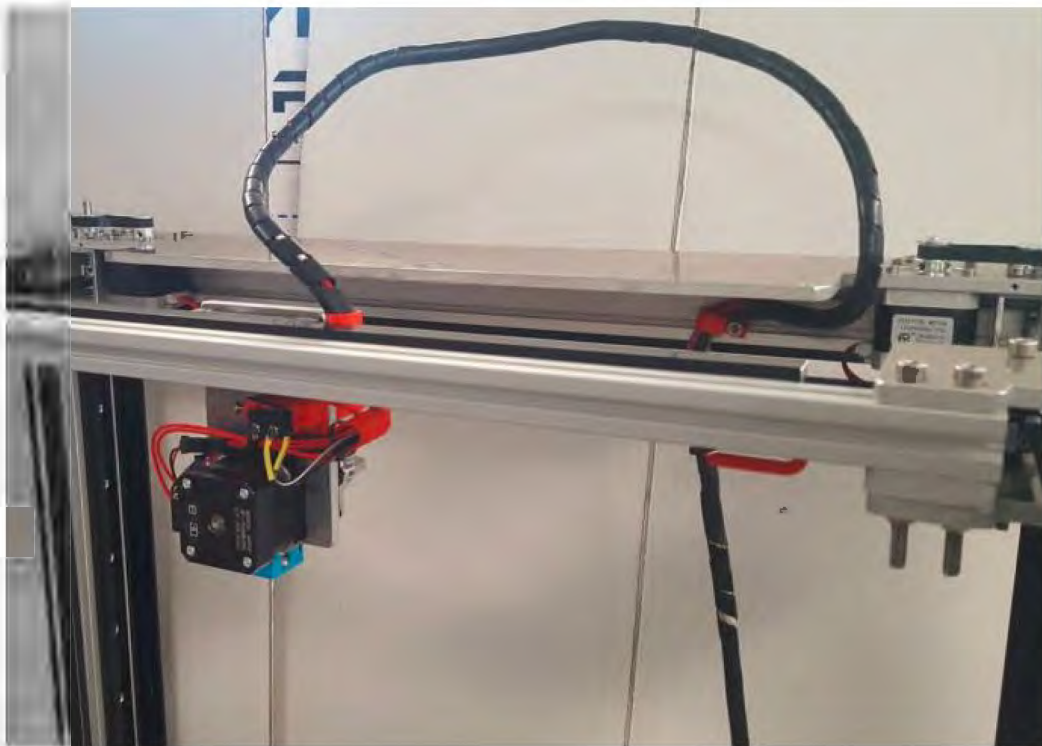


Figure 37 - Nylon-wrapped Hot End Cables Routed to the Print Head

3.5.4.3 – Electrical Access Tray Routing

Because the electrical access tray is mounted on rails and can extend up to 12” from its hard-mounted position on the frame, special consideration had to be made for wiring all electrical components. For this reason, cable lengths had to be increased by up to 16” to allow for ease of extension of the tray without overstraining the cables.

Initially, the design was intended to use DIY cable guides made from cut-up measuring tape wrapped in braided nylon sleeve and mounted to the frame and access tray using 3D printed brackets. The measuring tape was intended to provide consistent bending along the full extension of the drawer while maintaining the position of the cables [10]. This design is shown in Figures 38 and 39, to the right and below. This idea was unfortunately scrapped after the machine was fully wired. Using hookup wire supplied by Jason Brett, the cables for all of the printer’s DC components became quite large when routed to a single point and the measuring tape was no longer able to support their weight. This became even more evident for the 3/14GA power cable used to power the bed heater and power supply circuits because of its size and stiffness.

Instead, the cables were separated (two runs for the DC connections and one run for the AC connections) and fed into ½” braided nylon sleeve. Once securely mounted in the sleeve, these cable runs were given a single twist and cable tied to the original cable guides. The twist acts to put the wires in tension and promote consistent retraction when the drawer is fully extended and then closed. Once installed and tested with the access tray, this method was found to be quite reliable for routing the AC and DC wires back to their home on the tray. Figures 40 and 41, below, show the cables as mounted in the 3D printer, both in their closed and extended positions.



Figure 38 - Original Cable Routing Design Idea (1/2)



Figure 39 - Original Cable Routing Design Idea (2/2)

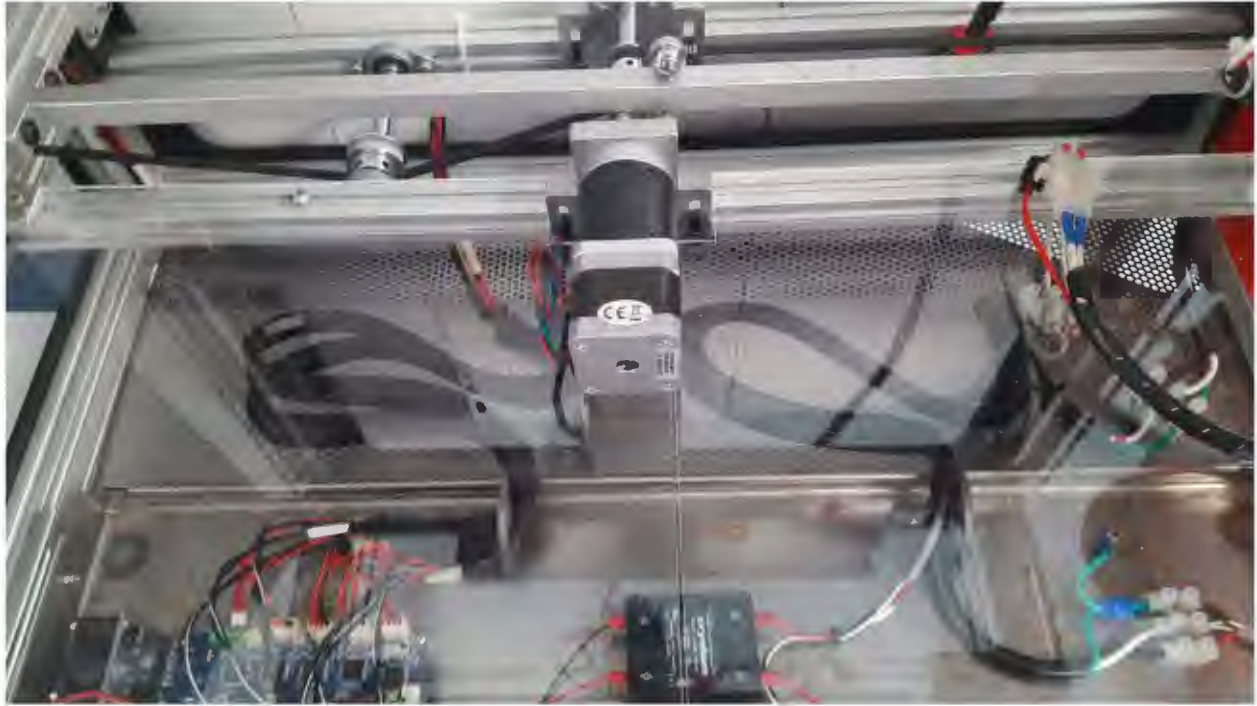


Figure 41 - Positioning of Electrical Cables (Neatly Coiled) With Closed Tray



Figure 40 - Positioning of Electrical Cables (Extended) With Open Tray

3.5.5 – Electrical Safety Considerations

User safety during machine testing, use, and maintenance was considered throughout the design of the electrical system. As a result, all circuits are fused at least once to currents above the operating currents of the system. Most importantly, the system is also earth grounded on the electrical access tray.



Figure 42 - Location of System Earth Ground (Circled in Red)

After performing intensive continuity testing at various points of the frame, it was determined that the entire machine is properly earth grounded back to the wall source grounding point. This grounding point is highlighted in Figure 42, below.

For the AC circuits, 10A glass fuses were placed in-line with the power supply and solid state relay in their respective circuits. Additionally, 10A resettable thermal circuit breakers were placed prior to these fuses; not only do they act as additional fuses in these high voltage circuits, but they also provide power switching at the front of the machine for both the power and bed heater circuits. Figures 43 and 44 below illustrate the locations of these switches and fuses for the reader's reference.



Figure 43 - Location of Circuit Protection Components (10A Glass Fuses and Switchable Fuses)



Figure 44 - Location of Switches and their Labels at Front of the Machine

All of the 120VAC circuits come with the inherent danger of AC at high voltages. For this reason, fuses and switches alone are insufficient for providing full user protection during operation of the machine due to the potential of wandering hands potentially causing a short to ground in any connections are left unprotected. For all wire terminations, 300V rated terminal blocks were used for housing each the line, neutral, and ground wires of the AC circuits. Another key consideration is the cover on the solid state relay, which has exposed 24VDC and 120VAC connections on its surface. The cover was custom designed for 3D printing and fits snugly over the top of the relay, as shown in Figure 45 below.



Figure 45 - 3D Printed Solid State Relay Cover (in black)

As mentioned in Section 3.4.3.2, an 184°C thermal cutoff fuse was soldered in-line with the bed heater lines. In the event of bed overheating, the fuse is designed to break to save delicate components around it from the excessive heating in order to prevent electrical fire due to component and wire melting.

Chapter 4: Description of the Project Activity and Equipment

4.1 – Design and Modelling

Initial project activity included rough hand sketches of different printer configurations, varying from size, shape, component placement, and motion design. The design process followed a series of weekly design reviews with our project sponsor where ideas were revisited, altered, and refined. After each individual design idea was concluded it was modelled in SolidWorks and added to the overall assembly to check feasibility. As the assembly progressed, mini design reviews amongst the team were held to ensure the practicality of the design where countless micro-adjustments were made.

Since each team member was responsible for different components of the printer, each member tackled their portion individually, created a sub assembly, and sequentially added their section to the master model. This practice worked very well for the team since each version was properly labeled and a constant stream of communication was kept, ensuring that no work was overwritten.

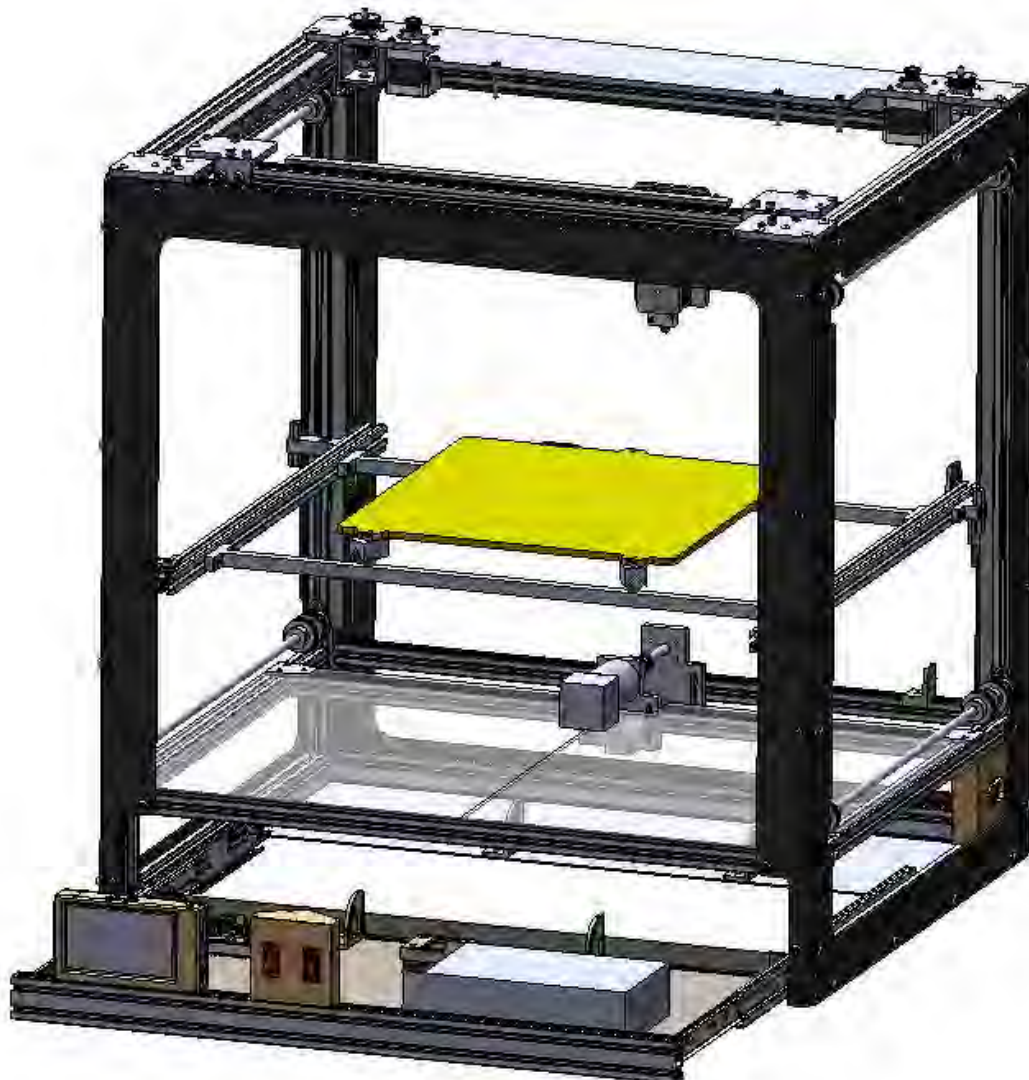


Figure 46 - Final SolidWorks Assembly Model

The final SolidWorks assembly, shown on the previous page in Figure 46, contains the vast majority of all the components used in the creation of the project. This includes all types of fasteners, stock material, 3D printed parts, purchased parts, etc. Certain exclusions were made in order to save precious time such as modelling the belts running through the pulley system and the wires connecting to each electrical component. These designs were sketched by hand instead and kept for the team's records. Additionally, not all fasteners were added to both save time and reduce the overall file size to allow for efficient modelling.

The largest difficulty of the design and modelling phase was the circular dependencies encountered by the team. It seemed that every decision to be made was reliant on several other decisions, which were in turn reliant on the decision at hand. This made the design of the printer aggravating at times, and many decisions had to be made, then later iterated multiple times before the final form of the printer was established.

4.2 – Manufacturing and Assembly

The manufacturing and assembly of the 3D printer was quite extensive. With over 100 custom components which were created through a span of processes, the manufacturing was a very hands-on and time-consuming task. The forming methods included 3D printing, CNC milling, lathing, spot welding, plasma and waterjet cutting. Finishing methods included drilling, tapping, filing, and powder coating. Due to the required high tolerances on several components, the manufacturing of the 3D printer was a lengthy process. Shop drawings for many of the custom manufactured components can be found in Appendix D – Manufacturing Drawings. These drawings were invaluable tools in the shop, allowing the team to quickly verify dimensions. Please note that due to the high number of custom components required for the 3D printer, the Appendix does not contain an exhaustive list of shop drawings, instead only for the components which required special attention during manufacturing.

The frame members were all ordered 2mm long, and CNC cut down to size to ensure that they were perfectly square to one another. This was important as the linear rails must be perfectly parallel to one another for the carts to slide smoothly without binding.



Figure 47 - Team and Sponsor (Stephen McMillan) Using BCIT's Haas CNC Mill

Several components were designed and cut using BCIT's waterjet cutter. Components were all constructed from aluminum, and required material ranging from one-eighth up to half inch thicknesses. Extra considerations were given to components which required tapped holes, meaning that all holes on the waterjet were created as pilot holes which were later drilled with a drill press, and tapped by hand.

The milling processes were again completed with utmost care. Numerous components had to be milled to their final shape and thickness. The most critical of these was the kinematic coupling blocks, requiring a vice to be setup at a 45° angle while remaining perfectly parallel to the tool path (setup seen in Figure 48 below). The mill was also used for drilling critical components, using the digital readouts to precisely locate the holes before drilling.



Figure 48 - Using a Dial Indicator for Calibrating 45° Vice

3D printing of components was limited only to elements that accompany electrical components (i.e. limit switch holders, the display screen holder, etc.).

4.3 – Testing and Calibration

4.3.1 – Electronics Testing and Calibration

To effectively test the electronics, firstly, components were powered up individually before mounting to ensure none were defective directly from the distributor. Most of the following tests were simple power-up testing to check functionality before installation on the printer.

First, the power supply was tested and tuned to output exactly 24.0V using an on-board potentiometer. The power supply was hooked up to a wall source and its output was measured to its hot and common terminals to test voltage.

The Duet Ethernet and Paneldue boards were then tested for functionality together. They were powered using the on-board microUSB hub connected to a computer to check the powering ability of the controller and its ability to connect to the LCD. The LCD's touchscreen function was also checked. Next, the Duet's Ethernet port had to be networked to one of the team member's computers in order to obtain the online functionality offered by this high-end controller. The first step to this involved establishing a static IP address to the computer's Ethernet port – 192.168.1.100. With this established, the Duet's firmware was configured to a static IP address that did not match any others on the network – 192.168.1.101.

With these network IP addresses established, Ethernet connection could be reliably made between the computer and the controller for further testing and use. Configuration files then had to be generated for the controller. Using online configuration software, RepRap Firmware Configurator, printer component types and technical specifications could be entered to generate the required G-Code parameters for use with the prototype's specific setup. More in-depth details for these procedures can be found in Appendix F – 3D Printer User's Guide.

To finally test the entire electrical system after assembly, several steps had to be taken to ensure that no faulty components were missed. As mentioned in Section 3.5.5, the frame's earth grounding was tested using the continuity tester on a digital multimeter to check grounding of all components (including the bed and the electrical tray). Once this was confirmed and the wiring meticulously checked, the fuse for the power supply was plugged in and powered. With the power supply confirmed working, the controller was then powered using the 24V supply. Motors, limit switches, fans, heaters, and sensors (except the bed heater) were then checked using prewritten macros for motor and heater testing on the Duet Web Control interface. Finally, the bed heater circuit was checked and powered through the solid state relay, again using the heater testing macro on-board the controller's web interface.

The results of this testing were for the most part successful. The heaters heated quickly to expected temperatures as defined by the testing macros and the LCD display and web interface appeared to display accurate temperatures as read by the machine's thermistors. Final calibration of the thermistors was done using a FLIR C3 compact thermal camera to check the validity of the readings. These results were also corroborated using a Fluke handheld IR thermometer. The results of this calibration test are shown in the thermal images and test parameters in Figures 49 to 51, below.

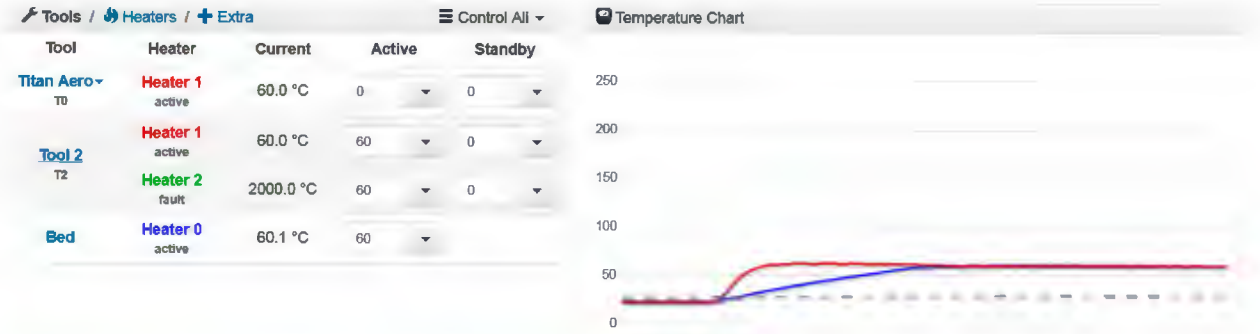


Figure 51 - Printer Heater Test Settings

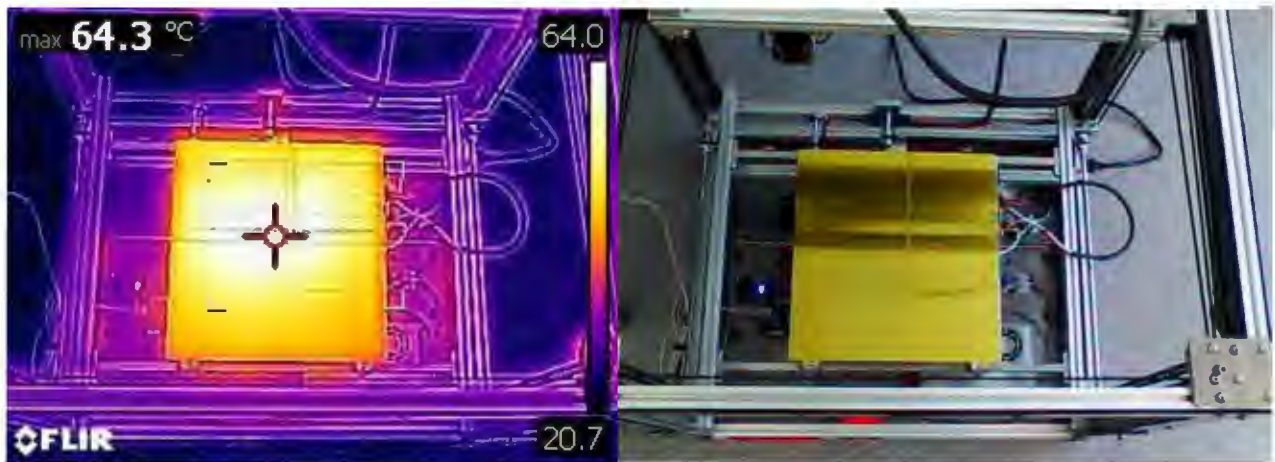


Figure 50 - Thermal Imaging Results of Bed Heater Testing

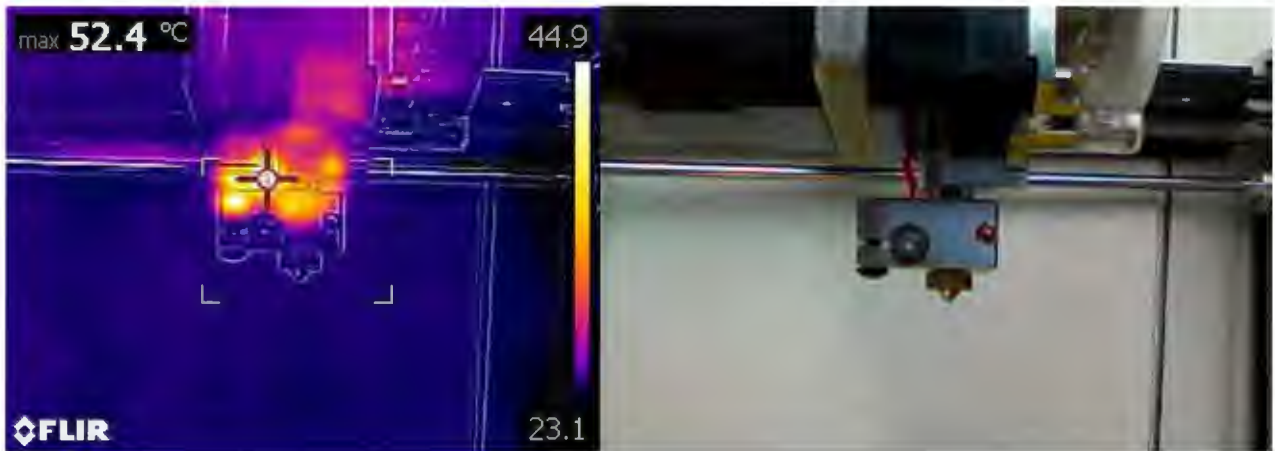


Figure 49 - Thermal Imaging Results of Hot End Heater Testing

The results of this testing confirm that the bed and extruder thermistors are functioning to approximately expected values. Although there is some error between the set temperatures, the computer read value, and the thermal images, the difference is not significant. Some sources of error include the reflectivity of the IR-measured surfaces which certainly affect the measured temperatures. Use of a blackbody surface for measuring would improve the measurement accuracy; however, none were on-hand at the time of testing. For the extruder head specifically,

there is a larger margin of error from the set temperature value; however, this test only measures the surface temperature of the hot end without its silicon insulation sleeve and temperatures at the nozzle may be differ from what was read. When configuring the thermistors, the R-values provided by the online configurator tool may differ from the actual measured values of the sensor. Further sensor calibration may be required, but these tests confirm the heaters and sensors function to approximately what is expected.

During motor testing, again using the macros, all stepper motors were found to be stalling at various points in the procedure. After some thorough investigation with the help of BCIT’s Jason Brett, it was found the testing macro was running the motors at speeds upwards of 833 mm/s. The XY motors’ linear velocity was found to be at maximum 590 mm/s and the Z motor’s found to be 5.90 mm/s. Calculations for these speeds are shown below using formulas provided through Duet’s online Wiki reference pages [9].

Belt – driven printer maximum belt speed calculation:

$$V_{max} = \frac{4 * \text{Pulley Teeth} * V_{supply}}{\frac{\text{Steps}}{\text{rev}} * \pi * L * I}$$

CoreXY – Motor Specifications:

Busheng 17HD40005-22B Motor Specification	Value
Steps per Revolution	$1.8 \frac{\text{deg}}{\text{step}} = 200 \frac{\text{Steps}}{\text{rev}}$
Supply Voltage	24V Supply
Rated Current (per phase)	$1.3 \frac{\text{A}}{\text{phase}}$
Resistance (per phase)	$1.6 \frac{\Omega}{\text{phase}}$
Winding Inductance	3.2mH
Drive Pulley Teeth	20T

Table 1 - Busheng 17HD40005-22B Motor Specifications

$$V_{xy \text{ belt,max}} = \frac{4 * 20T * 24V}{200 * \pi * 3.2e^{-3}H * 2.6A} \cong \mathbf{365 \text{ mm/s}}$$

Z – Motor Specifications:

StepperOnline 17HS15 100:1 Reduction Motor Specification	Value
Steps per Revolution	$0.018 \frac{deg}{step} = 20000 \frac{Steps}{rev}$
Supply Voltage	24V Supply
Rated Current (per phase)	$1.68 \frac{A}{phase}$
Resistance (per phase)	$1.6 \frac{\Omega}{phase}$
Winding Inductance	3.2mH
Drive Pulley Teeth	20T

Table 2 - StepperOnline 17HS15 100:1 Reduction Motor Specifications

$$V_{z\ belt,max} = \frac{4 * 20T * 24V}{200 * \pi * 3.2e^{-3}H * 3.32A} \cong 2.80\ mm/s$$

4.3.2 – Bed Levelling Calibration

Calibration was performed through the use of precise leveling tools and the positioning of the motors through slotted connections. A level used to check flatness was placed on the aluminum extrusions that raise the print bed. Throughout the process it was found that the level was not calibrated correctly. This was fixed through the use of tools available in the metrology lab, a master level was placed on a smooth surface where the current level being used was then calibrated to match it. Following level calibration, each extrusion was levelled through the rotation of individual pulleys, followed by tightening down the set screw to lock it in place. It was found that the levelling of each side was dependent on the other, therefore several iterations were required prior to achieving precise bed levelling. The kinematic coupling was employed to accommodate any micro-adjustments required.

As with typical printers on the market today, the printer bed final adjustments are performed by moving the print head to various areas on the build plate, and running a piece of paper between the printer nozzle and bed. The bed is raised or lowered until the paper can slide with just a small amount of friction between the bed and nozzle. Generally, four points near the outer corners of the print bed and a few towards the middle of the bed is a sufficient amount of areas to calibrate before printing. This method is a good rough height adjustment procedure which allows the first layer to press down onto the build plate and adhere properly, though final micro-adjustments can be made to perfectly calibrate the print bed.

4.3.3 – CoreXY Calibration

The first step of the CoreXY calibration was performed by hand placing the belts throughout the system with minimal tension to ensure that the belts ran level to the frame without any vertical deflection. Following this, the tension was increased on the belts by reducing the length of the belt and reinserting it in the belt clamping mounts once again. Once adequate tension was achieved throughout the system of one belt, both belts were removed and cut to the same length. Upon reinsertion of both properly tensioned belts, micro adjustments were made through the use of the slotted connection connecting the pulleys. Both motion control systems did not demonstrate any belt tooth disengagement throughout their operation.

4.3.4 – XYZ Limit Switch Location Calibration

Finally, the limit switches' locations must be accurately placed to calibrate the printer. These switches are at the low-end of the printer and thus must ensure that the print head can reach its outer limits of the bed to meet its print volume goals. These switches were calibrated by manually raising the bed and running the printer nozzle to its extremities; at this time, the bed's position with respect to the frame was also calibrated. With the positions set, micro-adjustments of the limit switches were made using features on their 3D printed mounting parts to precisely locate their homing positions.

4.3.5 – Printing Calibration

As of the submission of this report, final printing calibration has yet to be completed. Optimal settings will be discovered through a lengthy process spanning a huge number of prints, where settings are tweaked marginally after each print until perfection is achieved.

Chapter 5: Discussion of Results

5.1 – Design Results

Preliminary design results were focused around the overall shape and dimensions of the frame. Originally only 20X20 aluminum extrusion was decided to be used throughout the entire frame; however, a higher structural rigidity was of high priority. Following this, the type of motion systems to be used as well as their locations had to be decided. The team initially thought of using a couple lead screws to control the Z-axis motion. Upon further research it was found that minor backlash exists within the screw connection during the retention of the printing plate. It was also found that when multiple lead screws are used in conjunction there exists a possibility of binding. In a Cartesian-style printer, the Z-axis motion system controls the height of the print bed where proper leveling is crucial for achieving an accurate print.

Bed leveling was initially thought to be accomplished through the use of belt tensioning alone – which later proved to be ineffective. The team decided to employ a CoreXY system from the very beginning, though this was prior to designing the infrastructure to mount all the pulleys required for proper belt routing – which also included linear rail placement. Tool changing was initially conceived to be done using horizontally mounted dowel pins that slot into a part mounted on the print head; however, this method did not provide the required infrastructure for multiple print heads. The team decided that all the electronics will be placed at the base of the frame, underneath the print bed. Beyond this, electronics ease of access and wire routing was not yet considered.

Achieving the desired parameters resulted in the usage of 20X40 aluminum extrusions for all the structural members of the frame. This improved the overall rigidity of the frame and also offered a wider range of mounting points for auxiliary devices. The Z-motion was designed using a stepper motor with a gear reduction, coupled to a pulley-belt system used for accurately raising and lowering the bed. This provided greater tensioning ability as well as the elimination of any backlash or binding issues – granted proper calibration.

Bed leveling was accomplished through the use of a kinematic coupling where a spherical surface made contact with a machined v-block at three points. The height of the bed is adjustable through the use of an adjustable screw held in place with a nylon setscrew. The CoreXY system required the design of plates attaching to the sliding cart in order to mount the pulleys in the correct placement for the geometry of the motion system to function properly. The design of these plates then required the linear rails to be mounted vertically along the inside of the frame, rather than on the top surface. A large aluminum plate spanning the width of the frame was designed with vertically mounted dowel pins allowing for proper locating and mounting of multiple print heads. Following the design of the frame and both motion systems, the routing for the electrical system was then considered, where the majority of the wiring was ran behind the linear rails inside of the slotted extrusion. With the wiring out of sight, the possibility of damaged wires was greatly reduced. Finally, the electronics were mounted to a tray attached to telescoping rails, allowing for ease of access where any testing and modifications can be made.

5.2 – Prototype Manufacturing Results

Manufacturing became one of the largest learning areas for the team throughout the process for a number of reasons. First and foremost was learning (on in some cases re-learning) how to use machines appropriately. There are several intricacies involved in using mills, lathes, waterjet cutters, and more that the team had to overcome in the creation of the numerous high tolerance components. Chris Townsend was instrumental in this process, as his experience and patience allowed the team to get through the many tedious hours of setup and learning.

Some important lessons the team learned in the shop included:

- Using an edge finder to find the center of a cylindrical shaft;
- Using the digital readouts on the mills;
- Learning the process for CNC laser cutting and plasma cutting;
- Firefighting problems with the waterjet cutter;
- The importance of taking care during layout (i.e. locating holes to be drilled) to avoid unnecessary rework.

The second area where the team learned from manufacturing was that it's easy to design things, but difficult to design them well. What is meant by this is that the team often designed something with a press-fit bearing, or several locating features, or precise thicknesses which were not stock size. It is simple to create components such as these, but getting into the shop and attempting to locate properly, then remove material appropriately is a completely different case. Many hours of setup were required to make completely innocent looking holes. A great example of this would be the kinematic coupling steel V-blocks, which required a 45° slot down the center of a block to a precise depth, then needed a hole drilled and tapped directly in the center of that slot. Being that this was a prototype with many custom components, it was difficult to effectively review the design of all of them given the resource and time limitations throughout the project.

The mini design reviews held in the design phase of the project were able to identify many features which would be difficult to make. Design for manufacturing and assembly was one of the most important components of these design reviews; Stephen McMillan's wealth of knowledge helped to guide the team towards making components which met the functional requirements while still being manufacturable by the team.

During the assembly process, the team did their best to align the several components which required precise angles to properly function. These would be the printer head gantry which spans the width of the printer, and the build plate being parallel with the frame base. The use of several squares, levels, and other devices to properly align the components. The difficulty came with belt tensioning – if the belts had any amount of misalignment, or were tensioned more along one run compared to another, then the components would become torqued and misaligned. Several hours went into the alignment processes, and was definitely a major area of learning for the team.

5.3 – Final Prototype Results

Taking into account the results achieved through the design phase as well as the manufacturing phase, the final prototype successfully met the expectations laid out in the requirements. The final prototype was assembled using high quality parts manufactured and/or sourced by the team. The desired print volume, complete system integration, and budget was attained throughout the life of the project. Due to the final stages of calibration being performed as this project is being written, print resolution cannot be quantified with complete confidence; however, proper tension has been achieved by all belts coupled to motion systems, the systems are fixed using precise machined parts, and the motor control is responsive to the desired resolution.

With that being said, all the framework has been laid out in order to produce prints boasting a very fine resolution. Included in the final prototype are extra features to contribute to the functionality, safety, and aesthetic of the printer. Such features include aluminum powder coated gussets, an acrylic sheet used to cover the electronics, 3D printed removable adjustments knobs, and a removable electronics tray for maintenance.

5.4 – Setbacks

The largest setbacks encountered throughout the term of the project was the lack of knowledge by the team. All members were familiar with 3D printers at the onset of the project; however, none intimately knew the nitty gritty details of what was required to create a great printer. This lack of knowledge led to many design iterations, changes to system components, and tweaks during manufacturing resulting in many wasted design and shop hours.

Most setbacks were encountered during the manufacturing of the 3D printer. The team often designed components which were difficult to produce (mostly due to high tolerance levels). This required the team to spend numerous hours in the workshop calibrating and setting up machinery to make a single hole, before needing to completely re-tool and measure for the next.

Alignment also proved to be a major setback. Several subsystems and components need to be all perfectly square to one another for a quality print to be produced. These include the XY axes, and the Z axis. Creating the components and assembling them was difficult by itself, but when considering how to datum and square all the components up to one another the team found themselves taking apart and re-assembling many times before completion.

The biggest lesson learned from these tedious design and manufacturing iterations is the importance of understanding all of the design requirements for even the simplest parts. Many times, designs were finished, reviewed, and then manufactured before a feature was decided to be added. A good example of this is the many holes on the print head mounting plate which was installed and removed up to four times for adding new holes or features. Being that the 3D printer is a prototype, this is to be expected as the team develops new and better ideas; however, moving forwards, the team's review process must be updated to help capture these design iterations earlier into the design process.

Chapter 6: Conclusion

6.1 – Project Activity Summary

The project activity was typical to the workflow of an engineering design and prototype project. The team began by discussing the various motion system technologies available for controlling the print head and bed. This was followed by further researching the advantages and disadvantages of each system and which parameters were of utmost importance. Once the core elements were decided, the structural design of the printer was discussed and consisted of trying to optimize the placement for ease of assembly and serviceability. The most common of project activities included mini design reviews amongst the team members throughout each stage of the major design and manufacturing phases. Once each team member offered their input on the design, a decision was reached and changes were made accordingly.

Upon the completion of the design phase, it was decided that each team member will individually tackle the manufacturing process of their design with the remaining team members acting as support when necessary. With that being said, the team came together as a whole on numerous occasions to aid one another in the manufacturing process of their respective designs.

Completion of manufacturing was followed by the assembly of the printer. This phase was opposite of the manufacturing process – where the assembly was completed with the aid of each team member. Many times, a part would be freshly made and immediately installed to check fit and function on the machine. Here is where the previously mentioned late design iterations would come about.

Once the printer was fully assembled, extensive testing and calibration took place where each team member allocated their full attention to solving the challenge(s) at hand with respect to achieving the first high accuracy print.

All supplementary required documentation was completed by the team member with the most knowledge on the topic.

6.2 – Analysis of Project Success

Beyond printing, several successes can be noted about the 3D printer constructed by the team. First and foremost, the team has completely designed and manufactured a printer from scratch, a process which took roughly four months to design, and another four to manufacture and assemble. The amount of man hours involved in the design process were not logged, but many long nights, iterations, and complete restarts were completed before the final design was settled on. For manufacturing, hundreds of hours were spent in the shop across a wide range of machinery to accomplish this task.

The most important measure of project success lays in the performance of the 3D printer being able to print with a high degree of accuracy as well as demonstrate tool changing capabilities. With the final stages of calibration currently taking place, the positioning of the print head yields a high degree of accuracy and is capable of docking on to the inserted pins for tool locating. Further time is required to fine tune the print quality and achieve prints at the desired resolution.

Analyzing the project as a whole yields an abundance of other successes. The team successfully managed to perform a detailed engineering design process, apply theory from various subjects, employ a huge variety of manufacturing techniques, build a prototype directly representing the model, handle setbacks in a time efficient manner, demonstrate strong communication skills, and avoid any internal or external conflicts.

When viewing the project as a whole and taking the aforementioned factors into account, the project is considered to be an immense success.

6.3 – Future Work

The required 3D printer has been completed, though some features may be further developed and added to enhance the quality of the printer. The following section details the future work which may be done.

Part cooling fan

A part cooling fan could be implemented to help printing components which would benefit from being cooled rapidly after printing. These include items with large overhangs, and certain filaments. The fan would not be used for every print, but works well with materials such as PLA that benefit from rapid cooling after printing.

Auto-bed levelling

Automatic bed leveling could be applied to the printer to account for any imperfections in the bed level. Automatic bed leveling is a process where a capacitive sensor attached to the printer head detects the level of the bed, then adjusts the G-code of the print as required to match the planar angle of the bed.

Filament Sensor

A filament sensor can be implemented to monitor if the spool of filament has run out during a print. Essentially, it is an optical sensor which the filament runs through, and when it detects that no filament is passing through the sensor it shuts off. This process may save prints which would have otherwise failed, automatically pausing the operation, then allowing the print to be restarted when new filament is put in.

Calibration of settings for specific materials

The printer may be calibrated to find the optimal settings for many different materials, including commonly printed ones such as PLA, ABS, PETG, and many more. This would require running many printing operations, then evaluating the outcome and tweaking the settings as required in the slicing software.

Integration of tool changing

A tool changing system may be designed, or purchased once commercially available. The integration of this system would require some custom coding, detection of tool height, calibration of multiple heads at once, and more. This would be a good candidate for a new capstone project.

Printer enclosure

A printer enclosure could be added to fully close off the printer from outside air. Doing this would allow for temperature sensitive materials (i.e. ABS) which thermally contract heavily to be printed with ease. By enclosing the printer, the temperature inside the enclosure could be held at the appropriate temperature rather than that of the surrounding air.

Filament enclosure

A filament enclosure is important to maintain low water levels in the filament. If filament is old and has been sitting in humid air, it may absorb water from the air. As this filament is extruded, the water boils and expands, creating imperfections in the print by disrupting the smooth flow of filament to the print bed.

Electrical component enclosures

A rigid cover used to protect the Duet controller would prove useful for preventing metal or plastic debris from falling onto its sensitive electrical components, potentially resulting in a short. Currently, the printer uses an acrylic cover placed below the print bed to prevent falling debris from entering the electrical bay, but a dedicated controller cover would be more effective. Lastly, the cover could be designed in a fashion that funnels the air flow from the controller cooling fan across the motor drivers to promote a high degree of cooling.

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Appendices

Appendix A – Request for Proposal

Appendix B – Project Management Items

Appendix C – Design Review Package

Appendix D – Manufacturing Drawings

Appendix E – Electrical System Schematic Diagram

Appendix F – 3D Printer User’s Guide

Appendix A – Request for Proposal

Request for Proposal – Multi-Material 3D Printer Design

Executive Summary

Applicants should submit sealed proposals for the design and construction of a 3D printer with the ability to print multi-materials. This printer will have to be ready for demonstration at the BCIT Mech. Expo in May 2019, and will then transition to join the fleet of rapid prototyping machines at BCIT. The goal of the project is to create a device which will rival high end (\$10,000+) printers in terms of print quality and speed, and will including a tool changing capability to incorporate the ability to use multiple materials in a single print.

Calendar of Events

RFP release date:	October 16 th , 2018
Contract awarded:	October 30 th , 2018
BCIT Mech Expo:	May, 2019 (exact date TBD)
Project Close Date:	May 24 th , 2019

Introduction to Boundless Design Engineering (BDE)

BDE is a corporation committed to advancing the rapid prototyping and manufacturing field. Our extensive work with 3D printers has us at the forefront of mechanical innovation with new and exciting developments frequently hitting the market. Currently, we enjoy a leading market share in the 3D printing field, though are always looking for the next big break.

Project Background

There is a huge market for 3D printers ranging from different styles, qualities, and price ranges. The majority of the 3D printers available right now are restricted to printing a single material and have limited resolution. Very few high end 3D printers are available on the market, not to mention having tool changing capabilities; however, should they be available, it will be at an excessive price. Employing extensive research and an elaborate design process, a 3D printer capable of the aforementioned tasks can be built at a more reasonable price than what is available on the market.

Project Goals and Target Audience

Multi-material 3D printing may already exist; however, there are various issues associated with current methods. The development of a 3D printer with tool-changing has the potential for opening up manufacturing options exceeding current consumer marketed printer capabilities. Our ideal product will be marketed to those who use 3D printing beyond your average hobbyist. The ability to print easily with several materials opens up options for users to print components for specific applications, such as press-fit bearing surfaces or small high stress members. A successful printing device for our market needs will be accurate to 20 microns, including the ability to print across several materials using various printer head technologies.

Scope of Project / Deliverables

Minimum Requirement

A functioning 3D printer with tool changing capabilities with a 300x300x300mm print volume completed by the 2019 BCIT Mech Expo in May of 2019. With the final design, complete documentation of technical specifications, Bill of Materials, any required testing/calibration procedures, final estimated cost, and a basic user's manual are to be submitted along with the device. Complete printer functionality is expected for use at the BCIT Mech Expo.

Value Added Opportunities

- Water cooling of critical components (hot end and motors)
- Bowden remote drive system (instead of traditional direct drive system)
- High quality materials (i.e. aluminum) used exclusively over 3D printed components

Note: Emphasis should be placed on the quality of printing, rather than print speed.

Limits & Exclusions

It is not required that all components be designed. Use of existing products is acceptable, though must be included in the project budget with purchase prices and expected lead times.

Contact Person

It shall be the Proponent's responsibility to clarify any points in question with regards to this RFP. All inquiries should be directed to:

Liam Smyth – Engineering Manager *Tel:*

Email:

Proposal Requirements

Proposals must be submitted to Johan Fourie by October 23rd, 2018 at 8:30am. Late submittals will not be considered for the selection process. The proposal must include:

- Company profile
- Team Introduction and Background
- Technical Specifications
- Project Schedule Final budget

Evaluation & Selection Process

The selection process will be decided based on the previously stated proposal requirements. BDE reserves the right not to select the lowest bid for the project, but shall instead select the big which best serves the interests of the company. BDE reserves the right to reject any or all proposals received.

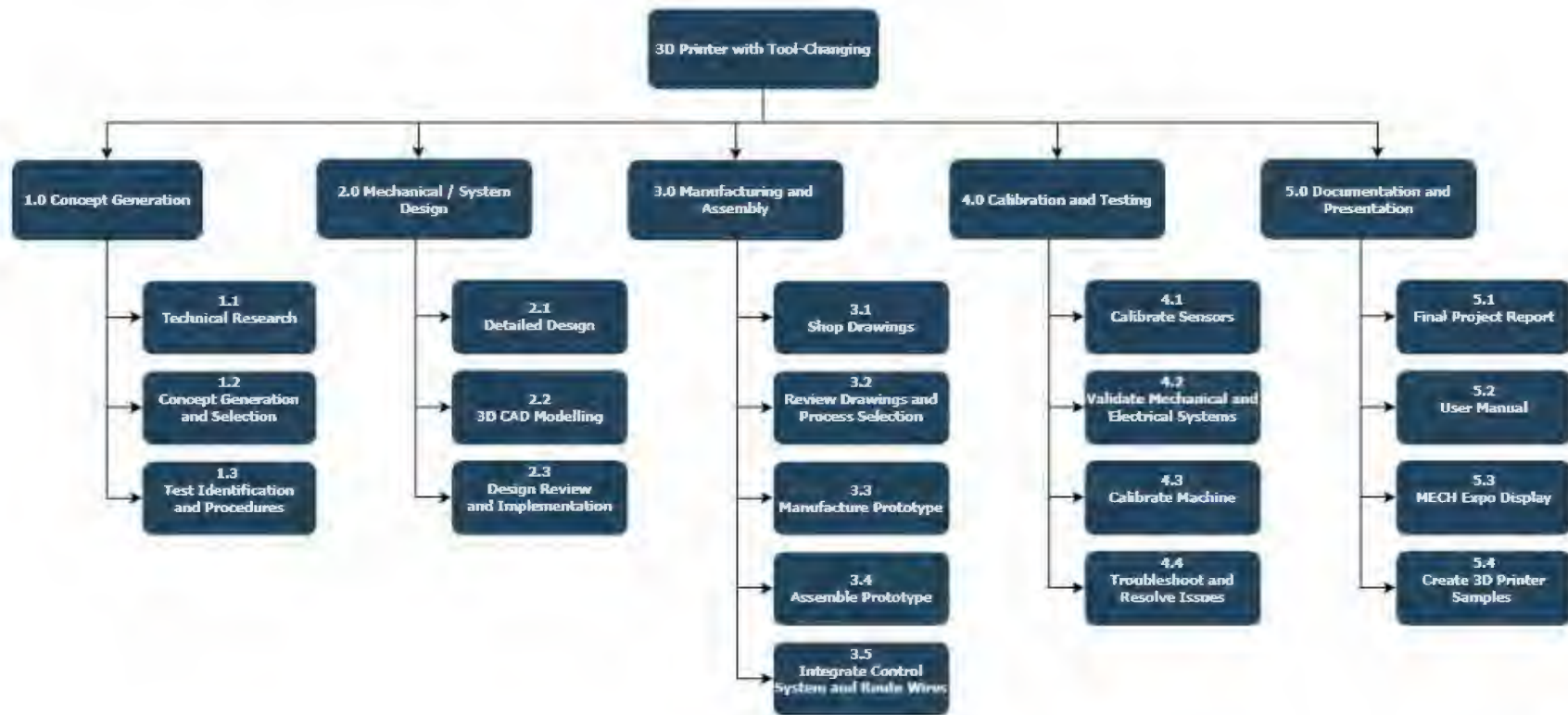
Legal documents

Company insurance will not be required as a part of this project; however, Boundless Design Engineering assumes no responsibility for any occurrences during the duration of the build.

Appendix B – Project Management Items

Work Breakdown Structure

3D Printer with Tool-Changing - Work Breakdown Structure



RACI Chart

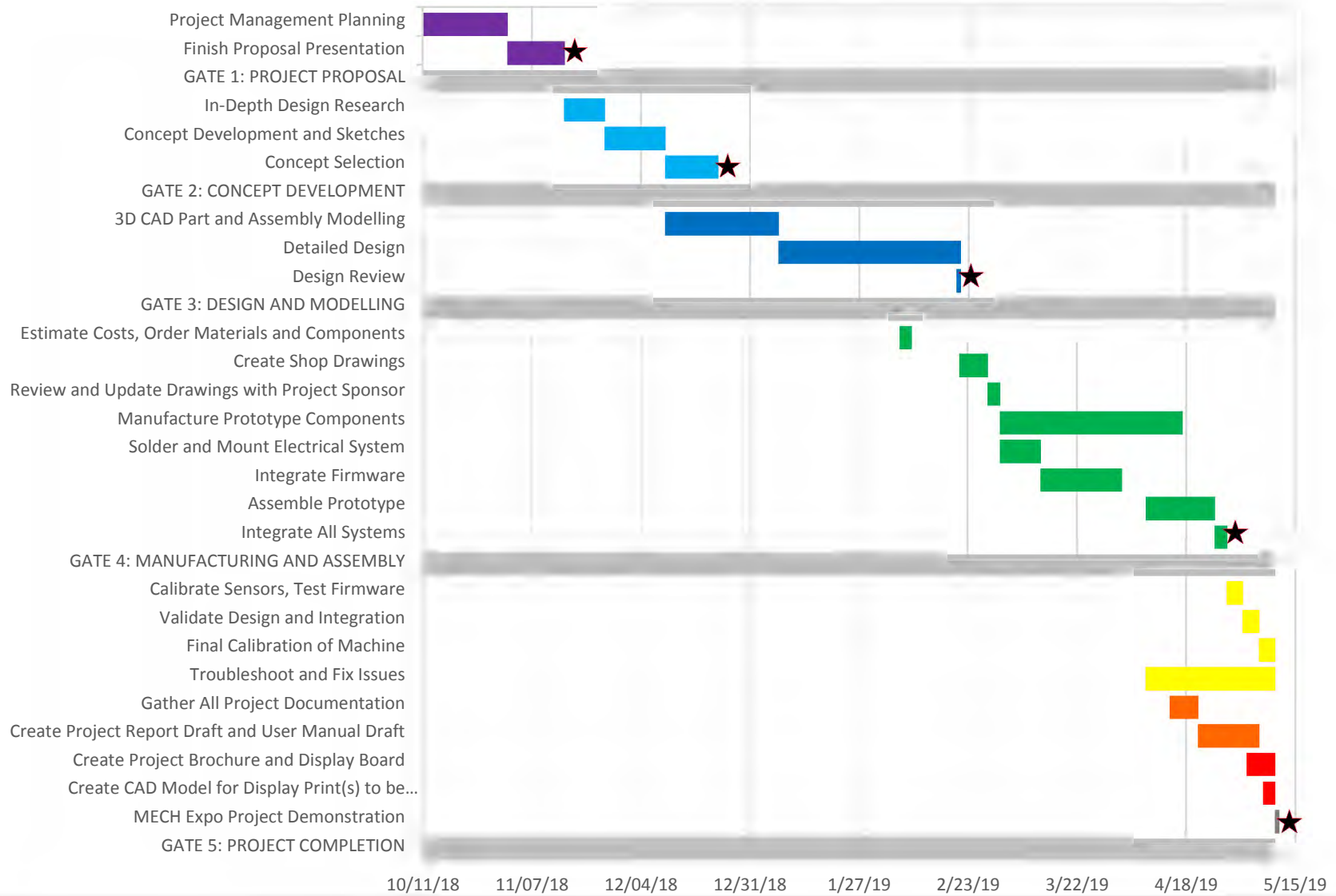
	Task	Liam	Devon	David	Project Sponsor
Research	Frame	A	C	C	I
	Control Systems	A	C	C	I
	Printer Carriage / Head	C	C	A	I
	Filament Drive System	C	C	A	I
	Motion System	C	A	C	I
	Tool Changing	C	A	C	I
Design	Frame	A	C	R	I
	Control Systems	A	I	I	I
	Printer Carriage / Head	C	C	A	R
	Filament Drive System	C	C	A	I
	Motion System	C	A	R	I
	Tool Changing	R	R	A	I
Manufacturing	Frame	A	R	R	R
	Control Systems	A	I	I	I
	Printer Carriage / Head	C	C	A	R
	Filament Drive System	C	C	A	I
	Motion System	C	A	R	I
	Tool Changing	R	R	A	I
Auxiliary	Writing Editor	R	R	A	I
	Communications	A	C	C	I
	Presentation Design	R	A	R	I
	User Manual	C	C	A	I
	Project Documentation	R	A	R	I
	Mech Expo Design	A	R	R	I

Project Milestone Schedule

Milestone	Date	Passing Criteria
Project Proposal	14/11/2018	Project Management Documents Proposal Presentation
Concept Development and Selection	22/12/2018	Final Selection of Concepts
Detailed Design and Modelling	20/02/2019	Completed Detailed Design Completed CAD Model
Manufacturing and Assembly	27/04/2019	Completion of Prototype Assembly ready for calibration and validation testing
Project Completion	10/05/2019	Functioning 3D Printer with Tool-Changing system MECH Expo Display Final Project Report & Presentation

Project Schedule (Gantt Chart)

3D Printer with Tool-Changing - Project Gantt Chart



Initial Prototype Budgeting

Prototype Expenses

Item	Quantity	Price/Unit	Total Price
Controller	1	\$ 191.38	\$ 191.38
LCD Display	1	\$ 87.72	\$ 87.72
Motors	3	\$ 40.00	\$ 120.00
Fasteners & Fixtures	N/A	N/A	\$ 112.60
Aluminum Frame Members	16.5	\$ 3.45	\$ 56.84
Print Head & Extruder	1	\$ 143.53	\$ 143.53
Belts & Pulleys	N/A	N/A	\$ 192.90
Print Bed & Cover	1	\$ 269.22	\$ 269.22
Sensors	3	\$ 2.00	\$ 6.00
Power Supply	1	\$ 51.00	\$ 51.00
Filament	2	\$ 15.45	\$ 30.90
Linear Rails & Carts	1	\$ 375.00	\$ 375.00
Miscellaneous Extras	1	\$ 20.00	\$ 20.00

CAD to USD 0.75

USD to CAD 1.33

Total \$ 1,657.09 USD

Total \$ 2,203.93 CAD

Final Prototype Expenses

Prototype Expenses

Item	Length (mm)	Quantity	Price/Unit	Total Price
Bearing Blocks	N/A	2	\$ 12.13	\$ 24.26
Heated Bed Pad	N/A	1	\$ 104.98	\$ 104.98
Printer Bed	N/A	1	\$ 60.00	\$ 60.00
Idler Shafts	N/A	4	\$ 2.50	\$ 10.00
Titan Aero	N/A	1	\$ 142.32	\$ 142.32
Nozzle X Volcano	N/A	1	\$ 32.95	\$ 32.95
Duet Ethernet	N/A	1	\$ 171.00	\$ 171.00
PanelDue	N/A	1	\$ 66.00	\$ 66.00
Square Al Tubing (1.5"x1.5"x0.120")	304	1	\$ 17.00	\$ 17.00
Aluminum Extrude Frame Members (20x20)	502	2	\$ 2.86	\$ 5.72
	642	3	\$ 3.65	\$ 10.95
	542	1	\$ 3.08	\$ 3.08
	600	4	\$ 3.42	\$ 13.68
Aluminum Extrude Frame Members (20x40)	582	4	\$ 5.42	\$ 21.68
	642	4	\$ 6.93	\$ 27.72
	637	4	\$ 7.74	\$ 30.96
GT2 Idler Pulley: 20T, 5mm Bore, 6mm Width, Bearing	N/A	6	\$ 4.46	\$ 26.78
GT2 Idler Pulley: 20T, Toothless, 5mm Bore, 6mm Width	N/A	2	\$ 4.46	\$ 8.93
GT2 Pulley: 20T, 5mm Bore, 6mm Width	N/A	4	\$ 2.96	\$ 11.85
GT2 Pulley: 36T, 5mm Bore, 6mm Width	N/A	2	\$ 4.46	\$ 8.93
GT2 Closed Belt Loop: 150mm, 6mm Width (150-2GT-6)	N/A	4	\$ 0.30	\$ 1.20
GT2 Pulley: 40T, 8mm, 6mm width	N/A	10	\$ 4.46	\$ 44.63
GT2 Pulley: Double 20T, 8mm, 6mm width	N/A	1	\$ 5.21	\$ 5.21
Nema 17 Stepper Motor, 100:1 Planetary Reduction	N/A	1	\$ 52.01	\$ 52.01
Flanged Ball Bearing (CoreXY DT)	N/A	4	\$ 6.79	\$ 27.16
SFJ5-75 - 5mm Precision Shafting, L - 75mm	N/A	2	\$ 4.12	\$ 8.24
Threaded Steel Balls, m4 - Kinematic Coupling	N/A	3	\$ 5.47	\$ 16.41
D1225-10 SolidState Relay	N/A	1	\$ 47.65	\$ 47.65
GT2 Belt (XY, Z-axis vertical)	9200	1	\$ 12.00	\$ 12.00
GT2 Belt (Z-axis Loops, to be joined)	2000	1	\$ 6.00	\$ 6.00
24VDC Power Supply - WEHO S-400-24	N/A	1	\$ 25.74	\$ 25.74
XY Linear Rails	400	3	\$ 28.00	\$ 84.00
Xy Linear Guides	N/A	3	\$ 47.00	\$ 141.00
Zaxis Linear Rails	535	2	\$ 47.00	\$ 94.00
Zaxis Linear Guides	N/A	2	\$ 47.00	\$ 94.00
Thermal Cutoff (184degC)	N/A	3	\$ 1.26	\$ 3.78
15A Glass Fuses	N/A	5	\$ 0.33	\$ 1.65
10A Glass Fuses	N/A	5	\$ 0.38	\$ 1.91
1/4"x1-1/4" Fuse Holders	N/A	3	\$ 1.27	\$ 3.80
Controller Cooling Fan	N/A	1	\$ 9.59	\$ 9.59
Shaft Coupling - 8mm to 8mm (pn 625234)	N/A	1	\$ 4.99	\$ 4.99
Steel Drawer Slides, 12" Travel	N/A	2	\$ 16.15	\$ 32.30
Switches for bed power, power supply power	N/A	2	\$ 5.63	\$ 11.26
Various Fasteners	N/A	1	\$ 150.00	\$ 150.00
Various Electronics Components	N/A	1	\$ 65.25	\$ 65.25
Roll of PLA for Testing and Printing	N/A	1	\$ 18.75	\$ 18.75

CAD to USD 0.75

Total \$ 1,737.05 USD

USD to CAD 1.33

Total \$ 2,310.27 CAD

Appendix C – Design Review Package

Note: Figure numbers in following Design Review document have changed from original document submission and may not reflect the figure numbers from this final report.

Design Review Package

3D Printer Design & Prototype

Prepared by:

David-Alexander Dabic
Liam Smyth
Devon Whitter

Prepared for:

Stephen McMillan, M.Eng., P.Eng
Johan Fourie, Ph.D., P.Eng

Design Review Date: February 20th, 2019

Project Number: 1819-10



Executive Summary

D2L Engineering will be hosting a **critical design review** on February 20th, 2019. The 3D printer with tool-changing capability being developed by our team of engineers is just about to enter its manufacturing stage with detailed design having just been completed. The following material in this document is provided in advance to participants so they may familiarize themselves with the project, review the various design elements, and develop any feedback that would be helpful in this stage of the project's development.

The 3D printer has been separated into subsystems critical to the design: the frame, CoreXY motion system, Z-axis motion system, and the electrical system. Each of these individual systems interact together in different manners requiring a holistic design approach throughout this project. Considerations for each individual subsystem, as well as the machine as whole are important, and the reviewers should bear this in mind.

As of the release date of this package, the project is currently on schedule and within budget.

Project Introduction and Background

The objective of the project is the design and prototype of a 3D printer. The original goal of the design was to create a printer capable of tool-changing between multiple printer heads during operation, allowing the creation of components made from multiple colours, or multiple materials. The design was to be based around a part created by *E3D*, a major 3D printer part manufacturer and supplier; however, their tool-changing mechanism (which can be found at the link below) has yet to make it out of beta testing.

E3D tool changing device: <https://e3d-online.com/blog/tag/tool-changer/>

As the weeks continued with the part still unavailable, the team had to settle on creating a printer which has the capability to host such a tool-changing system, without actually having one itself.

Base Constraints

- Minimum of 300x300x300mm print volume
- Printing accuracy between 0.25mm to 0.50mm
- High quality materials used (minimal/no 3D printed parts in the final assembly)
- Linear rails to be used instead of cylindrical rod
- Belt drive Z-axis (no lead screws)
- Core XY motion system with an ascending/descending print bed
- Fully functional printer delivered by May 10th for the BCIT Mech Expo

Frame

The main considerations when developing the frame was that it must maintain its shape and resist significant vibration throughout the motion of the XY-carriage, regardless of the printer carriage's accelerations.

For strength and stiffness, frame members will be made of 20x40mm aluminum extrusion for the upper and lower frame segments and the vertical members which join them. 20x20mm aluminum extrusion will be used to separate the printing bay and the electrical bay on the lower half of the frame. All members will be milled to length on the BCIT machine shop CNC machine in order to guarantee a high accuracy during assembly.

The frame will be joined with fasteners attaching the tapped ends of the extrusions, whose heads will be retained by the T-slots. These fasteners will be accessed by tool clearance holes in the adjacent frame members. In addition to the fasteners will be gusset skirts made of 6.35mm thick acrylic sheet, adding lateral stiffness to the frame while also providing a means of squaring all vertical members to their attached members during assembly.

The upper and lower frame portions were designed with full length members in the Y-axis, and separating members in the X-axis. This allows the frame members in the Y-axis (which support the CoreXY system linear rails) to maintain a high degree of parallelism with respect to one another.

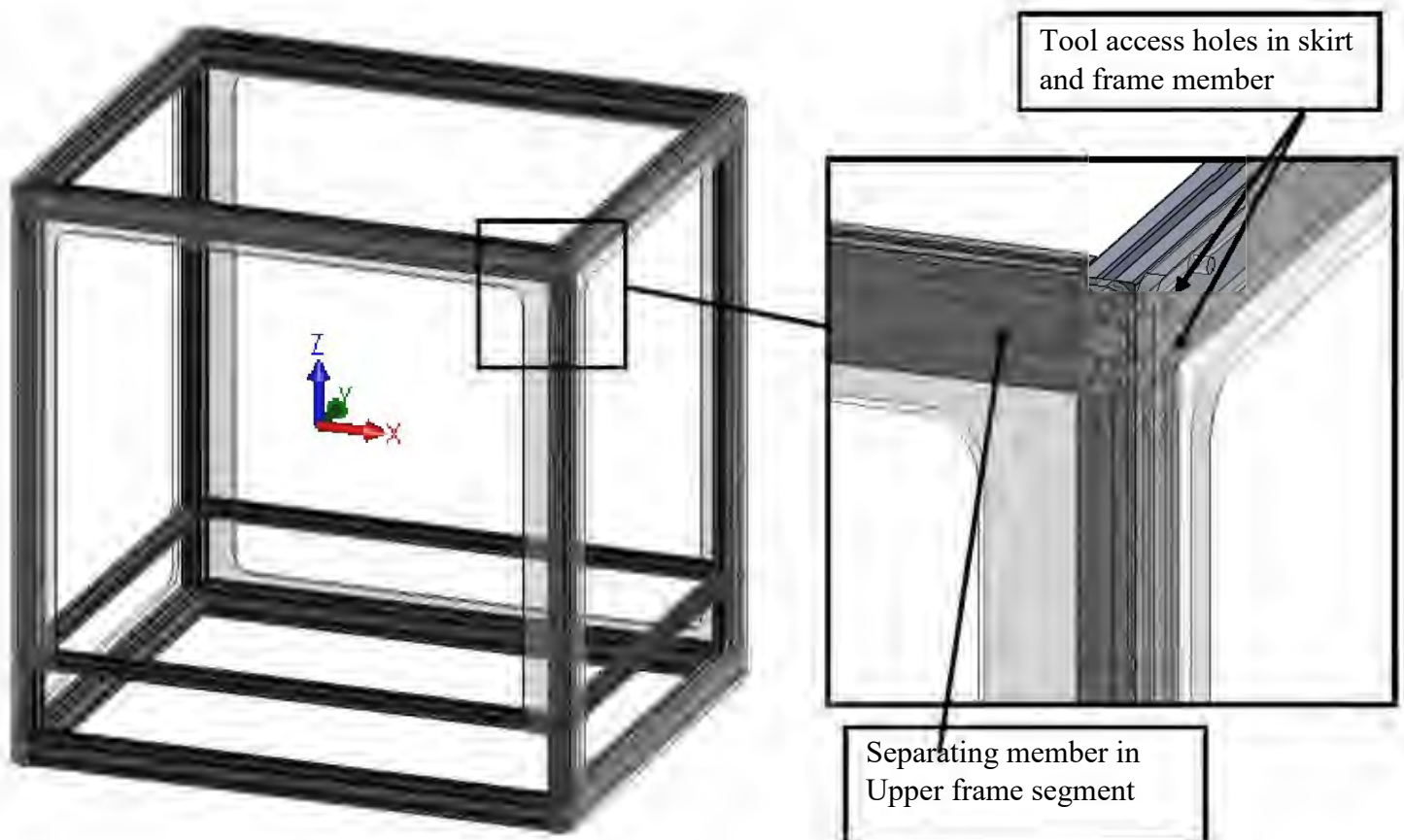


Figure 52 - Printer Frame

XY-Axes Motion

Motion System

A CoreXY drive system was used to locate the print head in the printer design. Figure 53 below shows the belt routing for a CoreXY system. When both motors rotate clockwise the print head moves in the positive x-direction, when the left motor rotates counter-clockwise and the right motor rotates clockwise the print head moves in the positive y-direction; where the opposite for both scenarios is true when the motor directions are reversed. A CoreXY system was chosen over other designs (H-bot, Prusa, etc.) due to the stepper motors being fixed to the frame and not moving with the gantry – resulting in far less vibration as the gantry accelerates. Furthermore, with a lighter carriage, the print head can move more efficiently and print at higher speeds. Finally, the longer belts used to accomplish the CoreXY orientation eliminate the net torque imbalance about the carriage's center of mass present in the H-bot design.

A substantial amount of time will be required to accurately tension and position the belts, as this is the most crucial step in ensuring that the CoreXY system functions as expected.

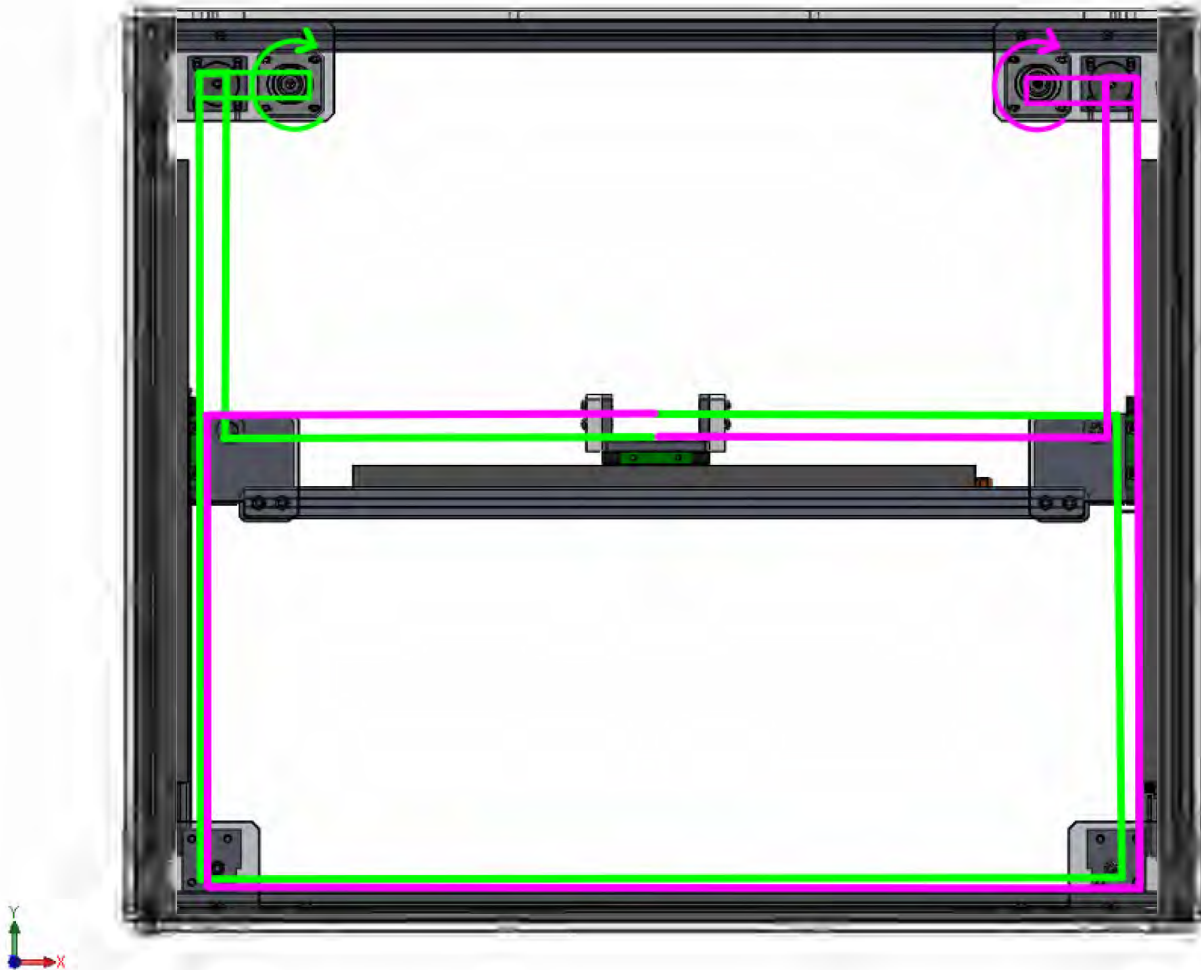


Figure 53 - CoreXY system layout

Drive System

The NEMA 17 stepper motor used has a resolution of $1.8^\circ/\text{step}$, and when combined with a 20 tooth to 36 tooth gear ratio, it allows the system to achieve a resolution of $1^\circ/\text{step}$. Elliptical slots have been placed in the mounting plate (seen in Figure 3) to allow for proper alignment and belt tensioning throughout the assembly process. The mounting plate(s) will be waterjet from $\frac{1}{4}$ " aluminum. As can be seen Figure 2 (previous), an idler pulley system is positioned in the opposite corners of the motors with a similar mounting plate design.

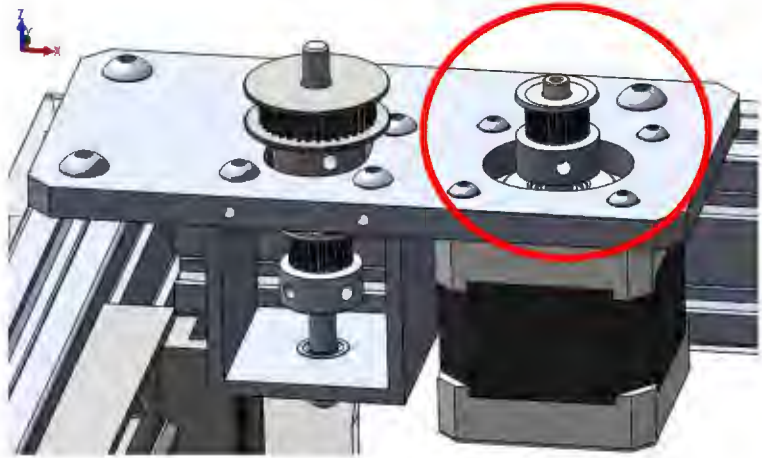


Figure 54 - Drive System

Carriage Mounting

Figure 4 illustrates the design that will allow for mounting from the linear rail carts to the cross member that locates and positions the print head. The two plates and the spacer will once again be waterjet from $\frac{1}{4}$ " aluminum. This design involves having to drill and tap into the top and bottom faces of the cart to allow for mounting. Since we are using a CoreXY system, only one toothed pulley will be required as the flat face of the belt will be making contact with the toothless pulley beside it.

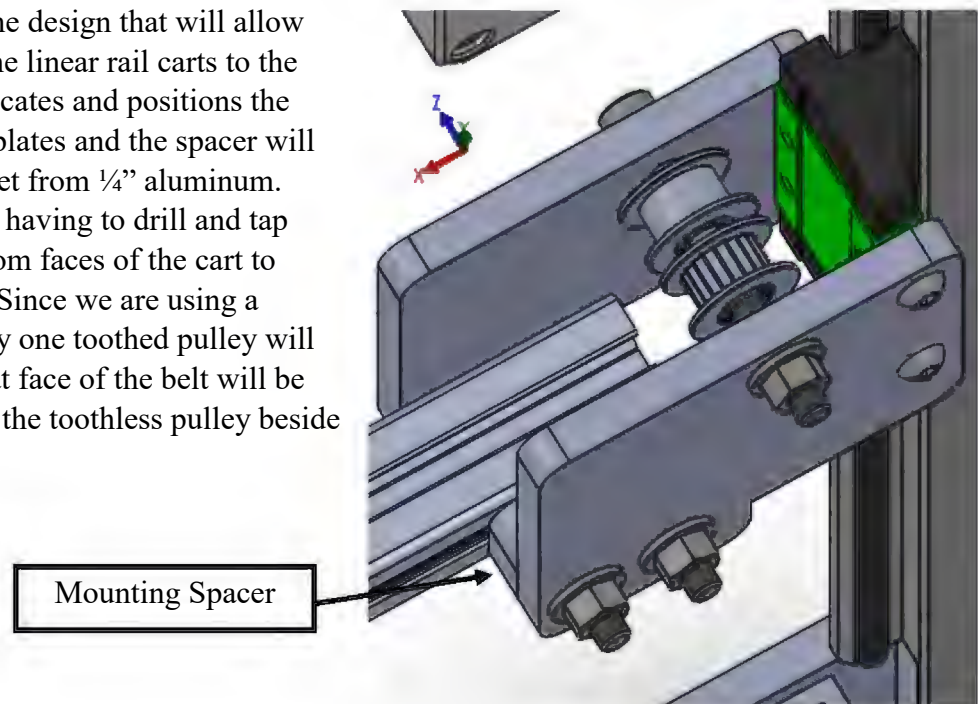


Figure 55 - Carriage Mounting Design

Print Carriage

The print carriage design involves connecting a waterjet cut aluminum plate to the cart of the linear rail. This plate will act as the mounting device for the print head – where the plate will be sandwiched between the stepper motor and the extruder drive system via a four bolt pattern. Two extra pieces will be mounted to the side of the plate to allow for docking and locating with dowel pins affixed to a plate on the printer frame. These pieces will be 3D printed and mounted to the plate using M3 fasteners.

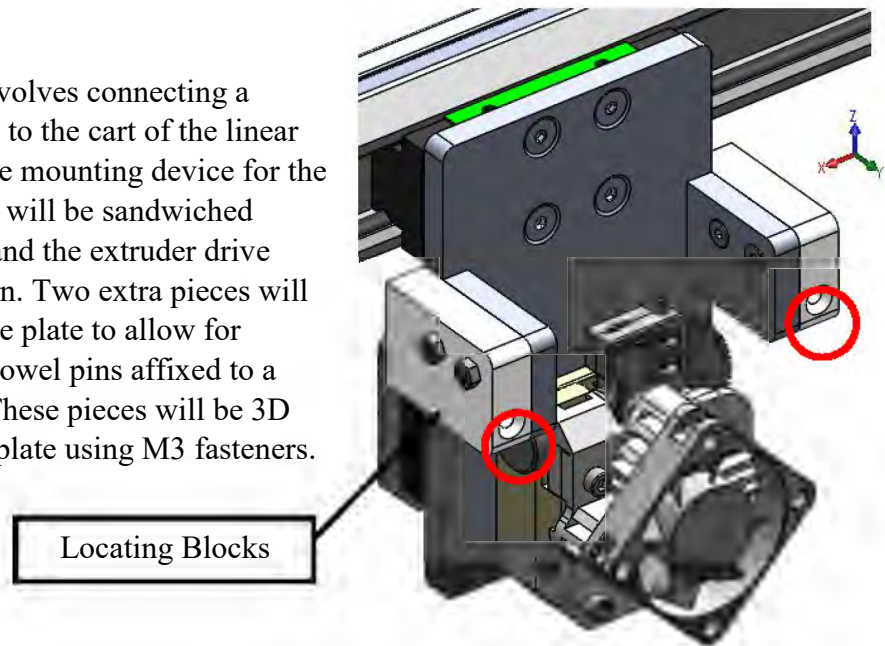


Figure 56 - Print Carriage

The belt clamps will be 3D printed and clamped over top the existing hardware. Only one clamp is shown for clarity; however, the assembly will require the stacking of two clamps where one belt is installed and tensioned prior to the addition of the second belt clamp.

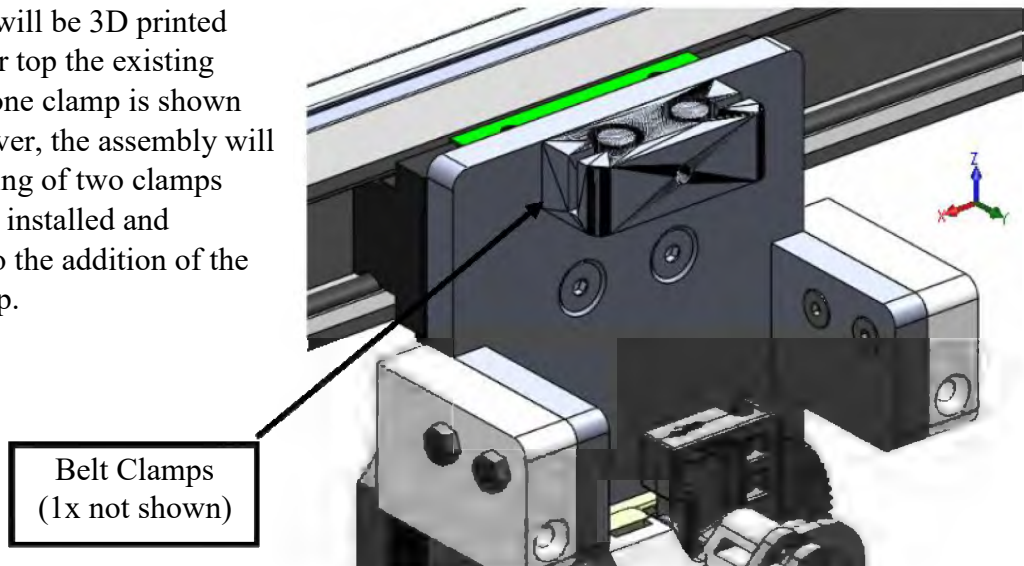


Figure 57 - Belt Clamps

Z-Axis Motion

Motion Guidance

As mentioned in the project constraints section, the Z-axis of motion is to use linear rails (as opposed to cylindrical rod) for the motion guidance. The linear rails are a superior method of motion guidance, using a cart with roller bearings instead of a plastic bushing found in the cylindrical rod method. Additionally, the linear rail system removes a rotational degree of freedom which is still present in the cylindrical rods.

Power Transmission

For power transmission, a belt driven Z-axis was chosen as opposed to the more traditional lead or ball screw setup. The major downfalls of this system are belt stretching, belt tensioning and no self-locking mechanism for the print bed. The belt stretching issue has been tackled by using four belts to lift the bed instead of two, cutting the load on the belts in half. Belt tensioning has been accomplished both at the motor mount itself (seen and explained in Figure 7 below), and on the vertical frame rails. Self-locking has been accomplished using a 200:1 gearing ratio on the motor, giving it 7800 N-cm of holding torque, capable of supporting the printer bed and largescale prints.

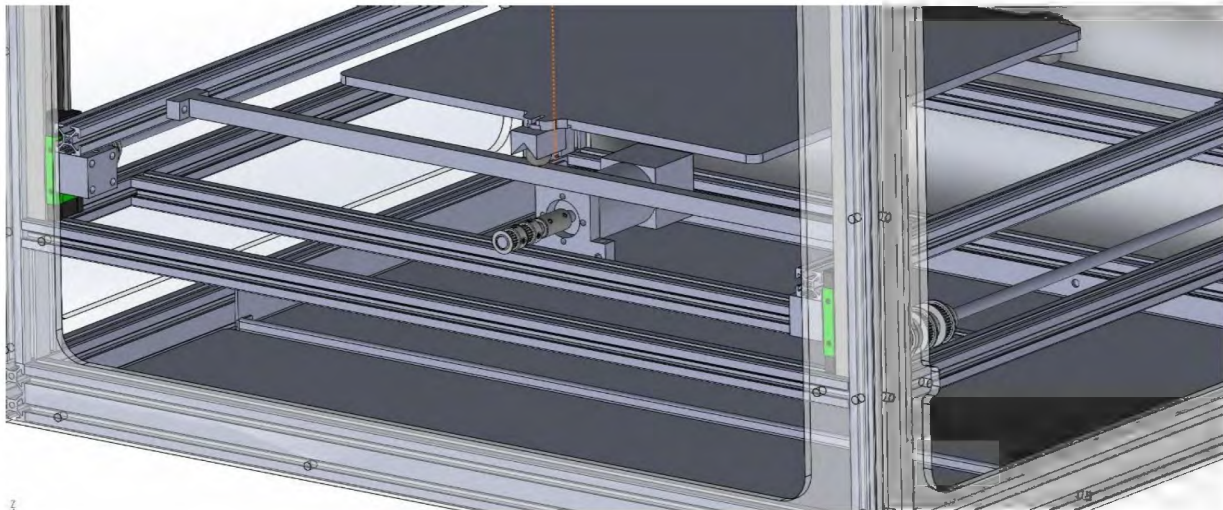
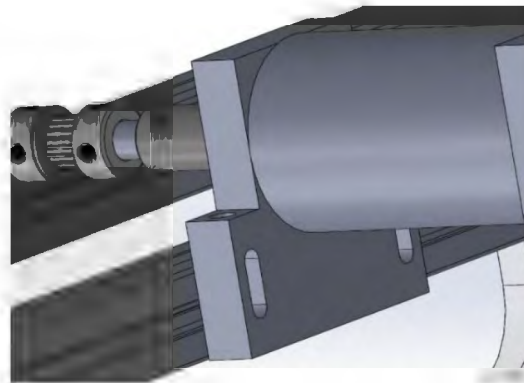


Figure 7 (above) shows the 3D printer and motor mount setup from the back.

Figure 8 (right) shows the motor mount as seen from the reverse view of Figure 7. The mount can move vertically by using two screws (highlighted by the red circle) in the top of the motor mount plate which push on the bolts connecting the motor mount to the T-nuts in the T-slot.



Kinematic Coupling and Bed Leveling

The bed rides on a kinematic coupling system, allowing thermal expansion in all directions without warping in the plate. This system is accomplished by having three 'V' shaped blocks, each sitting on a ball, separated by 120° of rotation. Creation of the coupling in this manner also gives a built-in leveling mechanism, as each of the balls can be lifted/lowered individually using an M4 screw through the support material into the base of the ball.

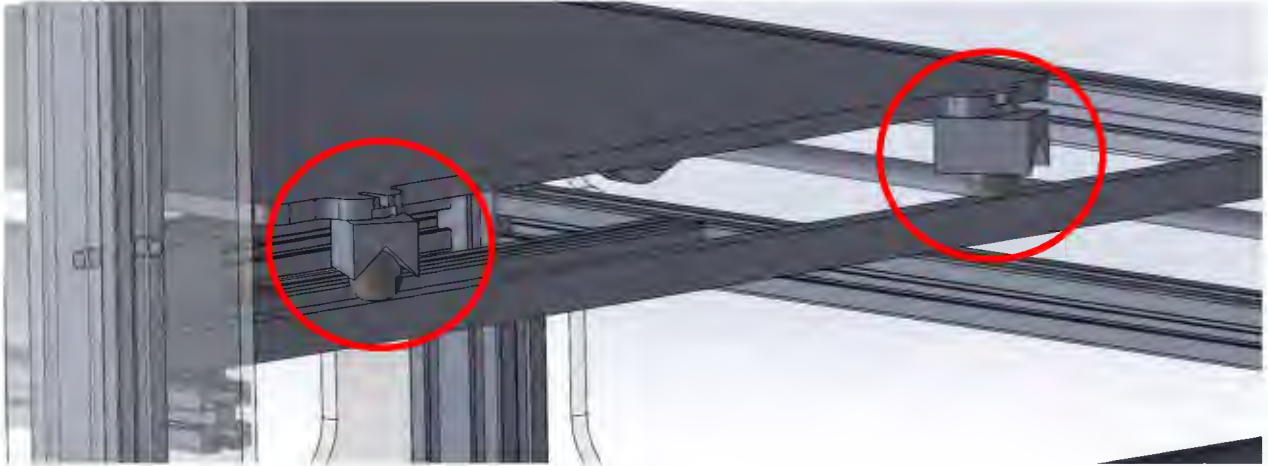


Figure 9 (above) shows a high level view of how the coupling are offset from one another, and ride on the support members running laterally across the printer.

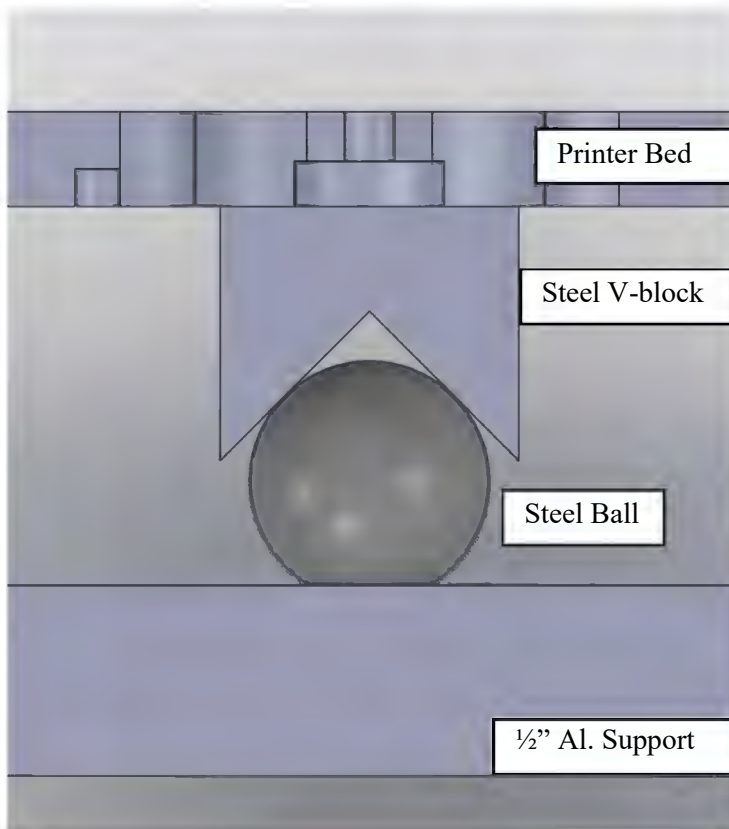


Figure 10 (left) shows a zoomed in view of the couplings, which are permanently fixed to the print bed via an M5 screw through the top of the blocks. The V-blocks are designed to fit into pre-cut grooves on the plate.

Electrical

The electrical system for the 3D printer is extensive, including many elements used for control, motion, and sensing. A Duet Ethernet 3D printer controller was selected, which offers hardware that is capable of controlling most of these elements. Firmware can be downloaded and configured using Marlin open-source firmware for setting up the controller's individual elements such as thermistors, cooling fans, motors, and heaters.

The circuit design was accomplished by adding standard 3D printer elements as seen in many consumer 3D printers with some modifications to their setup to optimize the design. This can be seen in the schematic diagram in Figure 11, below. First, a 400W-24VDC power supply will power the controller board to allow additional extruder heads to be added on the machine, the high wattage power supply giving the machine versatility for adding three or more extruder heads without concern. Next, a 720W-120VAC bed heater was selected to allow for rapid start-up heating times, estimated to be less than two minutes after powering. A Crydom D1225-10 solid-state relay was selected for controlling the AC input to the bed heater, controlled by the 5 VDC supply on the controller board. Circuit protection elements such as fuses, switches, and a thermal cut-off were also added. The thermal cut-off implemented is of importance to prevent catastrophic failure from the solid-state relay which, if it were to fail, fails shorted causing the heater to rapidly heat out of control.

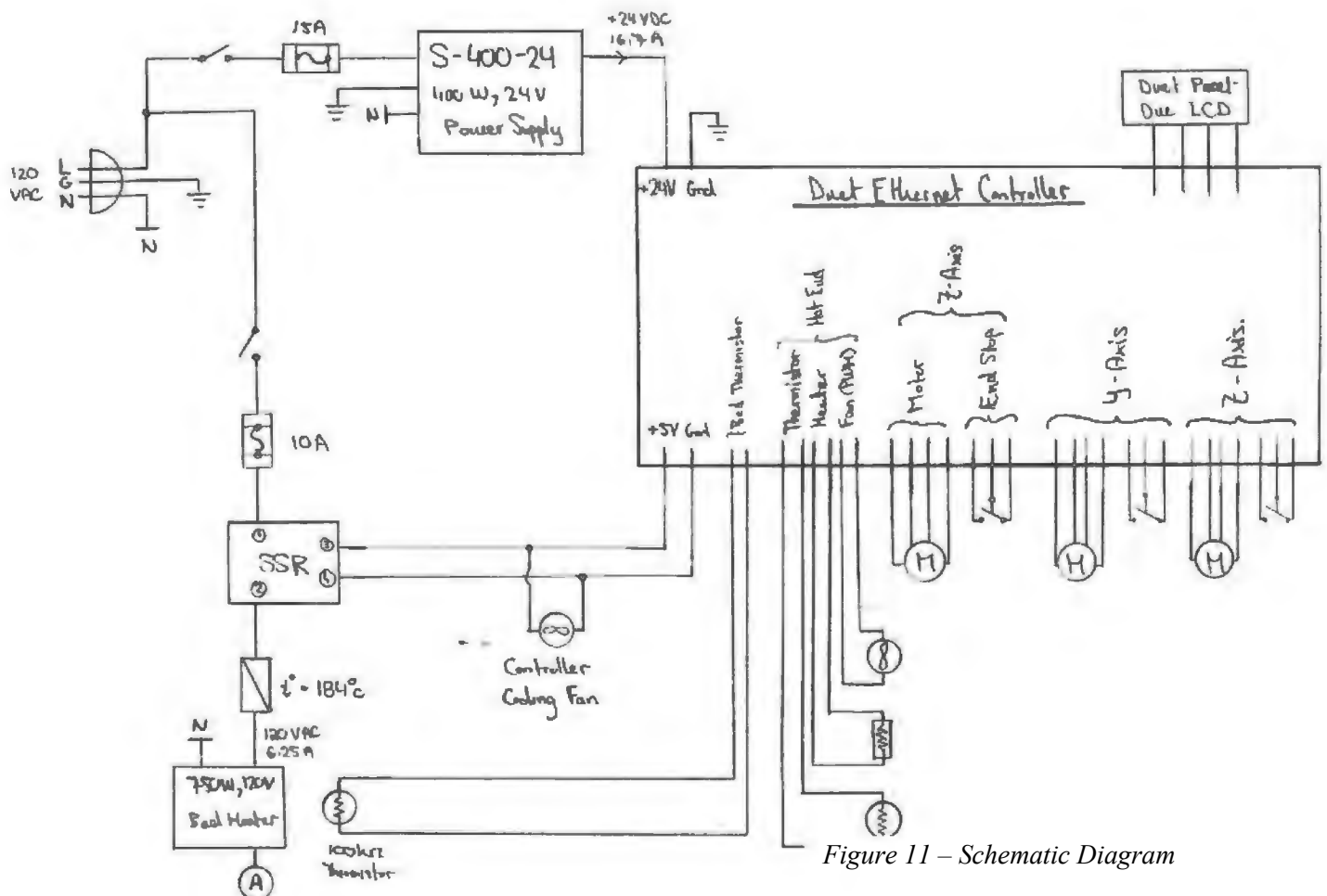


Figure 11 – Schematic Diagram

Project Summary

Schedule Status

As shown on the Gantt chart below, the project remains on schedule. Buffer times intended to account for variability in design, procurement, and manufacturing time will help the team reach individual milestones. The most recent design and modelling milestone was reached February 15th upon which detailed design of the 3D printer was completed, and the creation of shop drawings began. The team is confident in their progress to date, and they they'll meet the May 10th deadline.

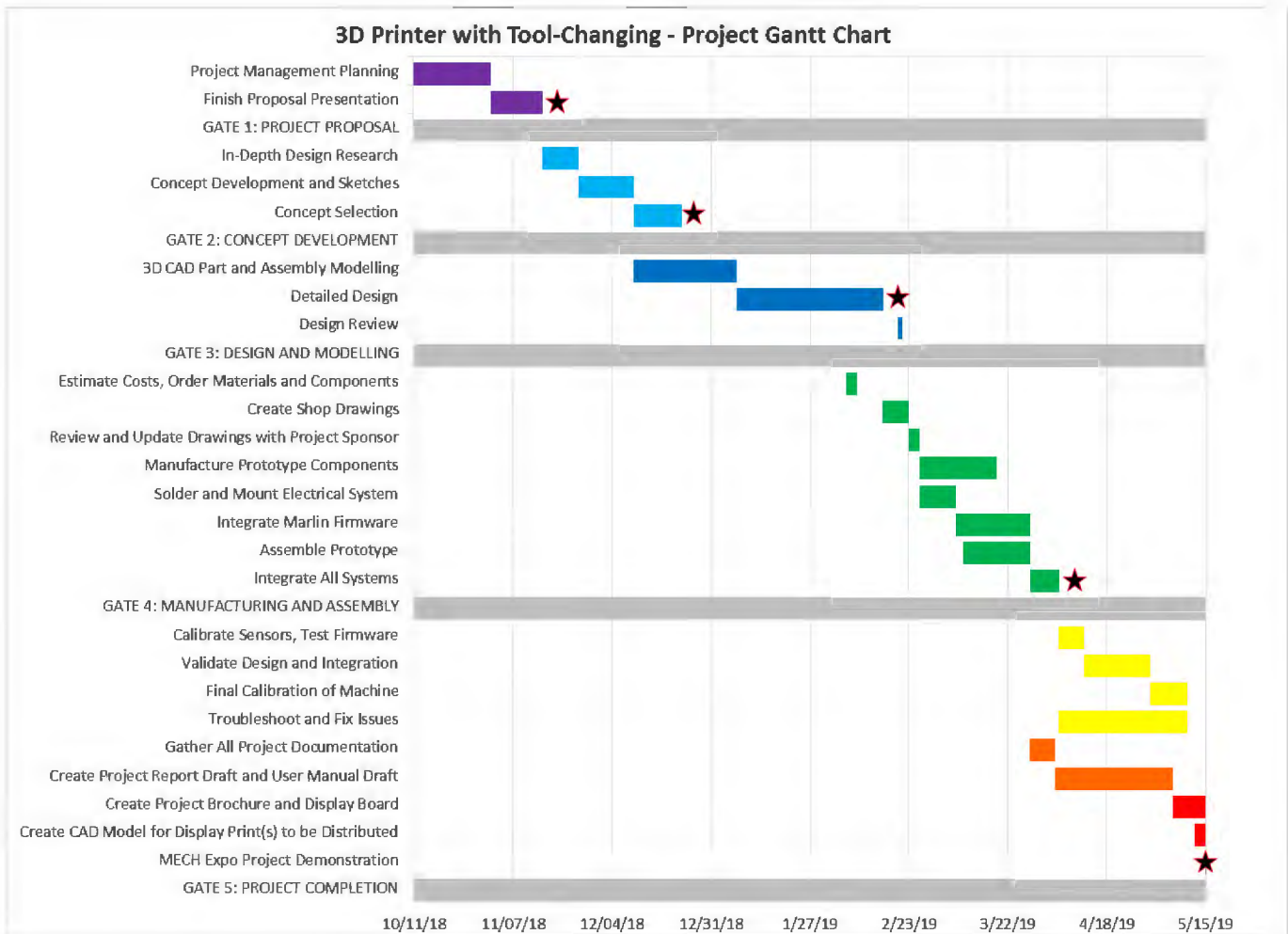
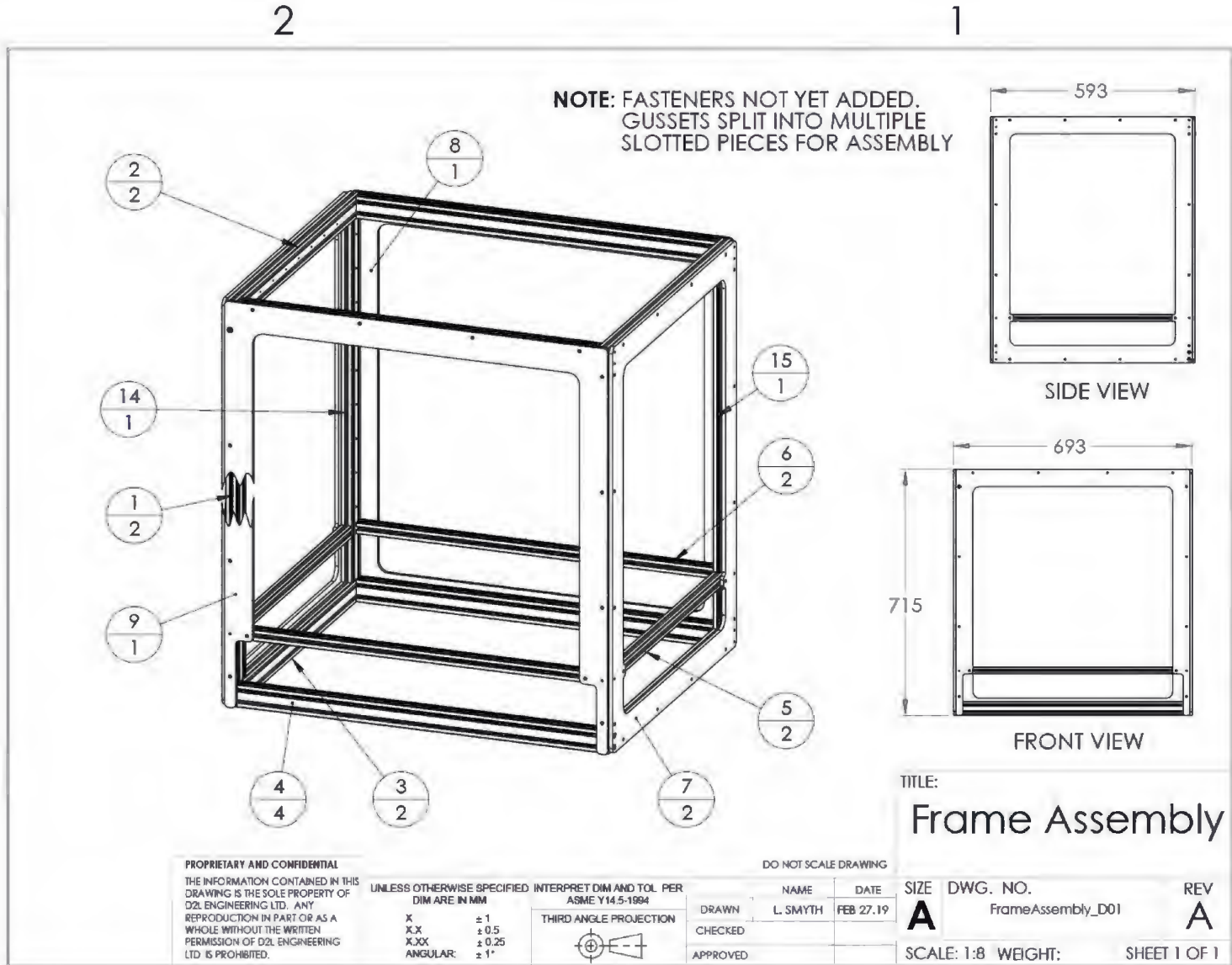


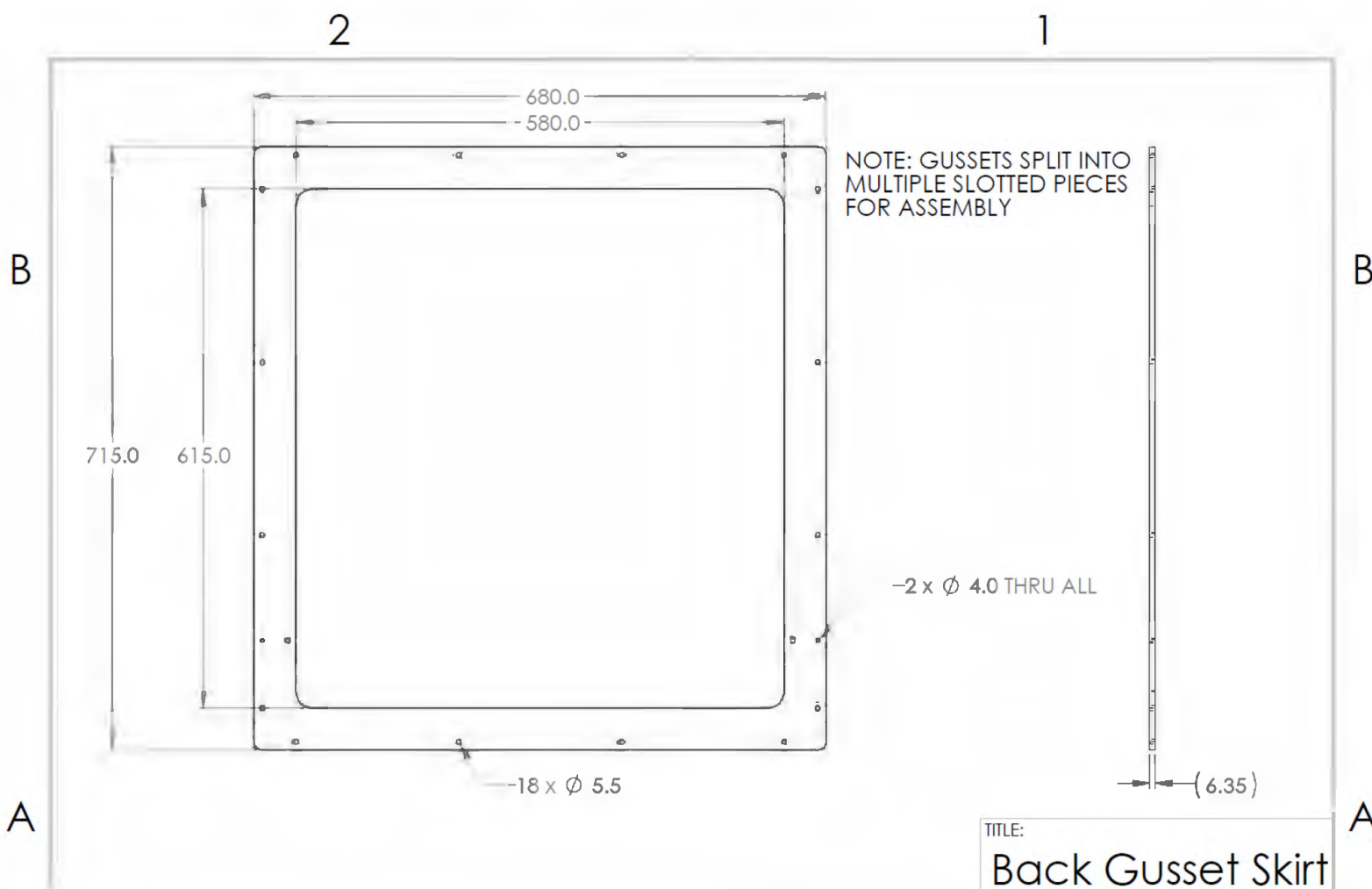
Figure 12 – Gantt Chart

Budget Status

The project's initially estimated budget of \$2170.00 CAD is still on target after the majority of the prototype's components were ordered at the beginning of February. Approximately \$1960.49 CAD has been spent on parts to date, allowing buffer for the purchase of any unforeseen parts or broken components as found during assembly and testing.

Appendix D – Manufacturing Drawings





NOTE: GUSSETS SPLIT INTO MULTIPLE SLOTTED PIECES FOR ASSEMBLY

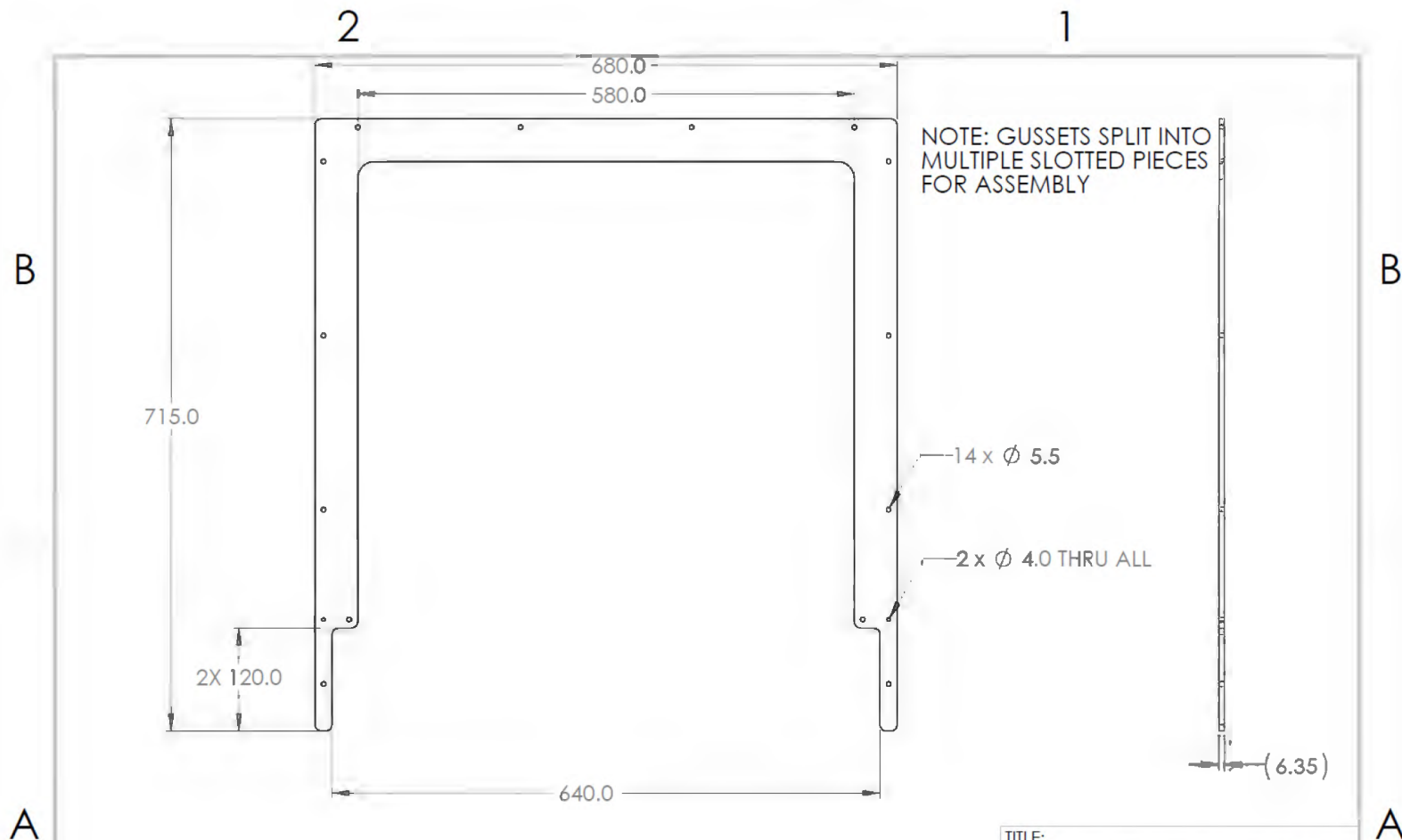
-2 x Ø 4.0 THRU ALL

-18 x Ø 5.5

(6.35)

TITLE:
Back Gusset Skirt

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	DO NOT SCALE DRAWING								



NOTE: GUSSETS SPLIT INTO MULTIPLE SLOTTED PIECES FOR ASSEMBLY

14 x Ø 5.5

2 x Ø 4.0 THRU ALL

(6.35)

715.0

680.0

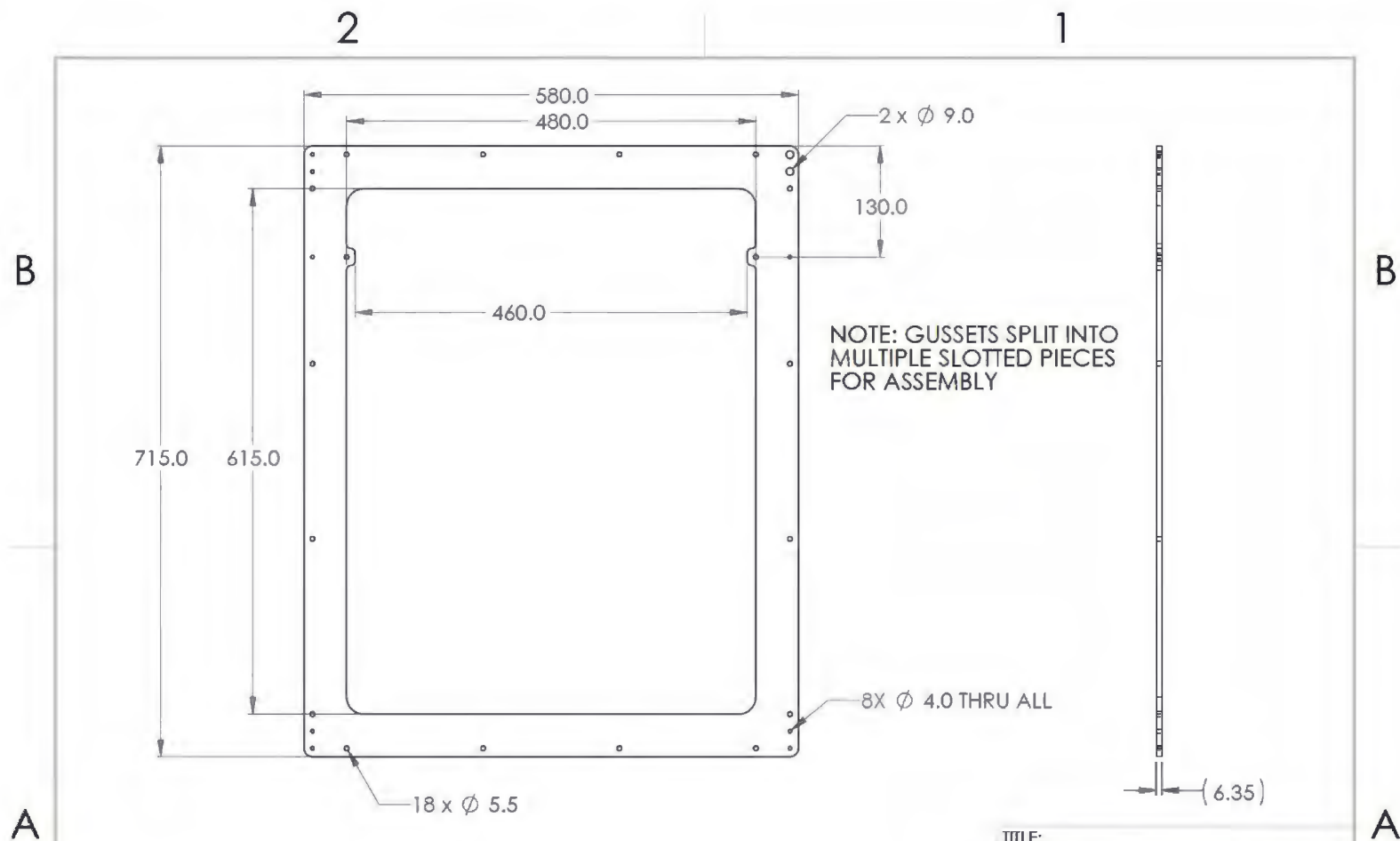
580.0

2X 120.0

640.0

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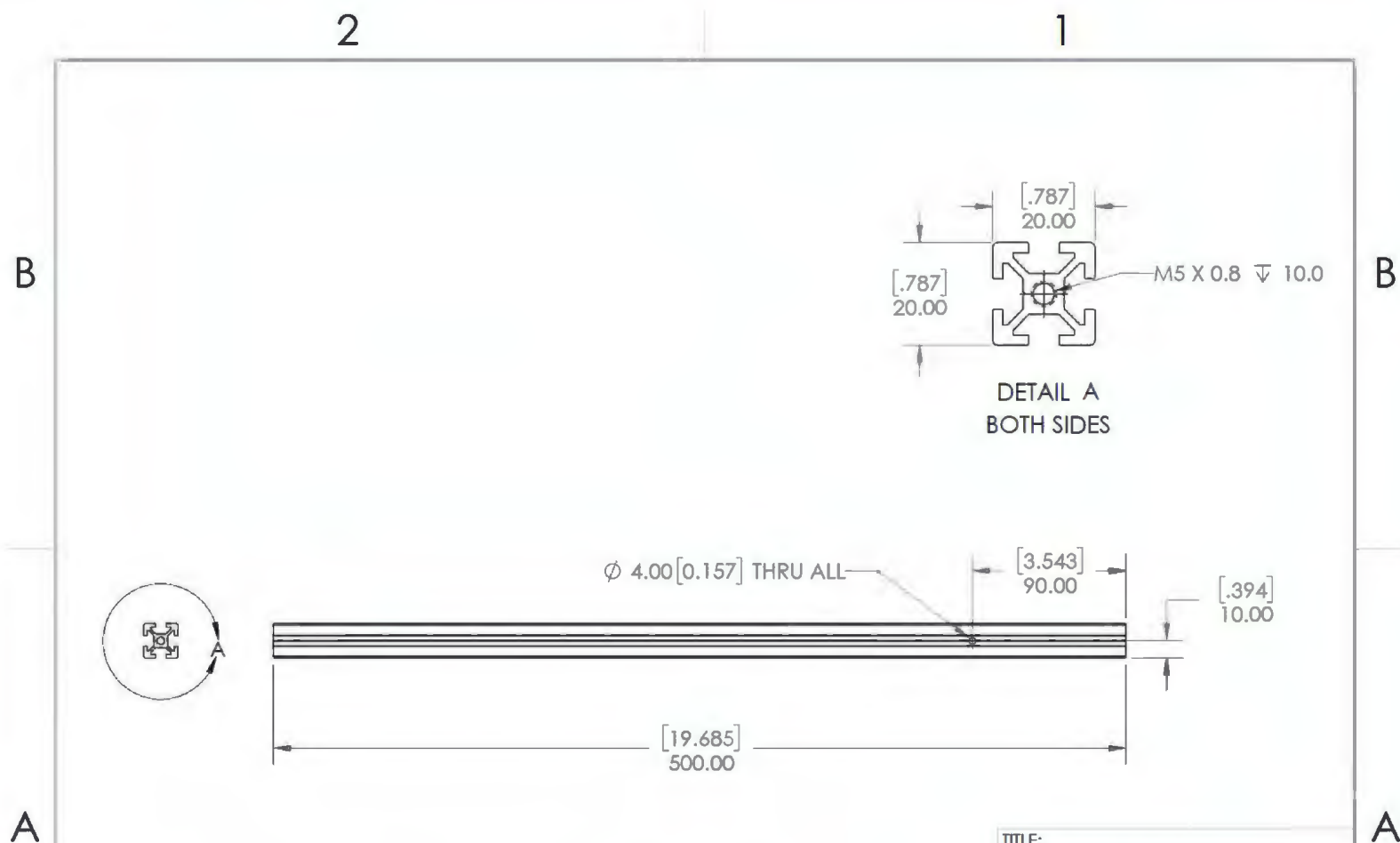
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NOTE: GUSSETS SPLIT INTO MULTIPLE SLOTTED PIECES FOR ASSEMBLY

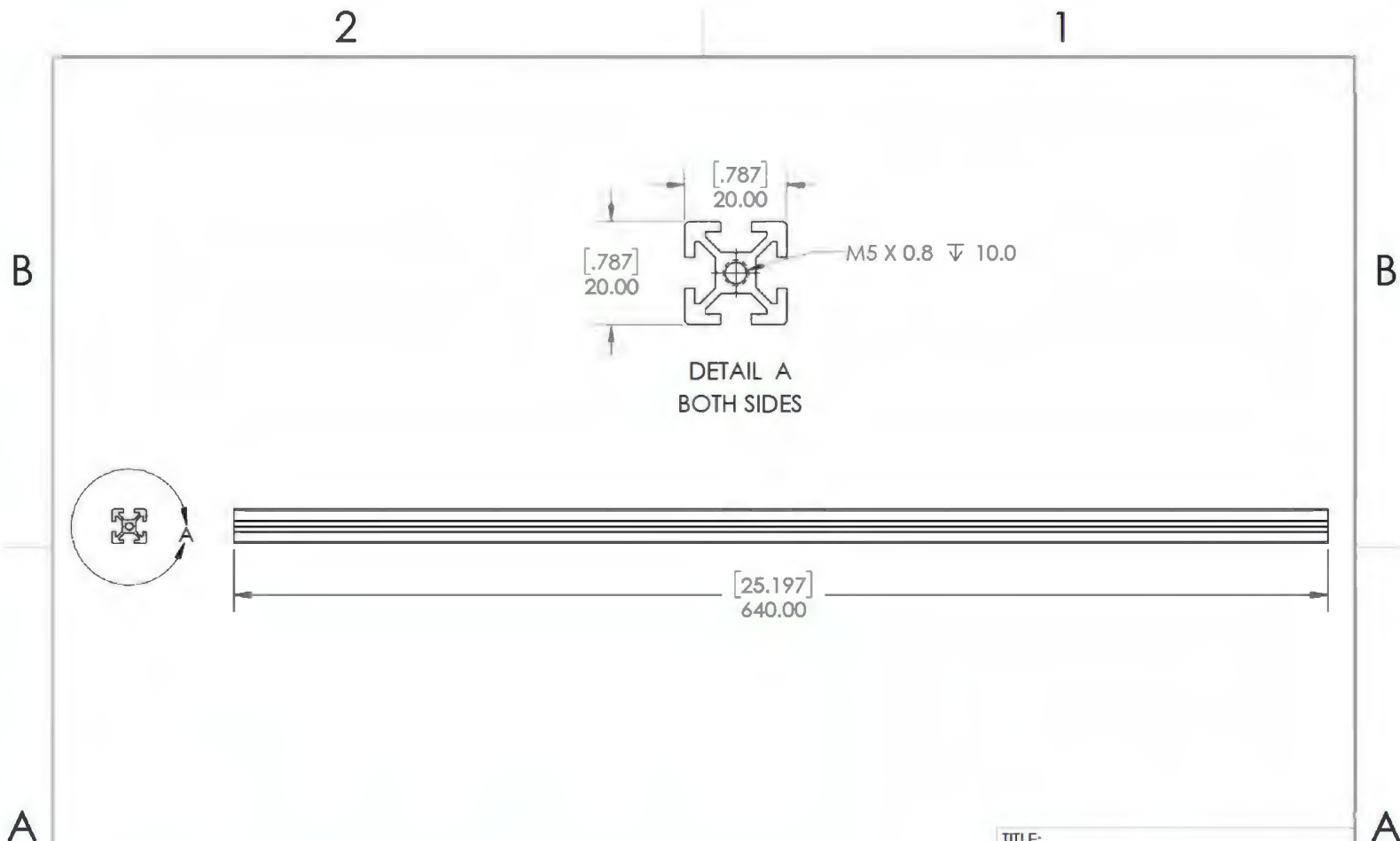
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Side Gusset Skirt

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				APPROVED	APPROVED	APPROVED	APPROVED	APPROVED	APPROVED



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A	Mid Frame Members_500mm	A	
SCALE: 1:3		WEIGHT:	SHEET 1 OF 1

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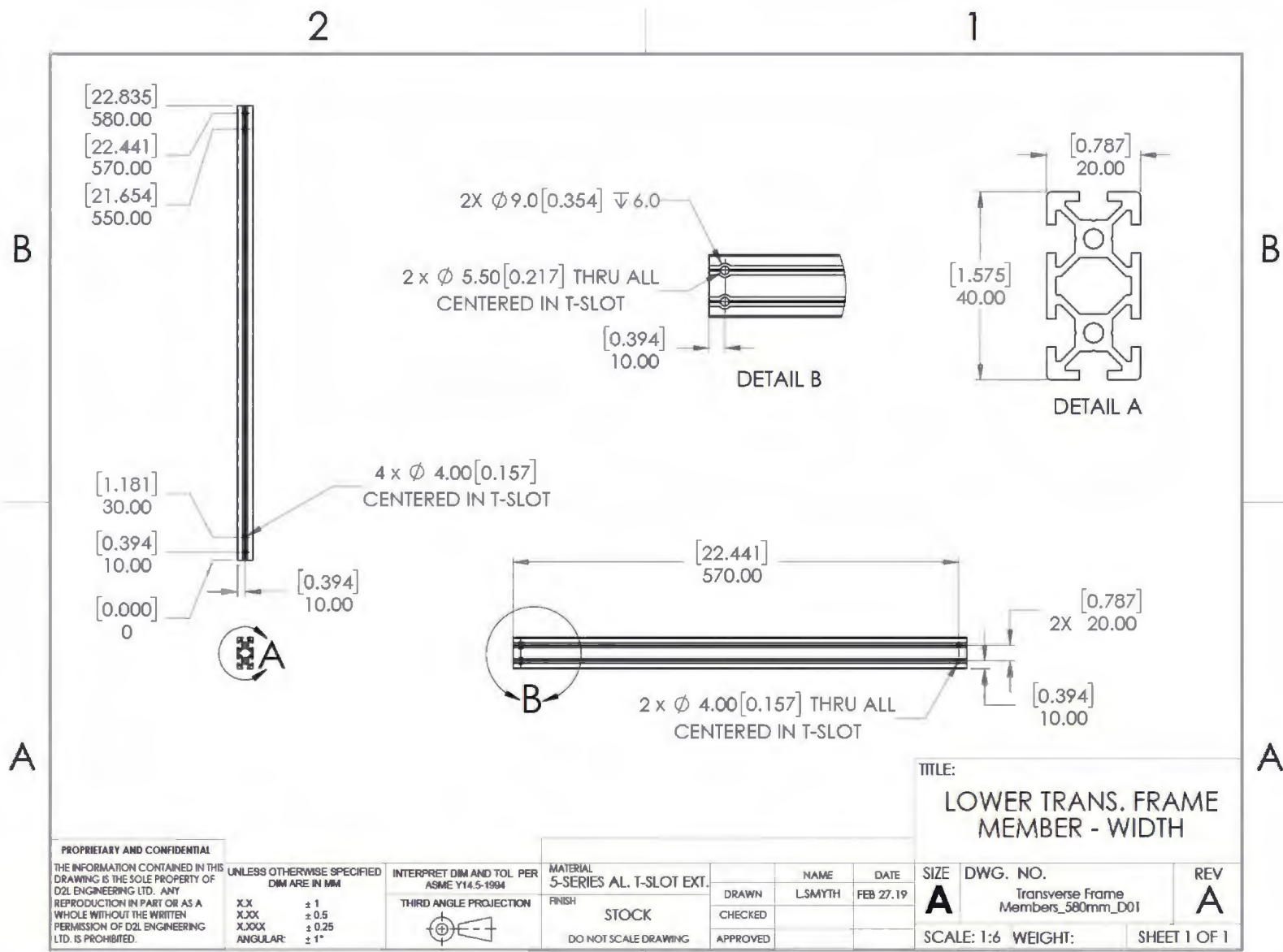
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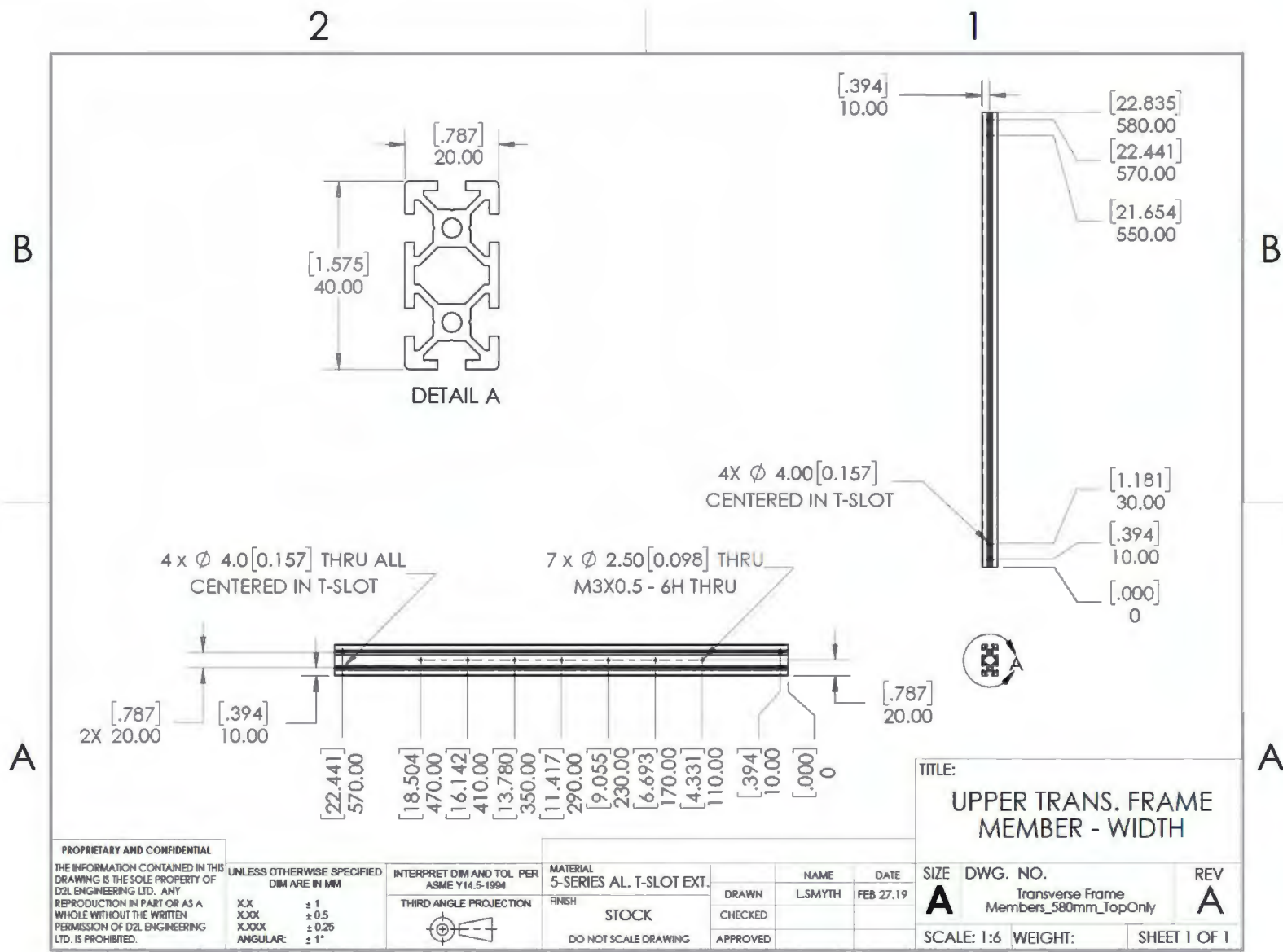
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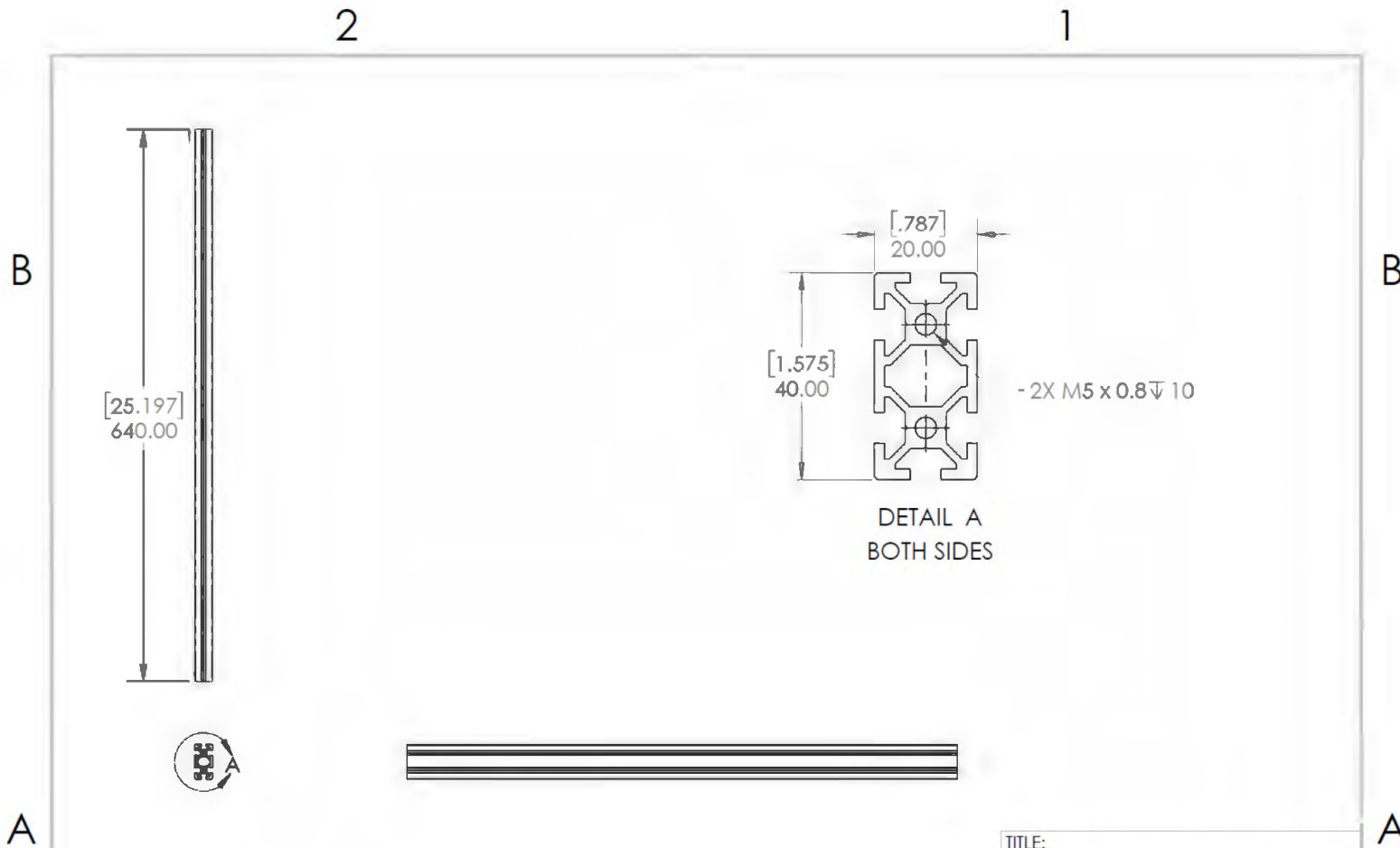
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SCALE: 1:3	WEIGHT:	SHEET 1 OF 1	







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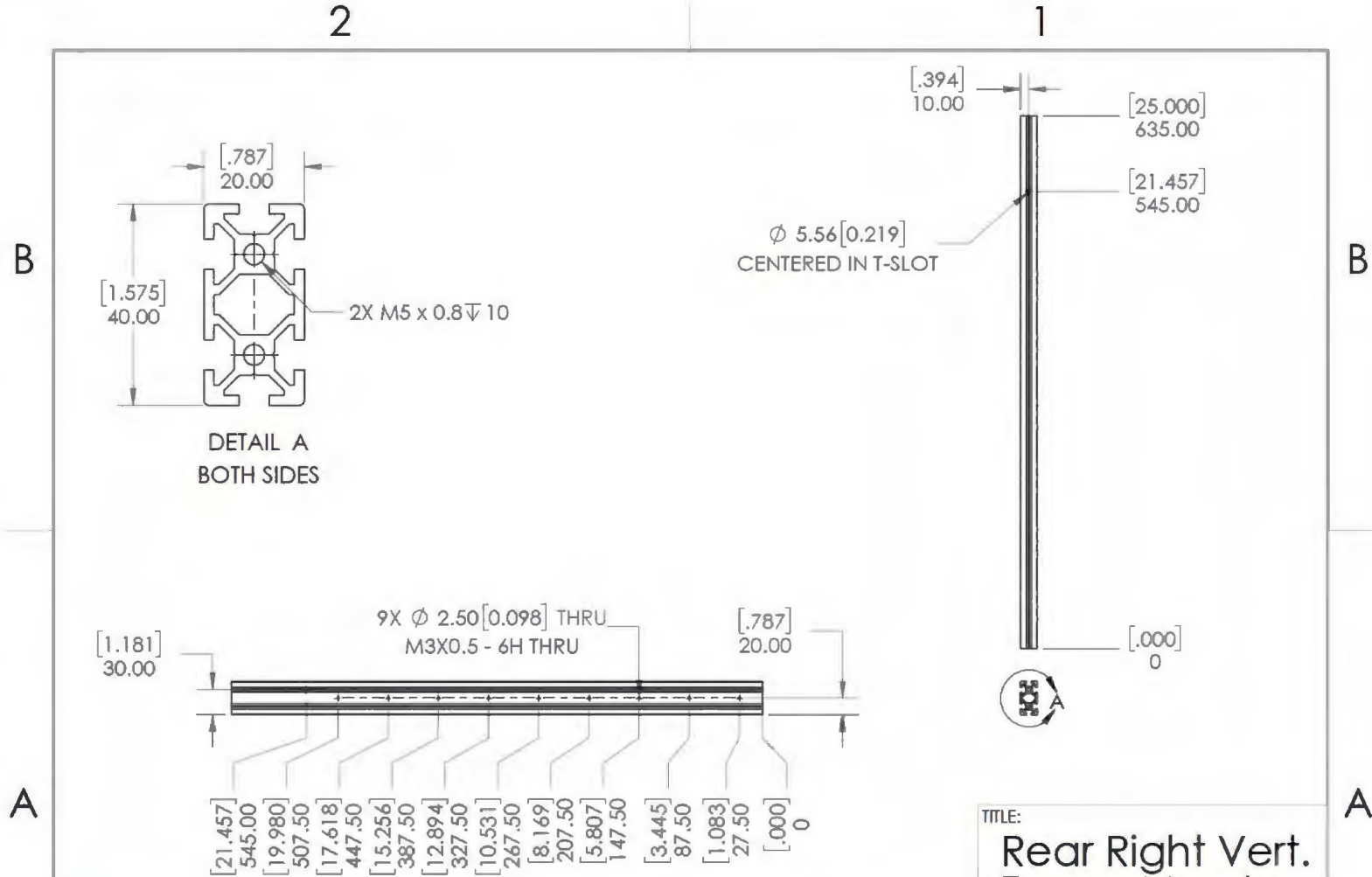
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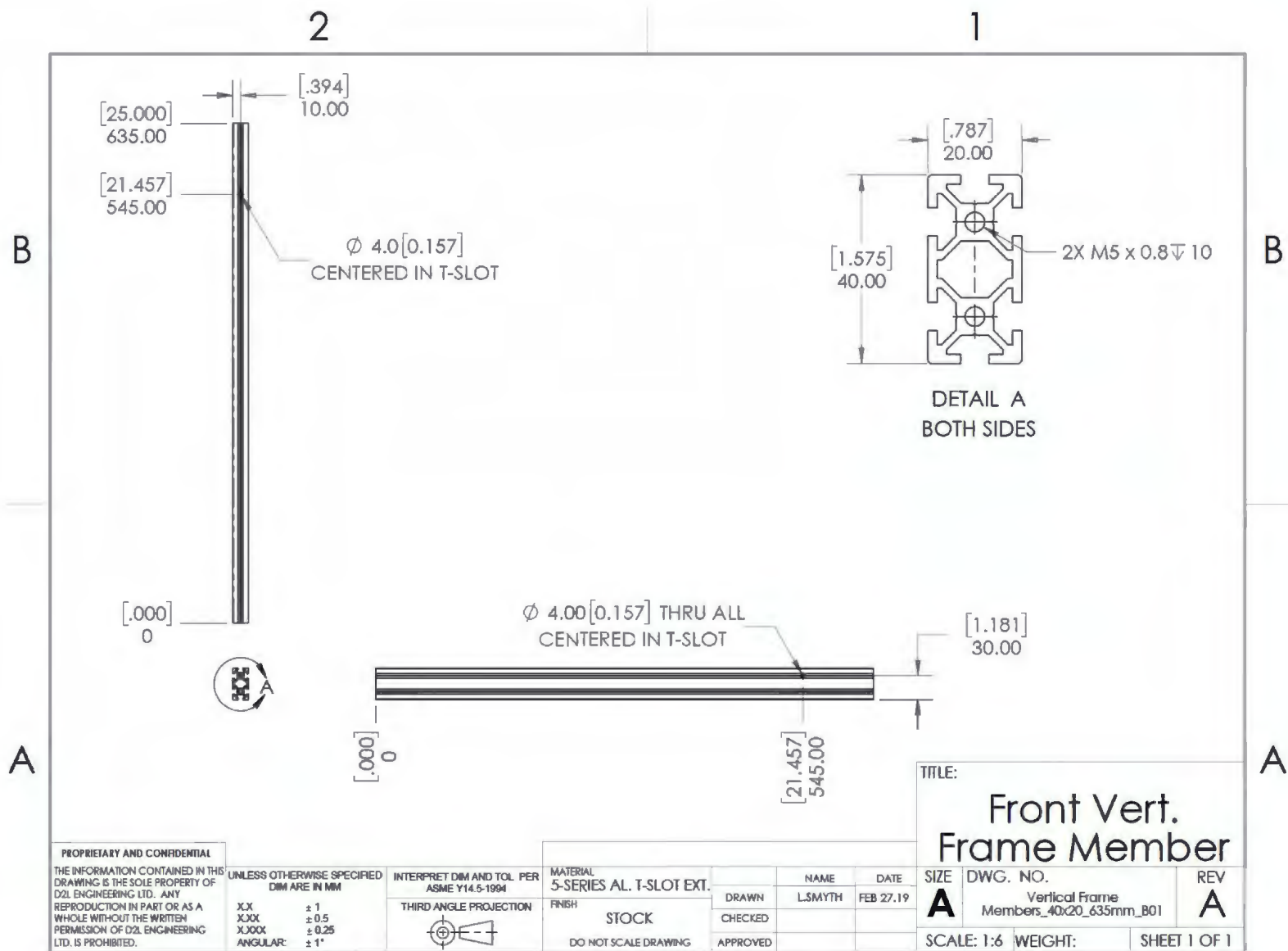
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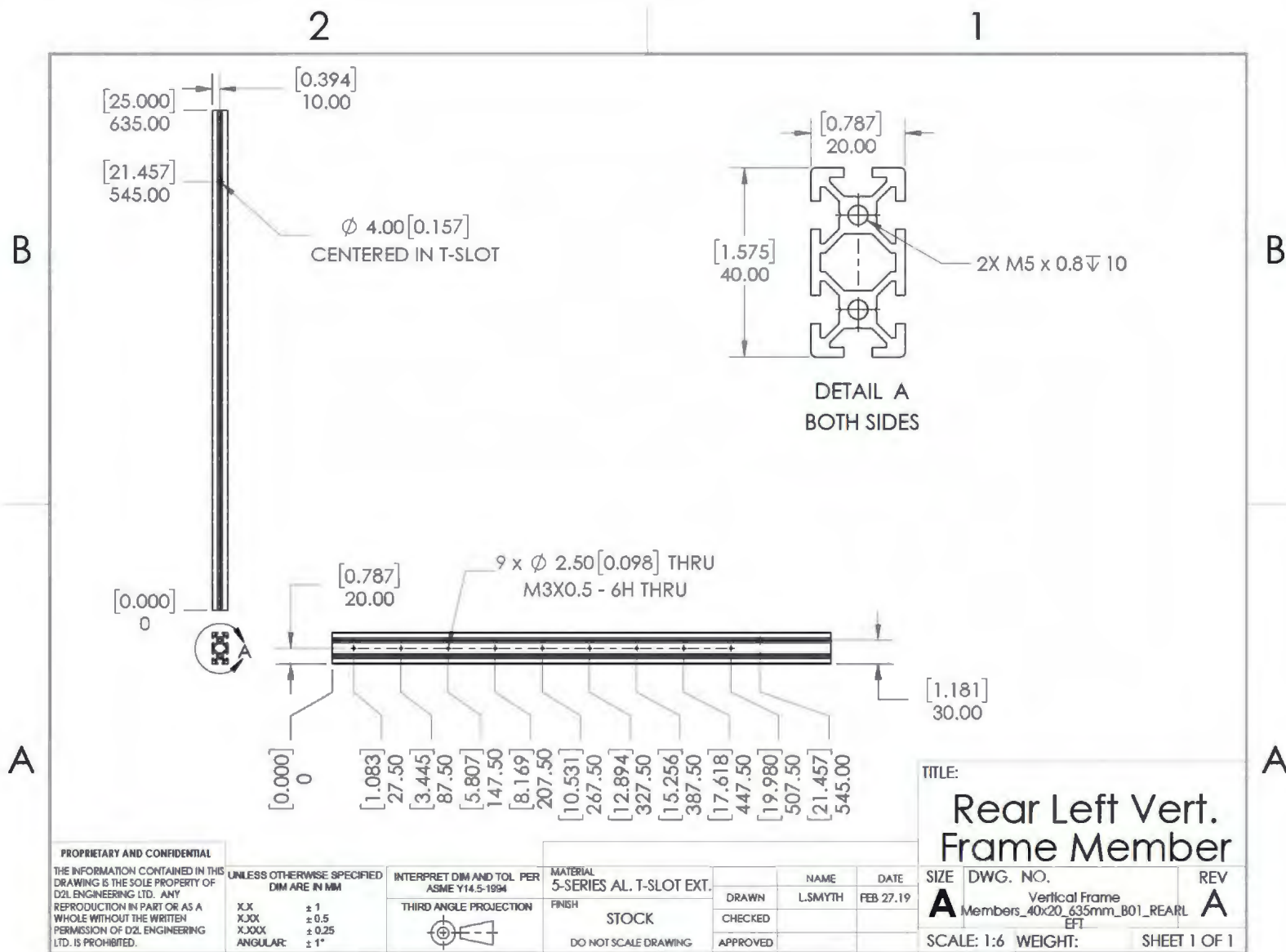
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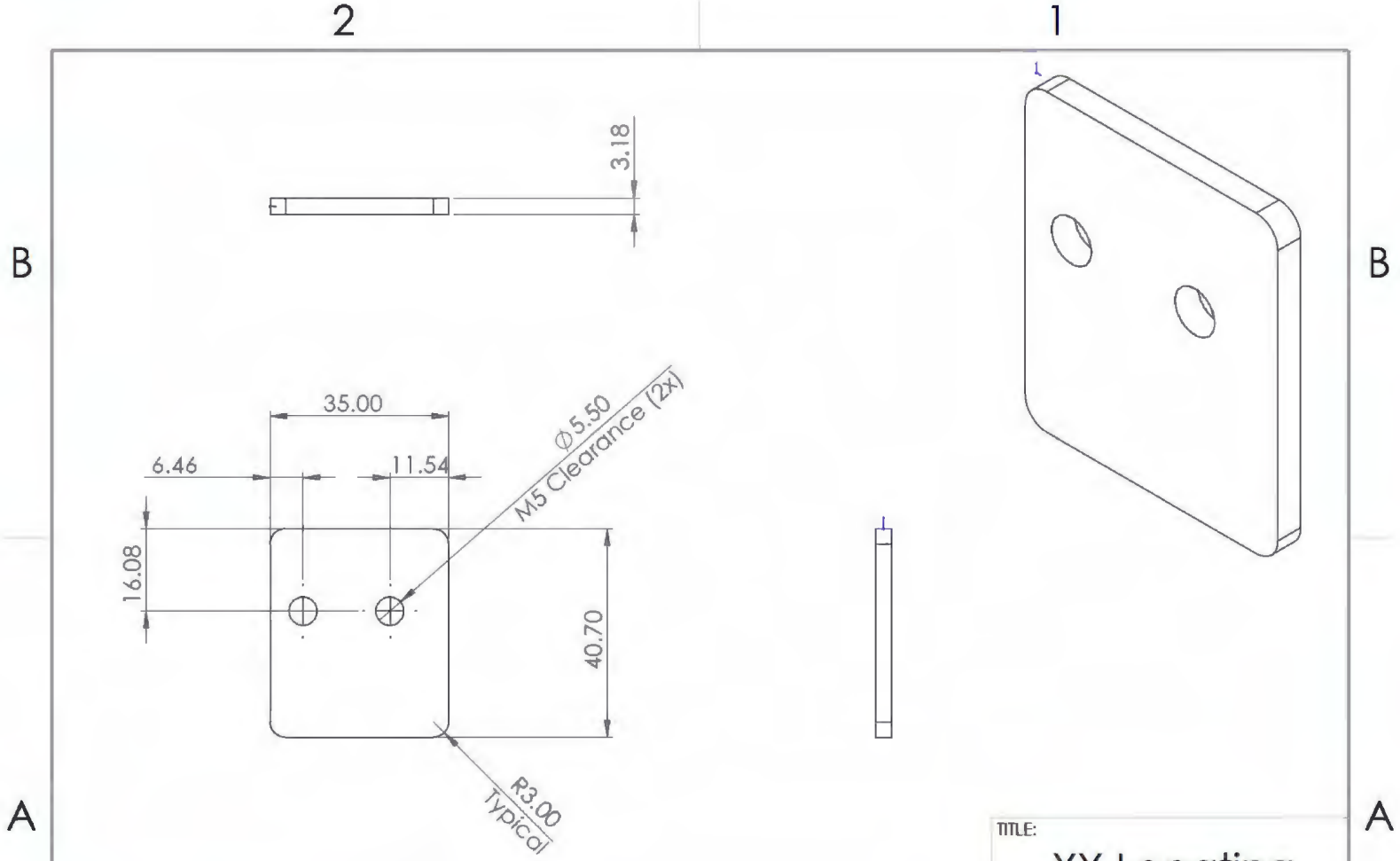
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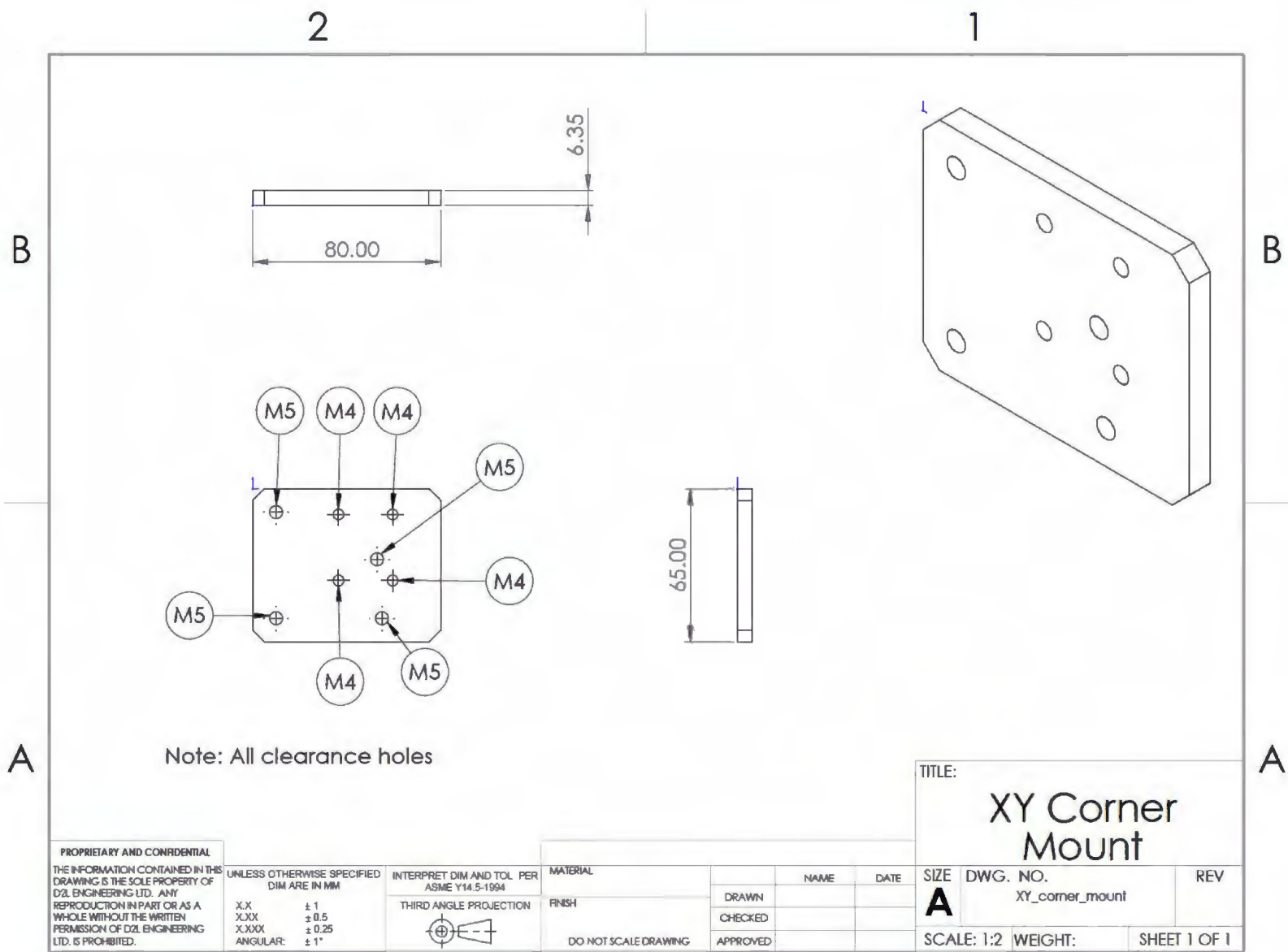
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Note: All clearance holes

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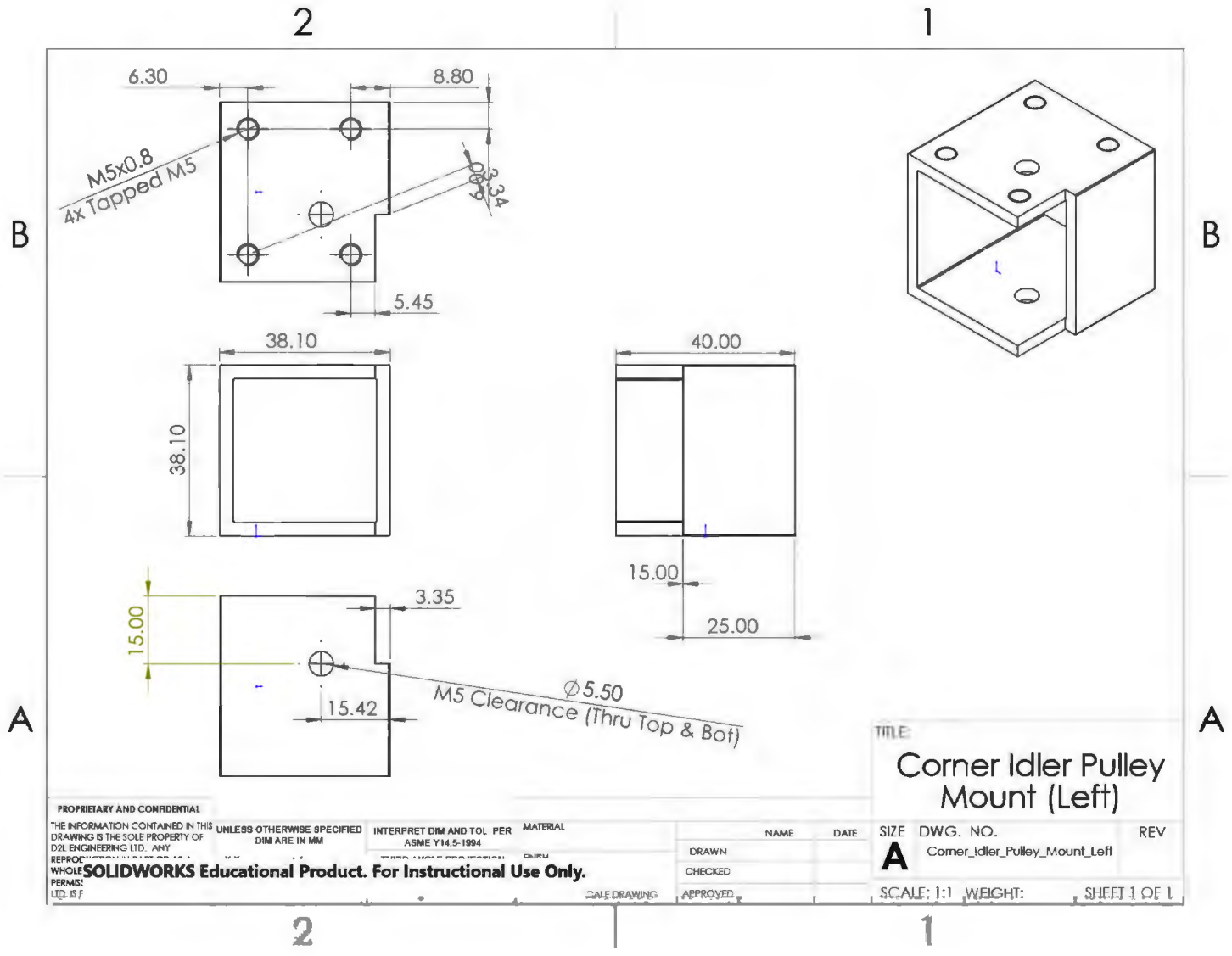
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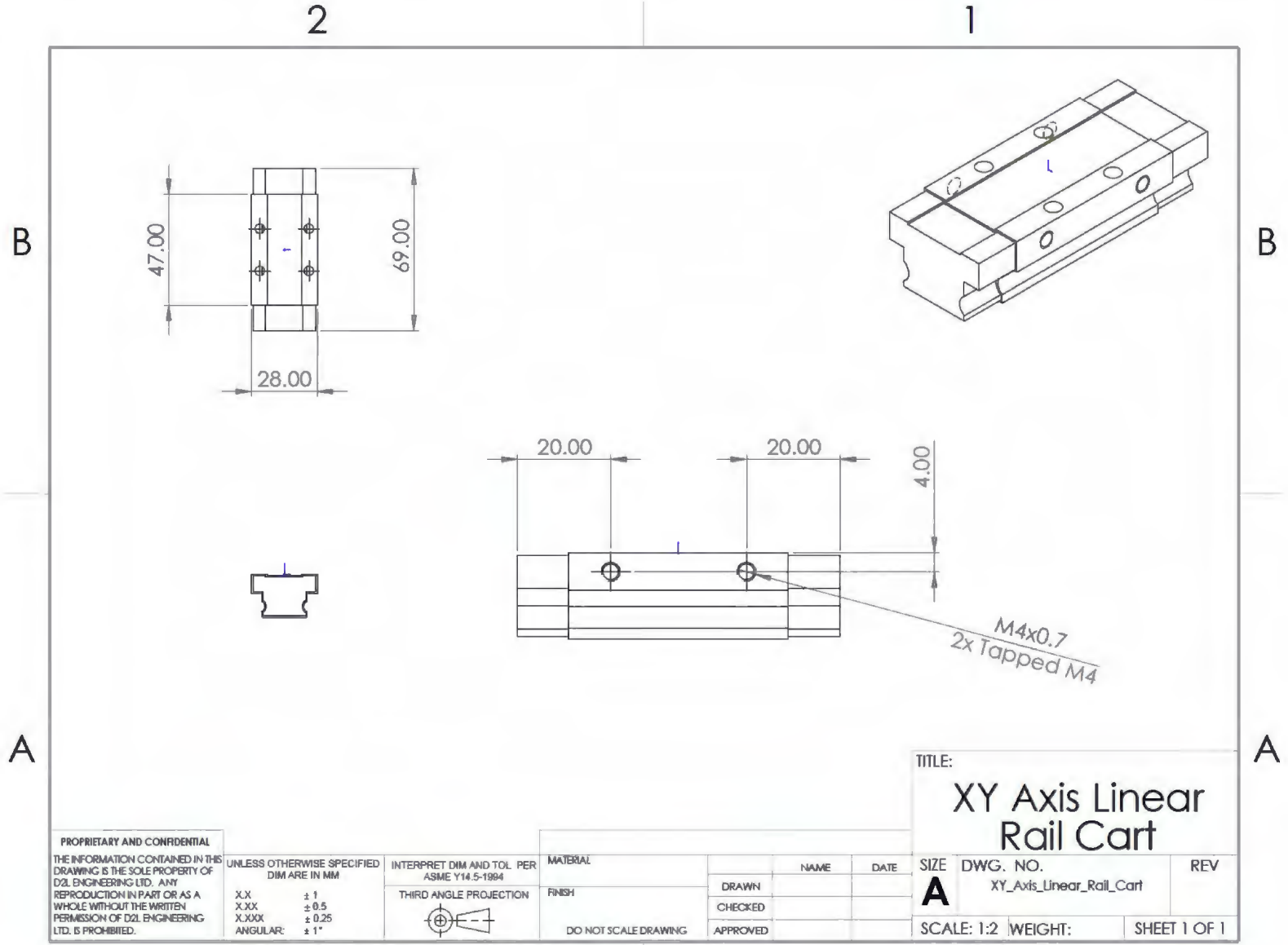
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TITLE	SIZE	DWG. NO.	REV
Corner Idler Pulley Mount (Left)	A	Corner_idler_Pulley_Mount_Left	
SCALE: 1:1		WEIGHT:	
		SHEET 1 OF 1	



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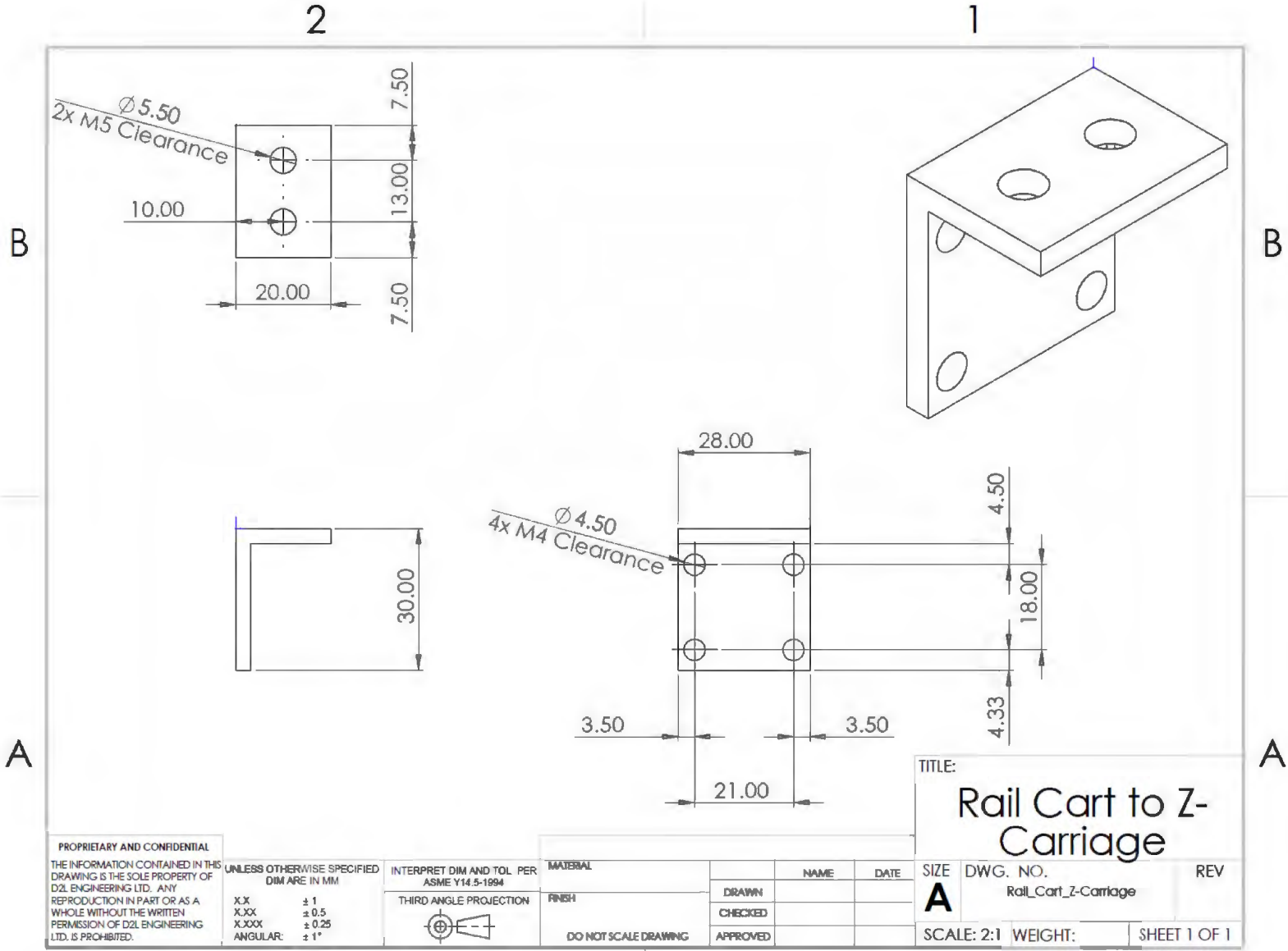
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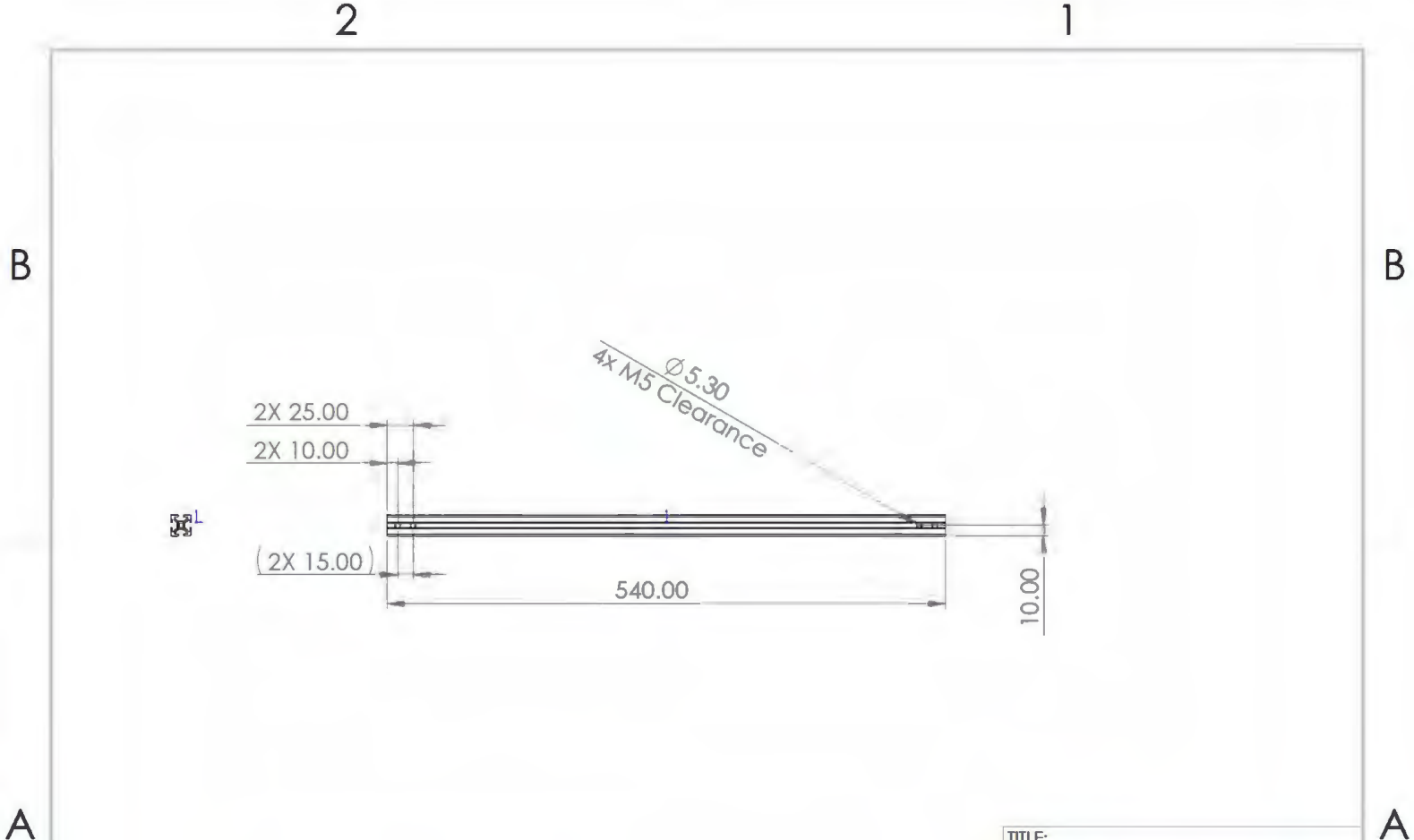
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APPROVED	

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SIZE A	DWG. NO. XY_Axis_Linear_Rail_Cart	REV
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1





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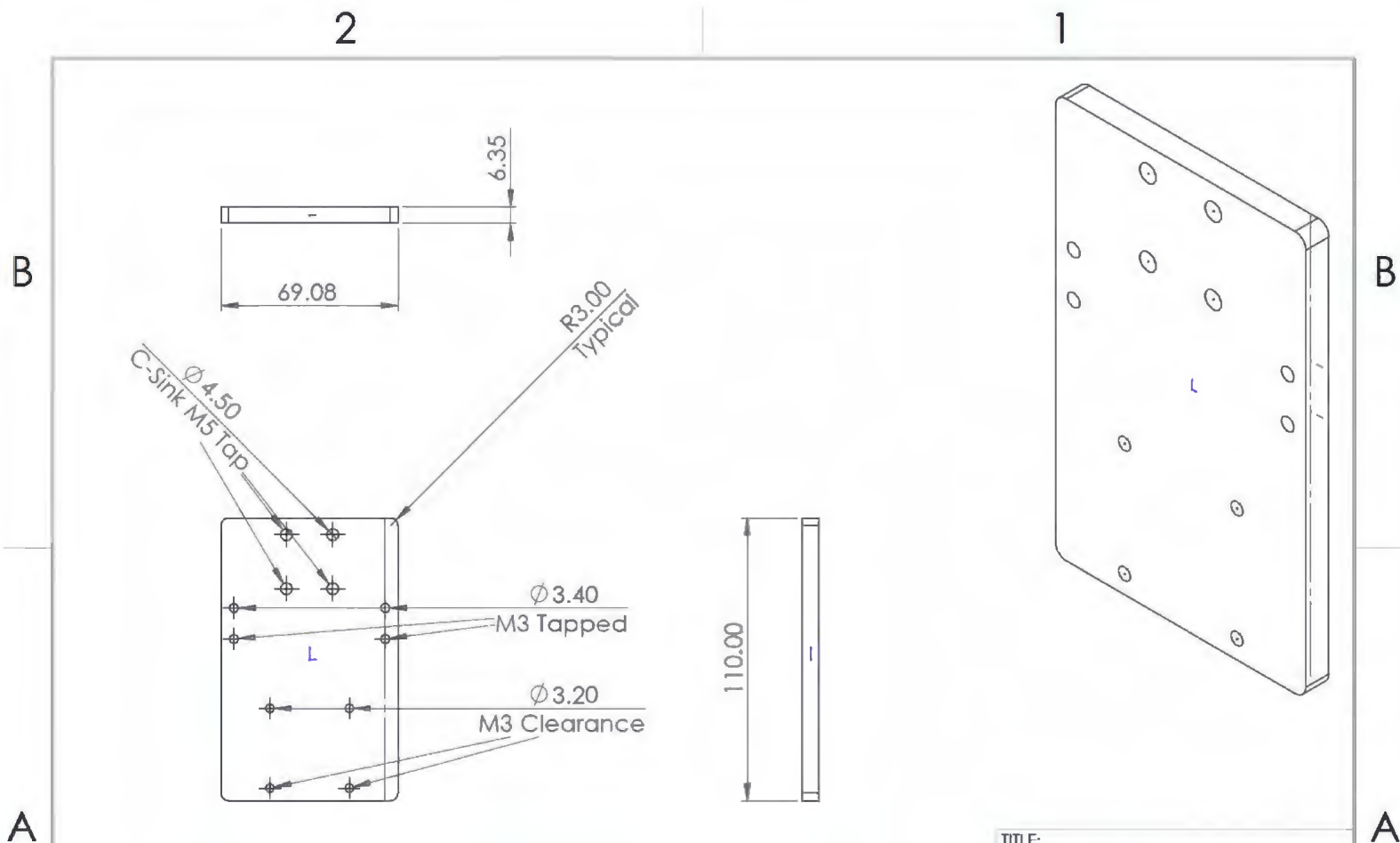
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DRAWN	
CHECKED	
APPROVED	


TITLE: Printer Head Cross Member		
SIZE A	DWG. NO. Printhead_Cross_Member	REV
SCALE: 1:5	WEIGHT:	SHEET 1 OF 1



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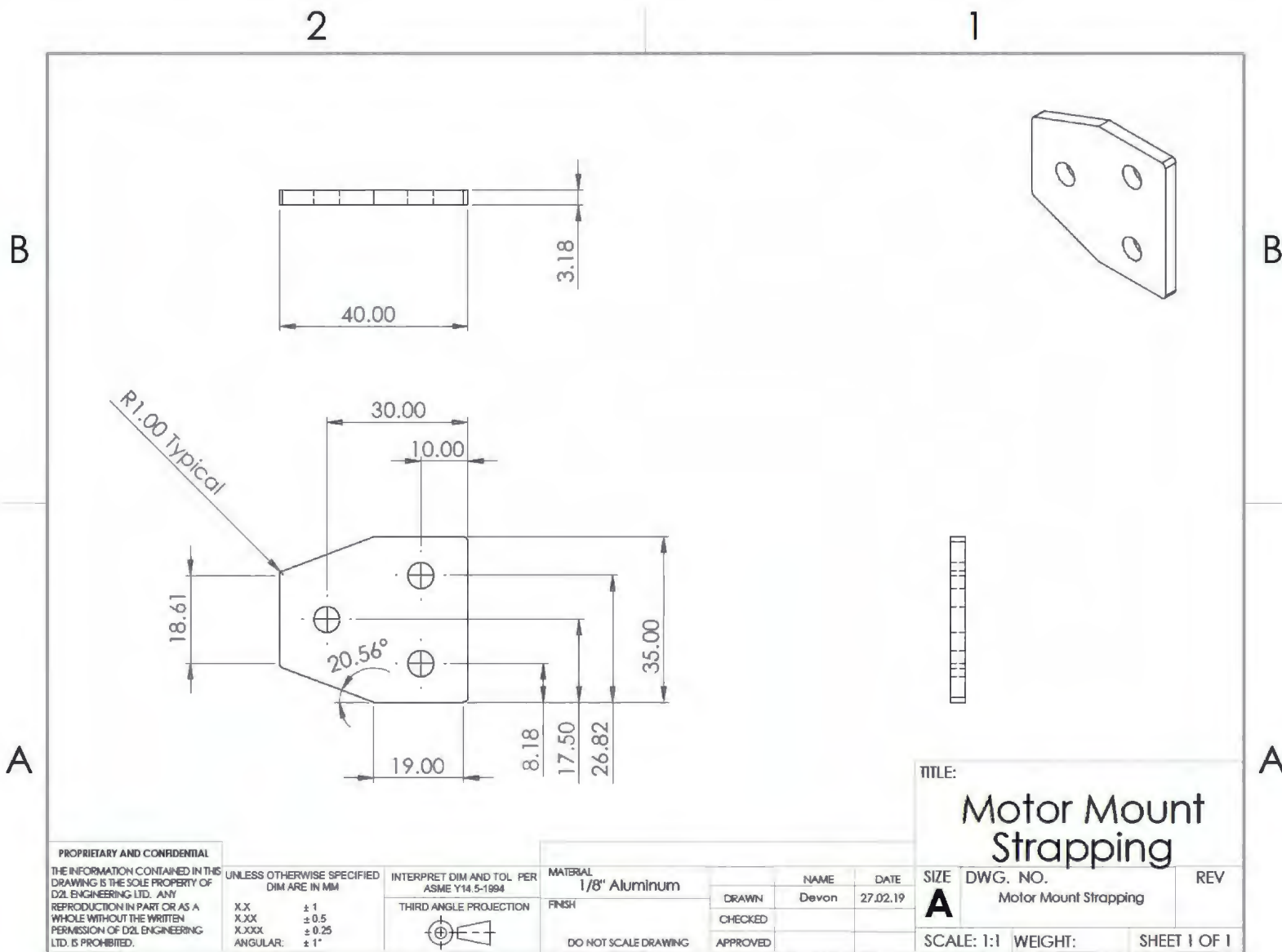
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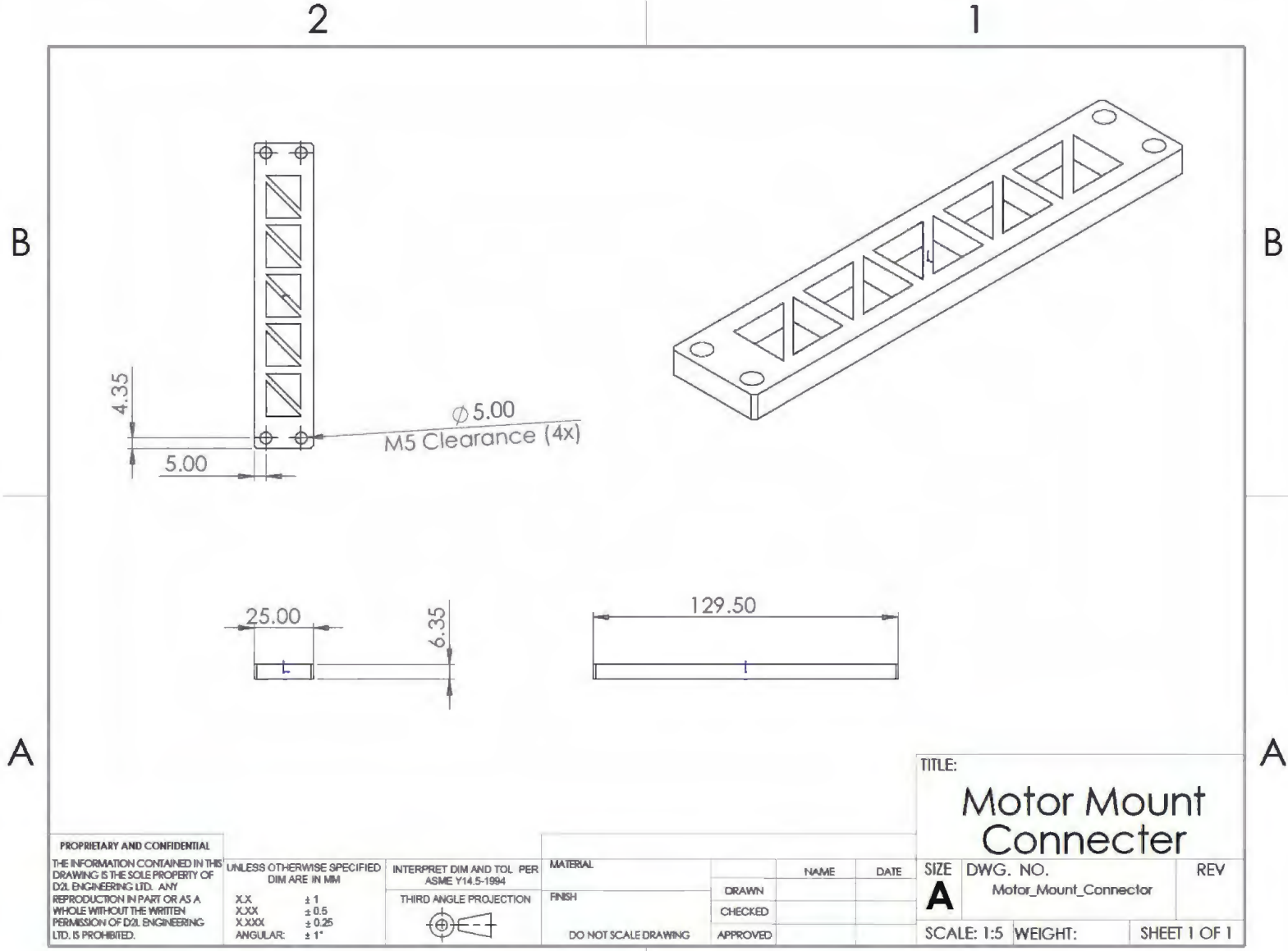


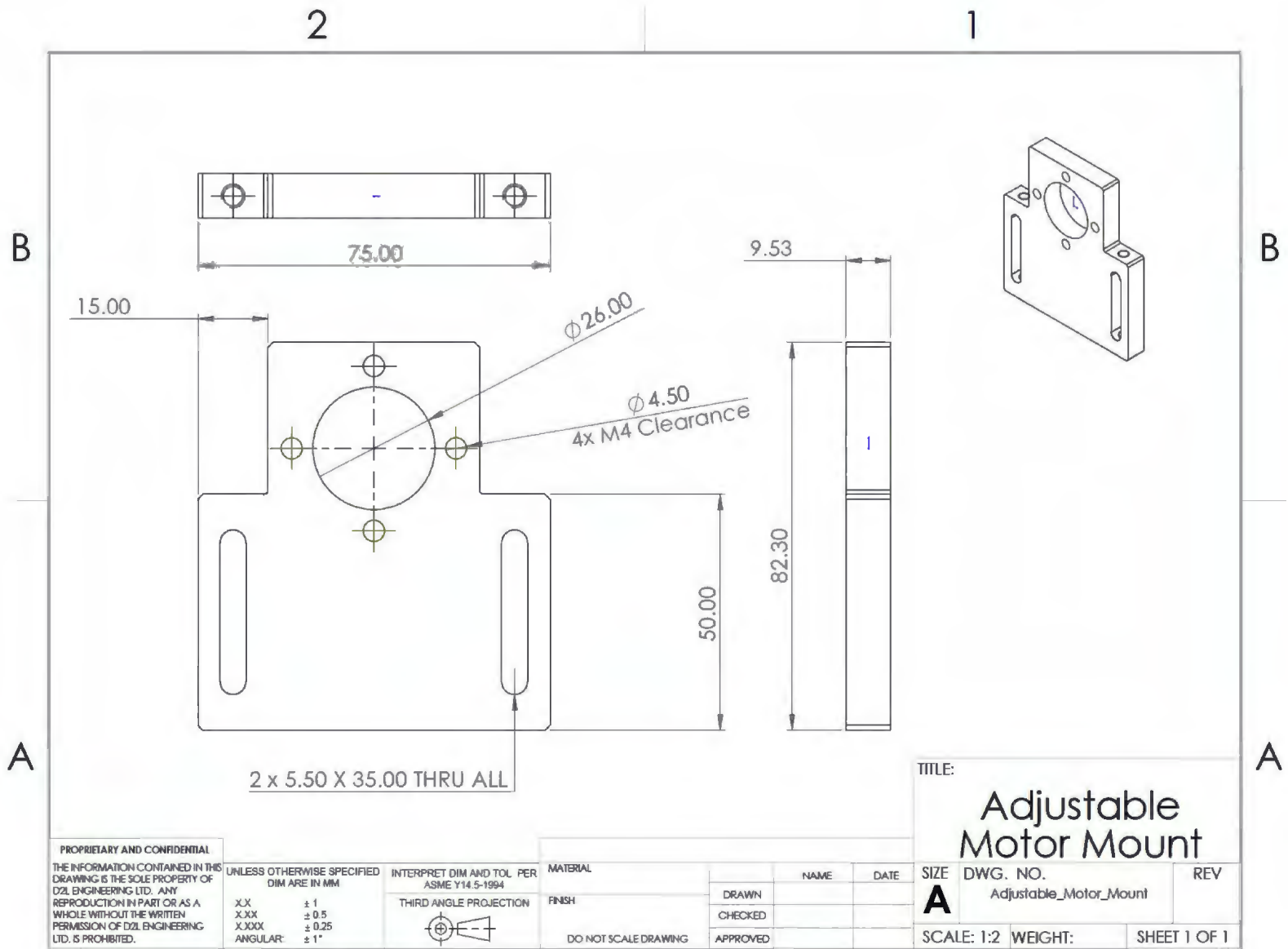
MATERIAL
 FINISH
 DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
APPROVED		

TITLE: Printhead Bracket		
SIZE A	DWG. NO. Printhead_Bracket	REV
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1








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UNLESS OTHERWISE SPECIFIED DIM ARE IN MM	
X.X	± 1
X.XX	± 0.5
X.XXX	± 0.25
ANGULAR:	$\pm 1^\circ$

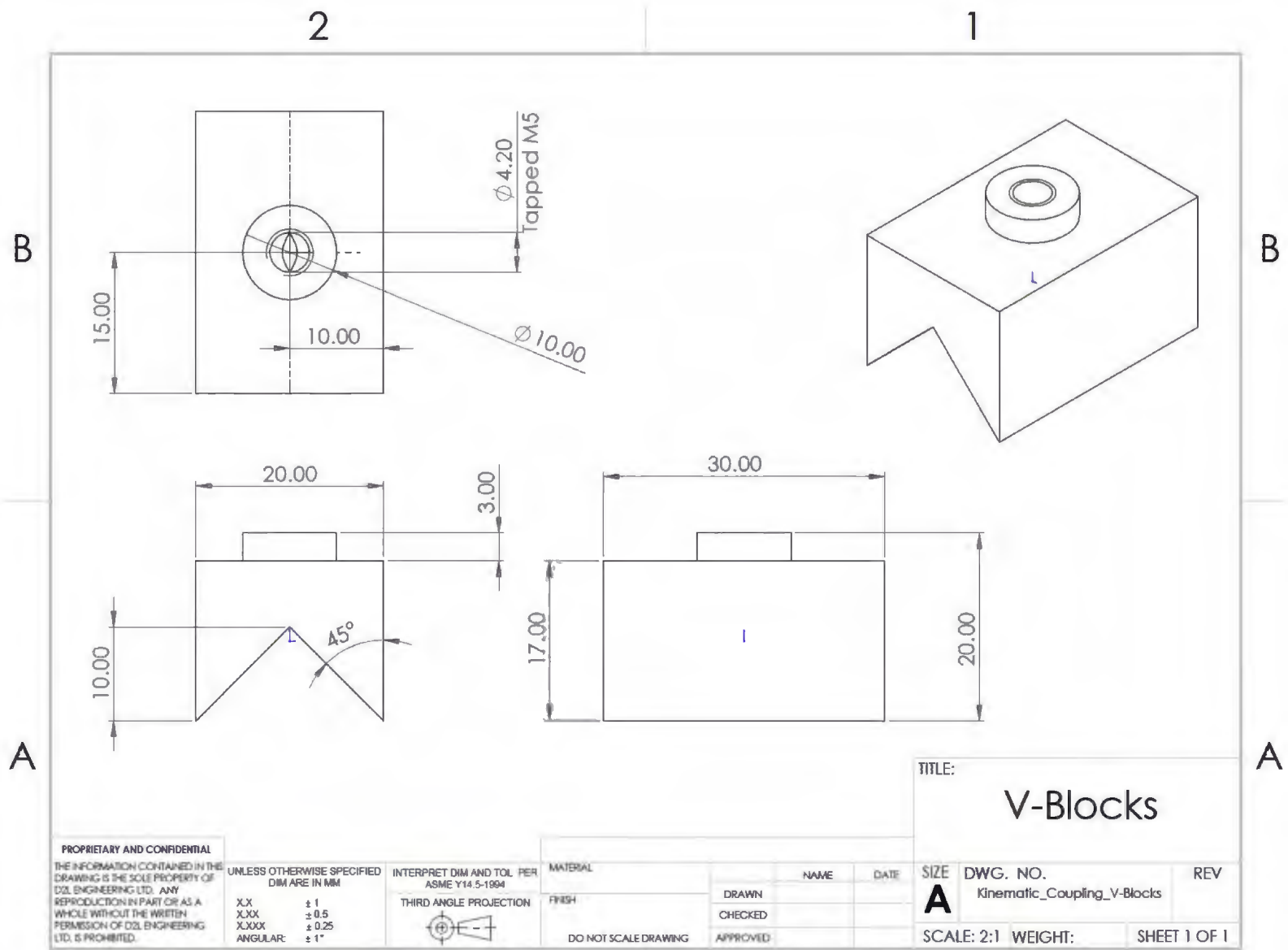
INTERPRET DIM AND TOL PER ASME Y14.5-1994
 THIRD ANGLE PROJECTION

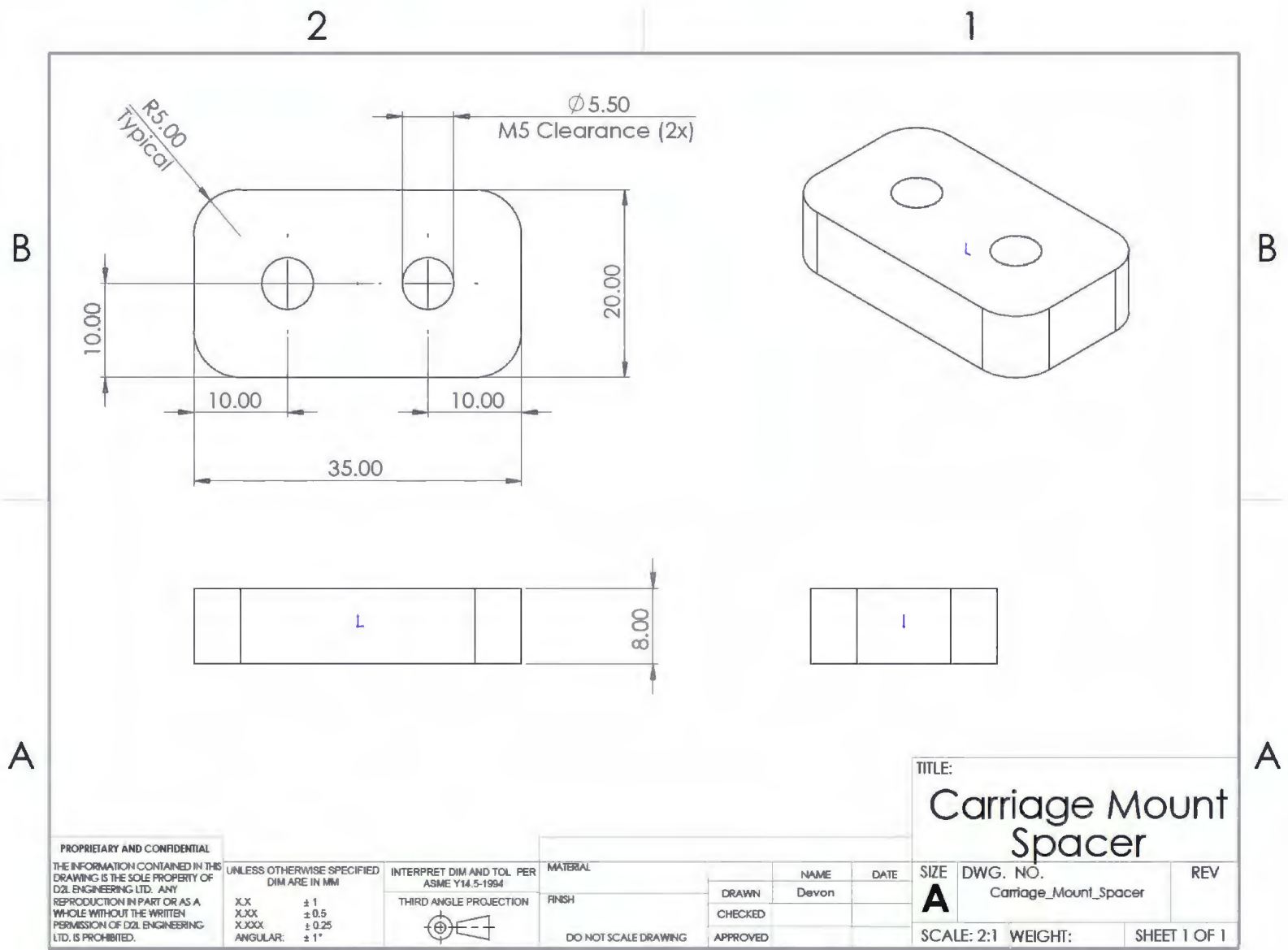


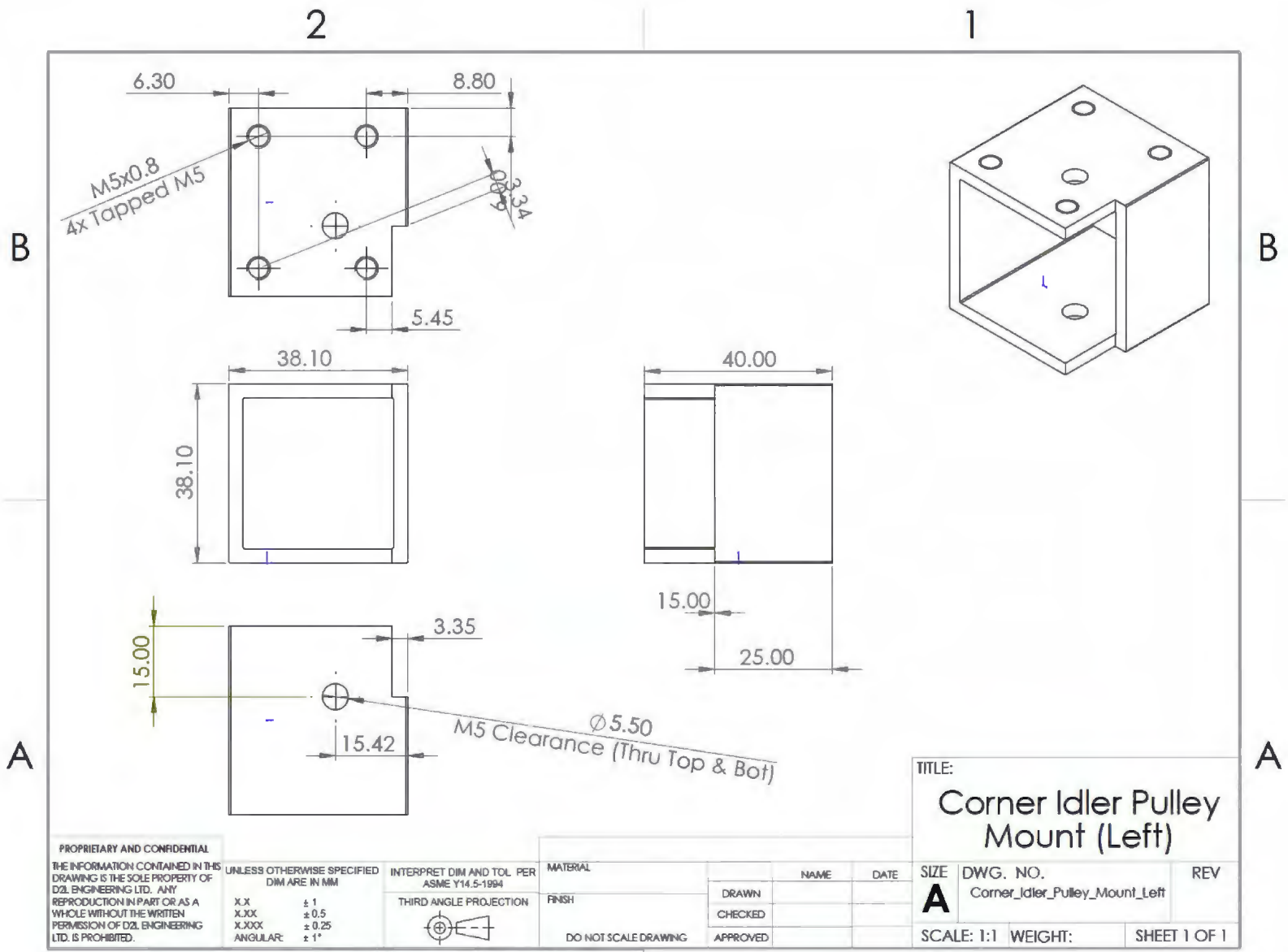
MATERIAL
 FINISH
 DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
APPROVED		

TITLE: Adjustable Motor Mount		
SIZE A	DWG. NO. Adjustable_Motor_Mount	REV
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1







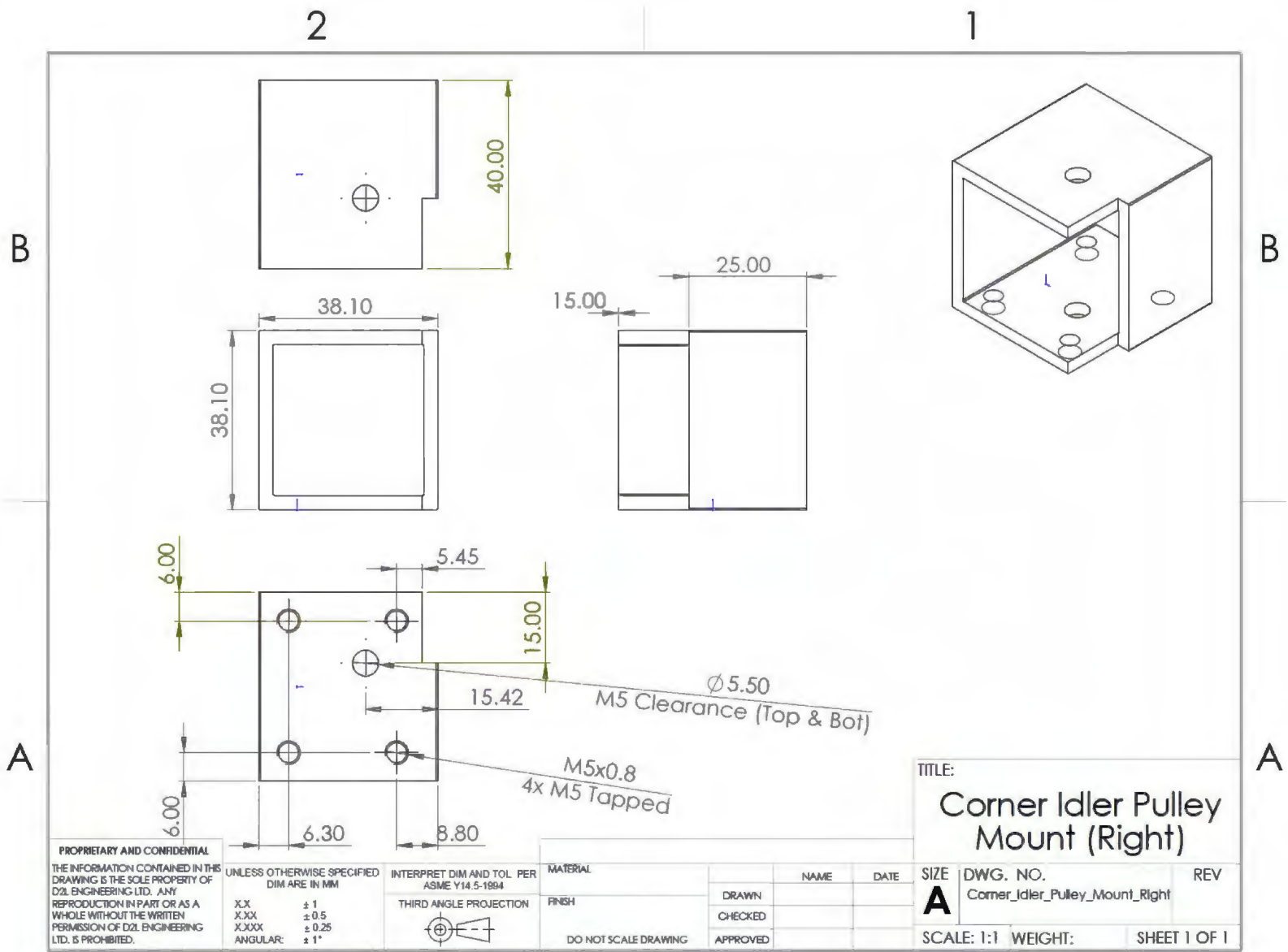
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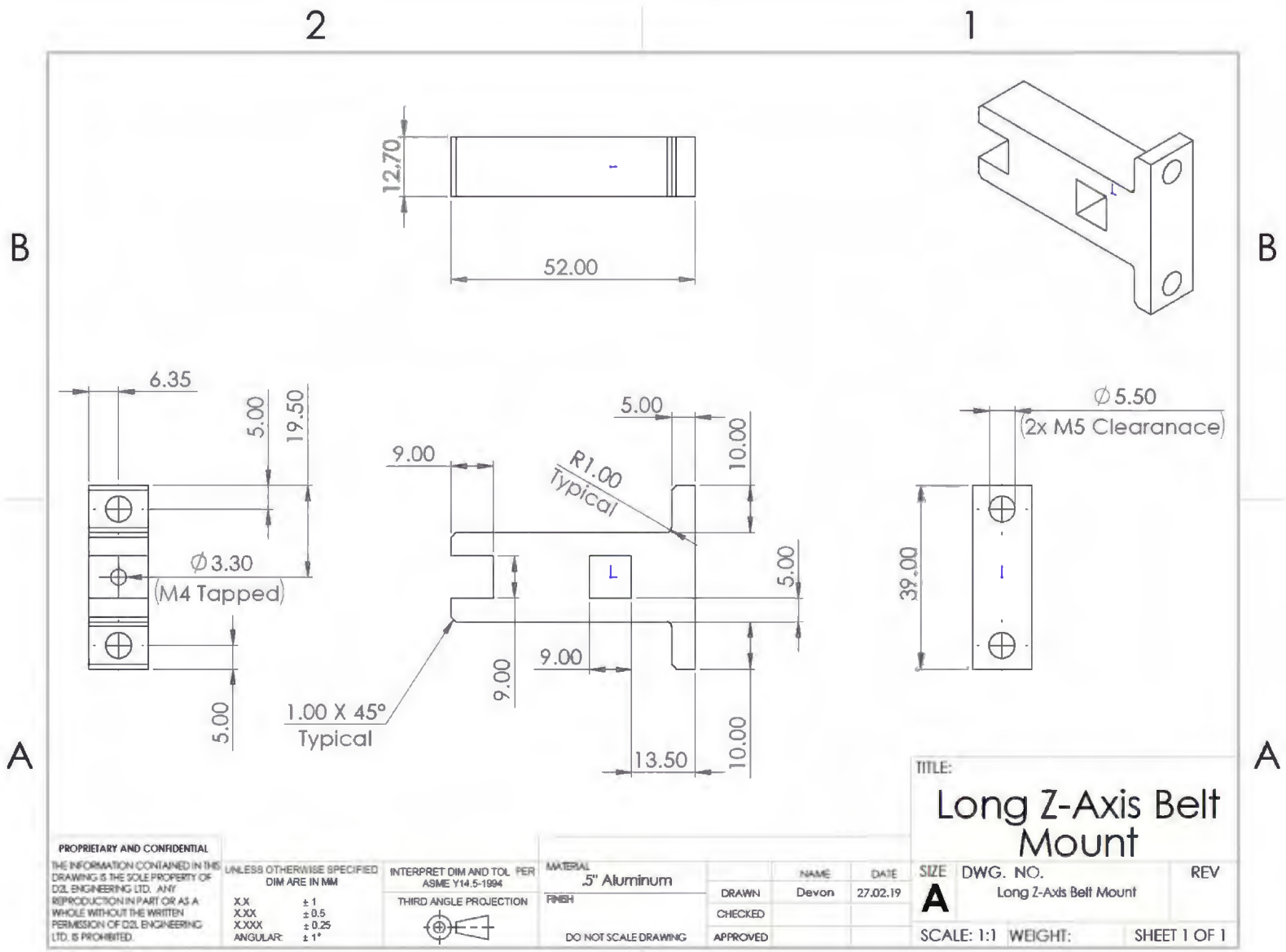
UNLESS OTHERWISE SPECIFIED
 DIM ARE IN MM
 X.X ± 1
 X.XX ± 0.5
 X.XXX ± 0.25
 ANGULAR ± 1°

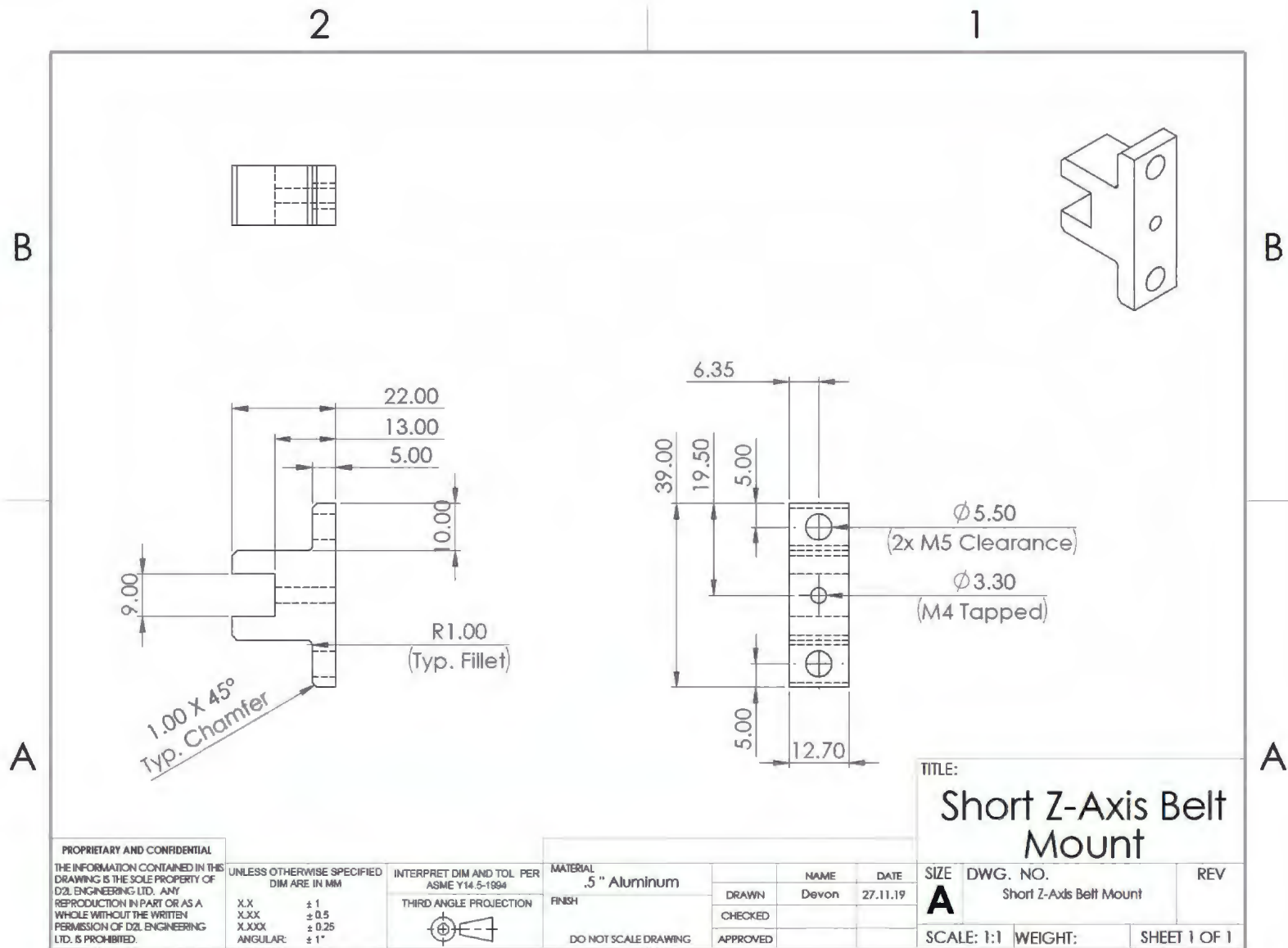
INTERPRET DIM AND TOL PER
 ASME Y14.5-1994
 THIRD ANGLE PROJECTION

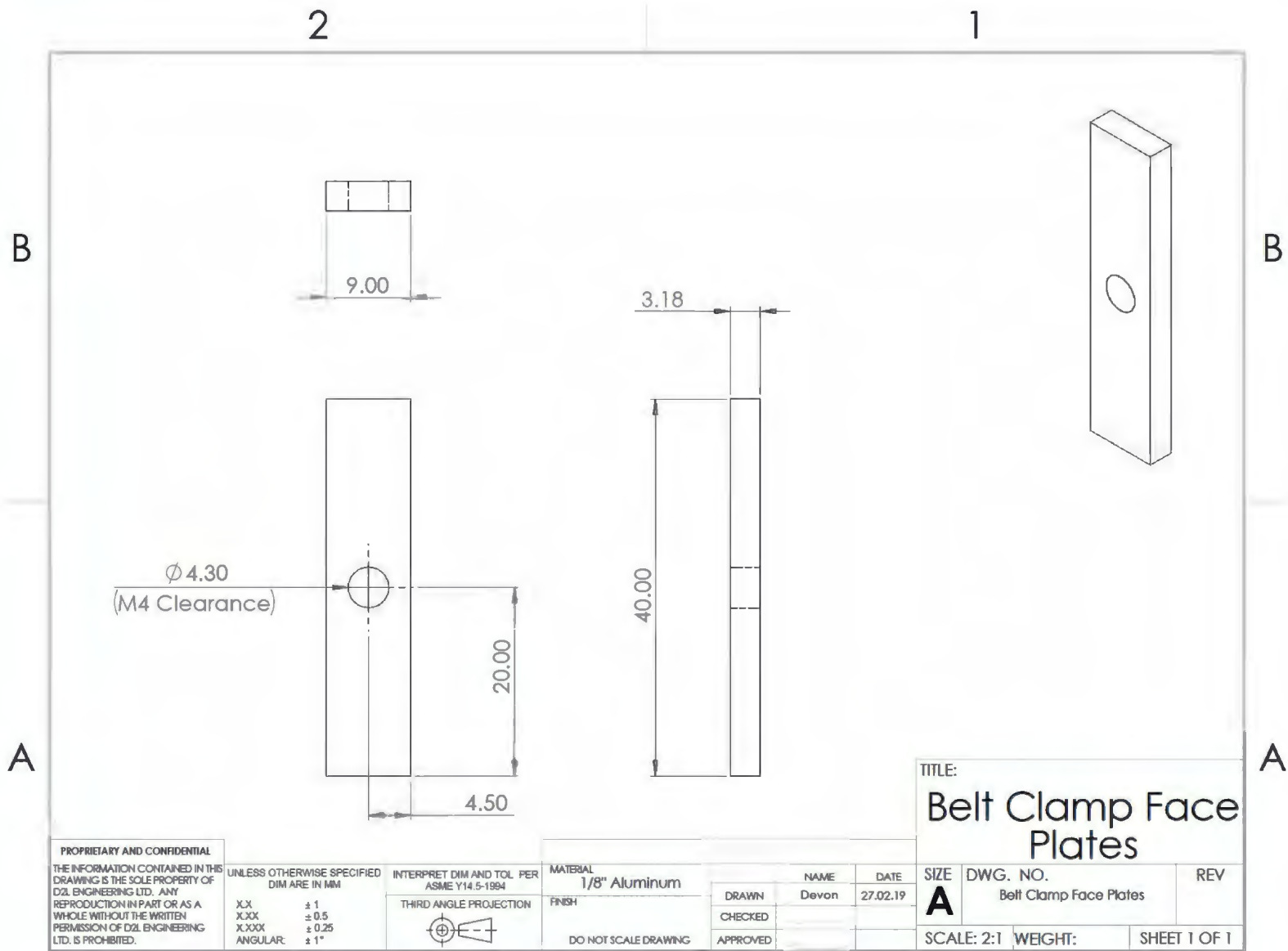
MATERIAL	NAME	DATE
FINISH	DRAWN	
	CHECKED	
DO NOT SCALE DRAWING	APPROVED	

TITLE: Corner Idler Pulley Mount (Left)		
SIZE A	DWG. NO. Corner_Idler_Pulley_Mount_Left	REV
SCALE: 1:1	WEIGHT:	SHEET 1 OF 1



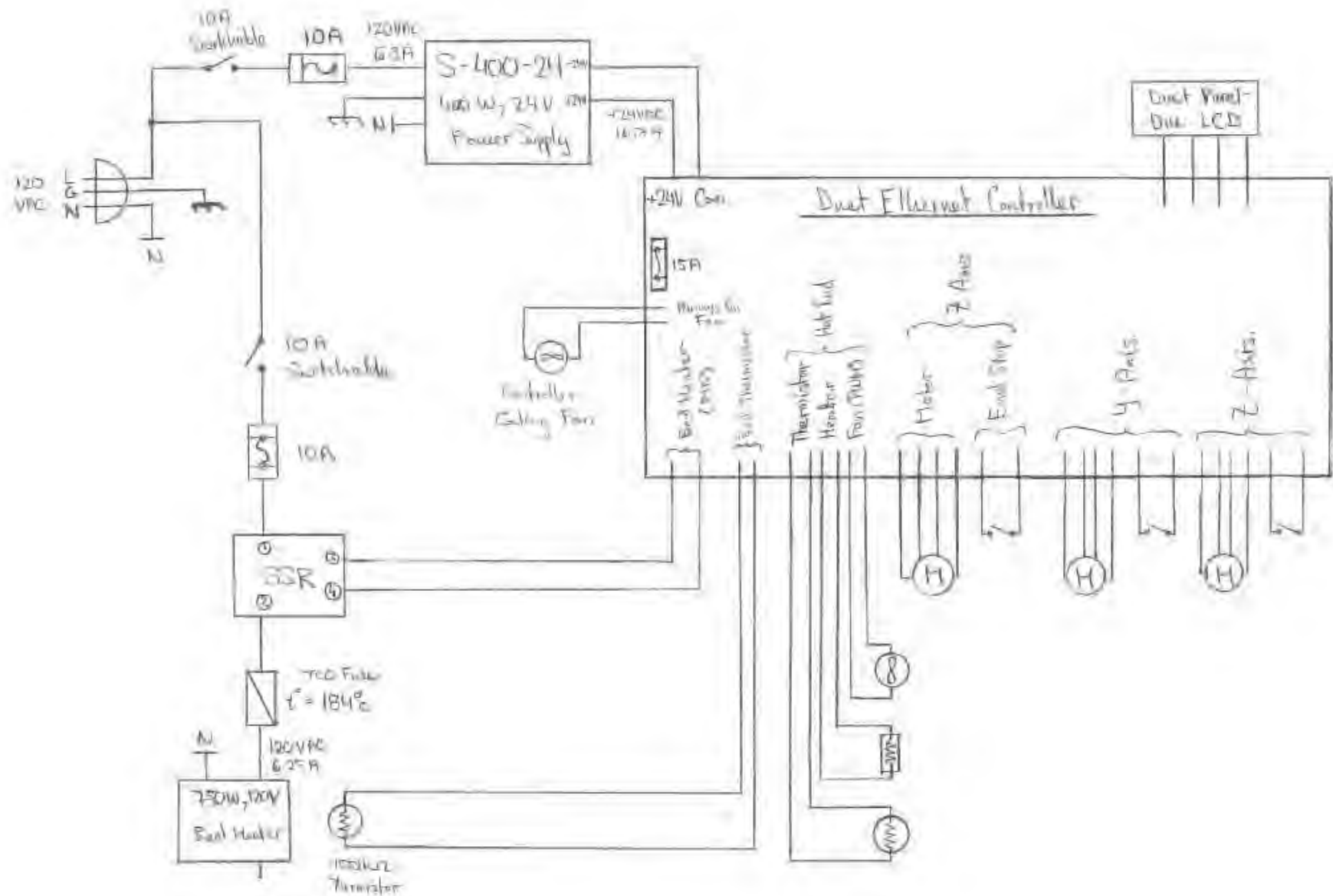






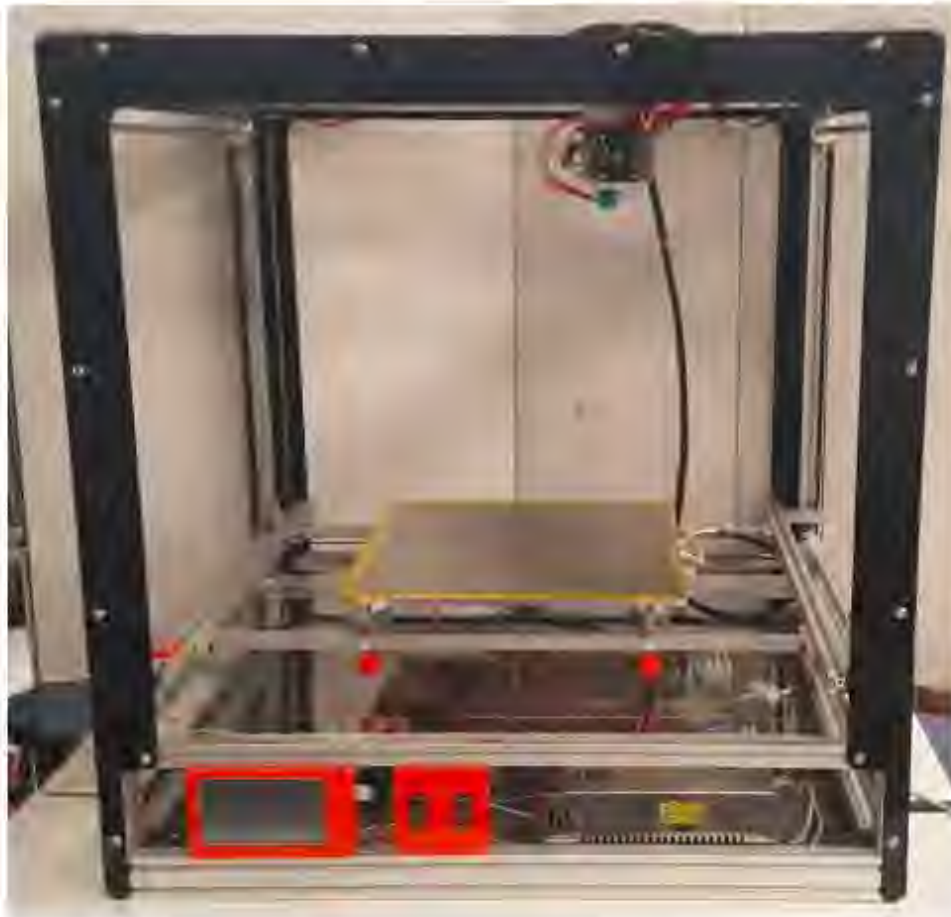
Appendix E – Electrical System Schematic Diagram

Schematic Diagram



Appendix F – 3D Printer User’s Guide

3D Printer User's Guide



By

David-Alexander Dabic, Devon Whitter, Liam Smyth

Faculty Advisor: Stephen McMillan, MEng, PEng

Program Head: Mehrzad Tabatabaian, BEng, MEng, PhD, PEng

Burnaby, British Columbia, Canada, 2019

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Preface

This user's guide is intended for all those who wish to set up this 3D printer and use it regularly. Because the printer is still a prototype, many issues are still unknown and this guide will simply provide a means of setting up and using the printer. As the printer becomes used more and more and issues are discovered, please consult Stephen McMillan, head of the Manufacturing Technology program at BCIT to address new problems and update this document.

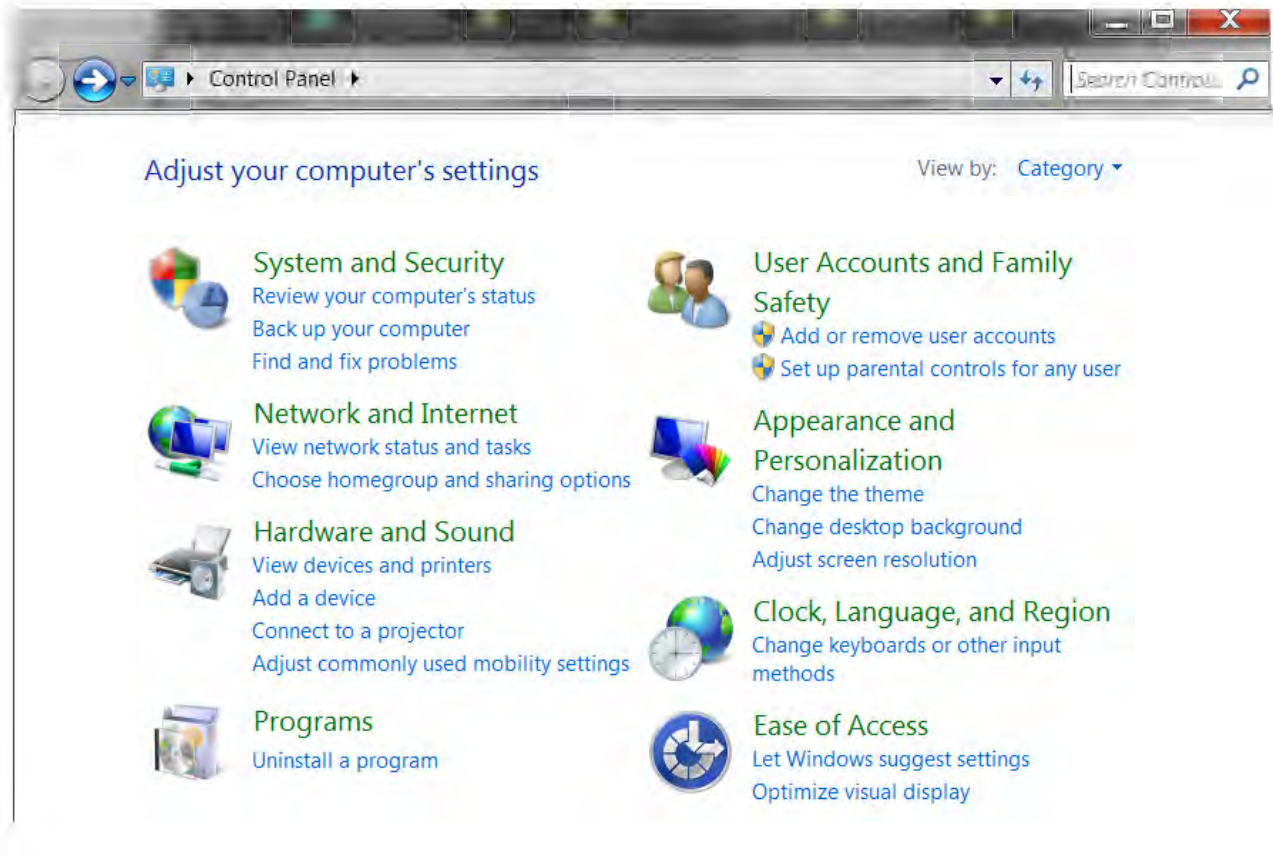
The following sections of this guide will cover important steps necessary to use the 3D printer. These steps are neither comprehensive, nor necessarily in order for daily printing use; however, they will be useful for setting up the printer to work with your computer and its network, operating it for regular 3D printing use, and for configuring the printer controller for any changes to the printer prototype. The Duet Ethernet controller at the heart of this machine comes with extensive documentation as provided by Duet3D through their Wiki page. For any questions and procedures not covered in this guide, please consult the following link for more information:

https://duet3d.dozuki.com/Wiki/Step_by_step_guide

Section 1 – Printer Network Setup to Computer

To effectively connect the 3D printer's Duet controller over its Ethernet network requires your computer to have an Ethernet port and be configured in the following way. With these steps, you can directly plug in your computer to the Duet's Ethernet connector to access the web control interface. To access the printer over the network rather than a hardwired connector, the printer may be directly connected to your internet router – set up should still be a similar procedure as will follow in the following sections. Please note, these steps use screen captures from Windows 7 and may differ for your personal computer.

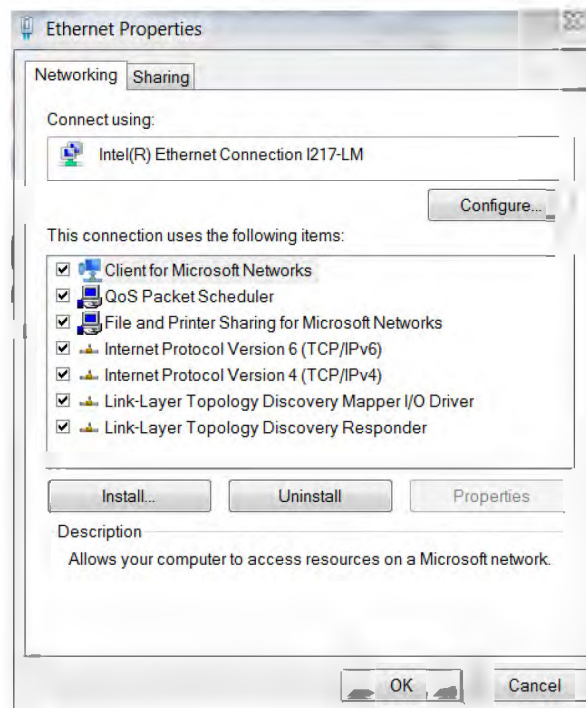
1. Go to computer *Control Panel*.



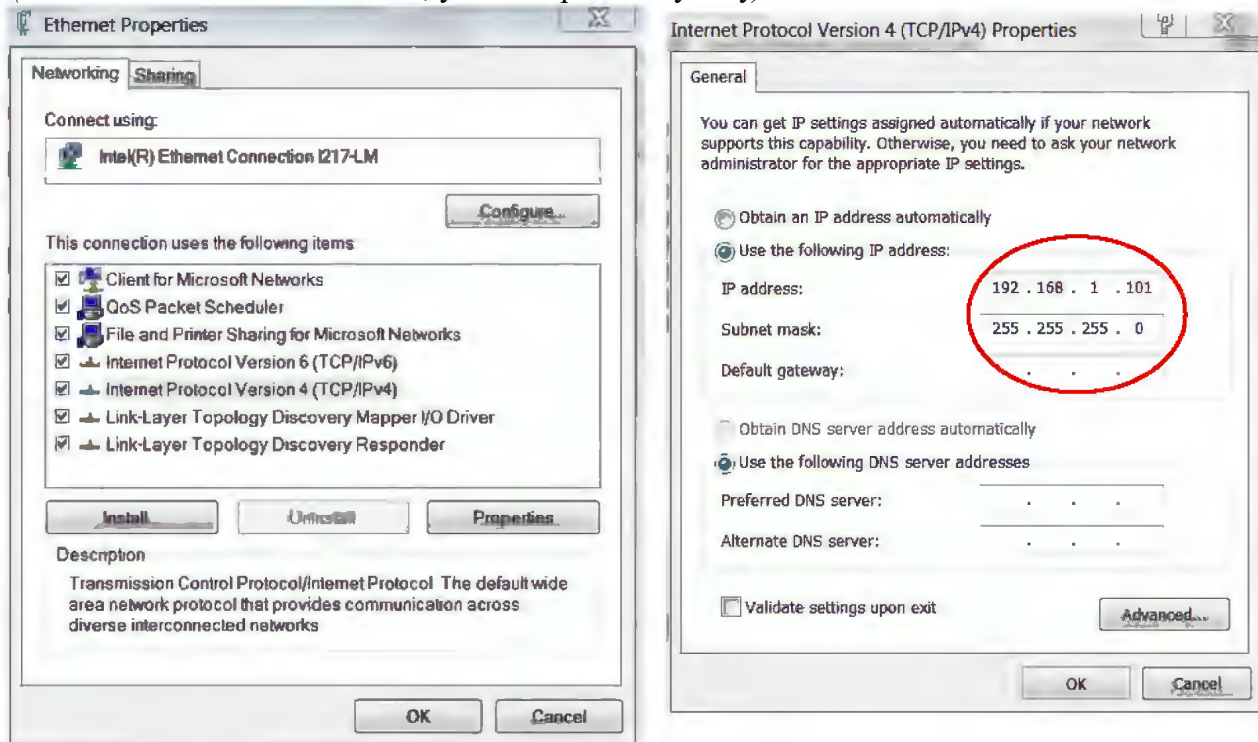
2. Control Panel -> Network & Internet -> Sharing Center -> Change Adapter Settings



3. Right-click on *Ethernet* and select **Properties**



4. Select *Internet Protocol Version 4 (TCP/IPv4)* -> *Properties* -> *Enter Distinct IP address* (192.168.1.101 used in this case, your computer may vary)



5. To check which IP addresses are already being used by your computer, open *cmd.exe* and enter "*arp -a*".

```
C:\Windows\system32\cmd.exe
Microsoft Windows [Version 6.1.7601]
Copyright (c) 2009 Microsoft Corporation. All rights reserved.

C:\Users\Liam Smyth>arp -a

Interface: 142.232.167.59 --- 0xe
Internet Address      Physical Address      Type
142.232.160.12        dc-ef-ca-c8-c6-99    dynamic
142.232.163.190       00-57-c1-b6-e0-da    dynamic
142.232.171.64        5c-1d-d9-23-01-9c    dynamic
142.232.175.254       10-0e-7e-98-ac-78    dynamic
142.232.175.255       ff-ff-ff-ff-ff-ff    static
224.0.0.2             01-00-5e-00-00-02    static
224.0.0.22            01-00-5e-00-00-16    static
224.0.0.251           01-00-5e-00-00-fb    static
224.0.0.252           01-00-5e-00-00-fc    static
239.255.255.250       01-00-5e-7f-ff-fa    static
255.255.255.255       ff-ff-ff-ff-ff-ff    static

C:\Users\Liam Smyth>
```

6. Ethernet Port is now configured to a static IP address for connection to the printer.

Section 2 – RepRap Firmware Configurator Tool

Using the RepRap Firmware Configurator Tool requires you to know what system specifications you are using. The following steps will show how the current configuration file is set up for the 3D printer handed off to Stephen McMillan at the close of the Capstone project.

1. Visit: <https://configurator.reprapfirmware.org/Start>

2. Select Custom Configuration

Start General Motors Endstops Heaters Tools Compensation Network Finish RepRapFirmware Configuration Tool

Welcome to the new RepRapFirmware Configuration Tool

Please follow this wizard to obtain an individual configuration bundle for your printer

If you are using a printer that was originally shipped with RepRapFirmware, you can select a predefined template here:

- T3P3 Mini Kossel
- RepRapPro Ormerod 1
- RepRapPro Ormerod 2
- RepRapPro Fisher

The following machine templates were contributed by users and have not been thoroughly tested:

- Anet A8
- Distech Prometheus System
- Reach3D Printer
- Wanhao Duplicator i3

Alternatively you can create your own individual configuration by creating a new one from scratch or by loading an existing JSON template:

- Custom configuration
- Use existing configuration

Note: If you encounter problems, please report your problems on the [Duet3D forums](#) or on [GitHub](#).
Some configuration options may not be available yet. In this case please refer to the [Duet3D wiki](#).

3. Under “General”, enter the following parameters. This printer is a CoreXY 3D printer with a Duet 2 Ethernet Controller with a maximum print volume of 300mm x 300mm x 300mm.

Start General Motors Endstops Heaters Tools Compensation Network Finish RepRapFirmware Configuration Tool

General Preferences

Board: Firmware version:

Read config-override.g file at end of startup process
 Save print state on power failure

Printer Geometry

Cartesian **CoreXY** CoreXZ Delta

X minimum: mm

Y minimum: mm

Z minimum: mm

X maximum: mm

Y maximum: mm

Z maximum: mm

This machine uses two coupled motors to position the nozzle on the XY plane

4. Under “Motors”, enter the following parameters. This sets the stepper motor microstepping, motor speed and acceleration, and motor current parameters. The motor current is based upon the rated current per phase of the stepper motors on this machine. For the CoreXY motors, this is 1.3A per phase and 1.68A per phase for the Z-motors. It is recommended to set these values between 50% and 85% of the total rated current in each motor to achieve maximum efficiency without burning out the motor. The maximum motor speeds are 365 mm/s for the CoreXY motors and 2.80 mm/s for the Z-axis motor. It is worth testing these values to see what will work and what won’t work on this printer.

Axes									
Drive	Direction	Microstepping (interpolation)	Steps per mm	Max. Speed Change (mm/s)	Max. Speed (mm/s)	Acceleration (mm/s ²)	Motor Current (mA)	Motor Driver	
X	Forwards	x16 (on) <small>interpolated to x256</small>	9.523 ✓	15 ✓	100 ✓	500 ✓	1600 ✓	0 (X)	
Y	Forwards	x16 (on) <small>interpolated to x256</small>	9.523 ✓	15 ✓	100 ✓	500 ✓	1600 ✓	1 (Y)	
Z	Forwards	x16 (on) <small>interpolated to x256</small>	1000 ✓	0.2 ✓	3 ✓	20 ✓	1680 ✓	2 (Z)	

Extruders									
Drive	Direction	Microstepping (interpolation)	Steps per mm	Max. Speed Change (mm/s)	Max. Speed (mm/s)	Acceleration (mm/s ²)	Motor Current (mA)	Motor Driver	
E0	Forwards	x16 (on) <small>interpolated to x256</small>	837.1 ✓	2 ✓	20 ✓	250 ✓	800 ✓	3 (E0)	

Motor Current Reduction

Reduce motor currents when idle

Idle Current Percentage: ✓

Idle Timeout: ✓

[← Back](#)

[Next →](#)

5. Under “Endstops”, enter the following parameters. At the time of completing the printer prototype, no Z-probe was installed. All limit switches are active low (NO) at the low end of the printer.

Start General Motors Endstops Heaters Tools Compensation Network Finish RepRapFirmware Configuration Tool

Z-Probe

Probe X Offset: 0 mm Probe Y Offset: 0 mm Probing Speed: 2 mm/s Deploy/Retract Probe

Probe Type

No Z-Probe Switch Unmodulated or Smart IR Probe Simple Modulated IR Probe Smart Effector or Piezo BLTouch

No Z-probe is installed. The distance between the nozzle and the bed must be manually determined.

Endstop Configuration

Note

Axis	Endstop Type				Endstop Location
X	None	Active high (NC)	Active low (NO)	Z-Probe	Motor Stall Detection At low end At high end
Y	None	Active high (NC)	Active low (NO)	Z-Probe	Motor Stall Detection At low end At high end
Z	None	Active high (NC)	Active low (NO)	Z-Probe	Motor Stall Detection At low end At high end

Homing Preferences

Homing Speed (First Pass): 30 Homing Speed (Second Pass): 6 Travel Speed: 100 Z Dive Height: 5

Set dive height to 30mm for initial calibration

6. Under “Heaters”, set a maximum possible temperature for the heaters and select the type of sensor used (both thermistors in this case). Under the R25 value, a pop-up menu will appear for thermistor presets – select the Semitec 104-GT2 for this machine. Custom values can be configured based upon measurements taken using these thermistors for further tuning.

Start General Motors Endstops Heaters Tools Compensation Network Finish RepRapFirmware Configuration Tool

General Heater Settings

Heated Bed

Bed Heater Output: Bed Heater Control Method: PID Bang-Bang

Assign Bed Heater to First Nozzle
 Heated Chamber

Heater Configuration

+ Add Nozzle - Remove Nozzle

Heater	Type	Temp. Limit	PWM Limit	R25	β	C	Sensor Channel
Bed	Heated Bed	120 <input checked="" type="checkbox"/>	100 <input checked="" type="checkbox"/>	100 <input checked="" type="checkbox"/>	Ω	ϵ <input checked="" type="checkbox"/> K	Bed Thermistor
E0	Nozzle	280 <input checked="" type="checkbox"/>	100 <input checked="" type="checkbox"/>	100 <input checked="" type="checkbox"/>	Ω	ϵ <input checked="" type="checkbox"/> K	E0 Thermistor

[← Back](#) [Next →](#)

7. Under “Tools”, take the default parameters unless otherwise desired.

Start General Motors Endstops Heaters Tools Compensation Network Finish RepRapFirmware Configuration Tool

Tool Preferences

Wait for Temperatures to be Reached on Tool Change
 Select First Tool on Start-Up

Tools

[+ Add Tool](#) [- Remove Tool](#)

Number	Name	Extruders	Heaters	XYZ Offsets (mm)			Mixing Ratio
0	optional	E0	E0	0	0	0	N/A

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8. Under “Compensation”, enter the following values.

Start General Motors Endstops Heaters Tools Compensation Network Finish RepRapFirmware Configuration Tool

Note: 3/4/5 Point Bed Compensation has been deprecated. It has been replaced by the new Mesh Bed Compensation.

Bed Probing for Mesh Bed Compensation

X Minimum: 15 mm X Maximum: 285 mm Y Minimum: 15 mm Y Maximum: 285 mm Grid Spacing: 20 mm

Orthogonal Axis Compensation

Enable Orthogonal Axis Compensation

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9. Under “Network” enter a printer name and password. Deselect *Acquire Dynamic IP Address via DHCP* and enter a pre-set IP address for the printer. In this case, use *192.168.1.100* (remember the computer was previously set to *192.168.1.101*). The subnet mask and gateway are both okay left as their default values.

Start General Motors Endstops Heaters Tools Compensation Network Finish RepRapFirmware Configuration Tool

Network Settings

Enable Network

Printer Name: ✓ Password: ✓

MAC Address: ✓

Acquire Dynamic IP Address via DHCP

IP Address: ✓ Subnet Mask: ✓ Gateway: ✓

Enable HTTP (required for Duet Web Control)

Enable FTP

Enable Telnet

[< Back](#)
[Next >](#)

10. Enter your desired parameters under “Finish” which sets cooling fan frequency and speeds.

Start General Motors Endstops Heaters Tools Compensation Network Finish RepRapFirmware Configuration Tool

Cooling Fans + Add Fan - Remove Fan

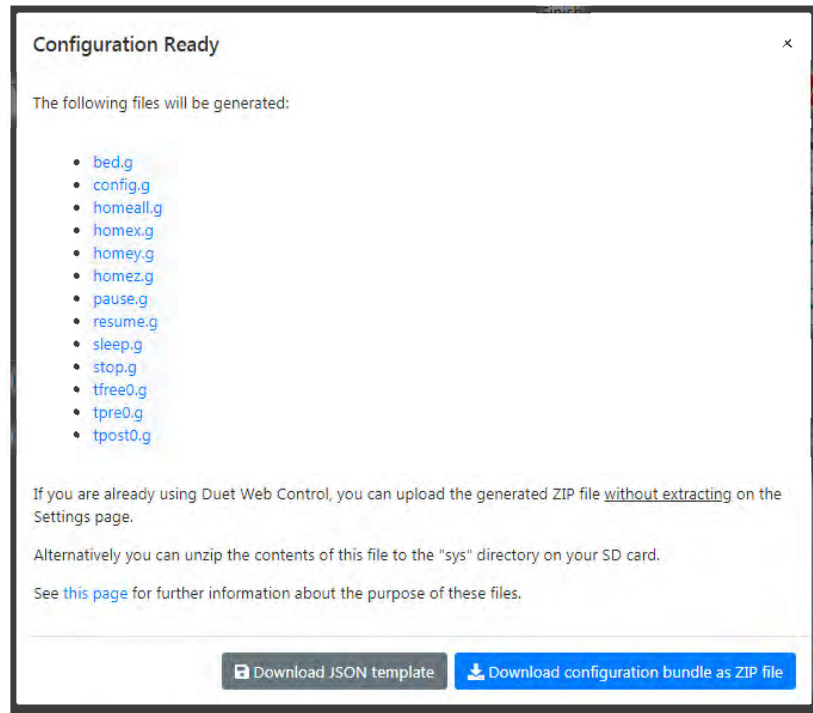
Name	Speed	Inverted	Frequency	Thermostatic Control	Monitored Heaters	Thermostatic Mode Trigger Temperature
FAN0	<input type="text" value="0"/> % ✓	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No	<input type="text" value="500"/> Hz ✓	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No	<input type="checkbox"/> Bed <input checked="" type="checkbox"/> E0	<input type="text" value="45"/> C ✓
FAN1	<input type="text" value="100"/> % ✓	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No	<input type="text" value="500"/> Hz ✓	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No	<input type="checkbox"/> Bed <input checked="" type="checkbox"/> E0	<input type="text" value="45"/> C ✓

Miscellaneous

Custom Settings for config.g: [Full list of all available G-codes](#)

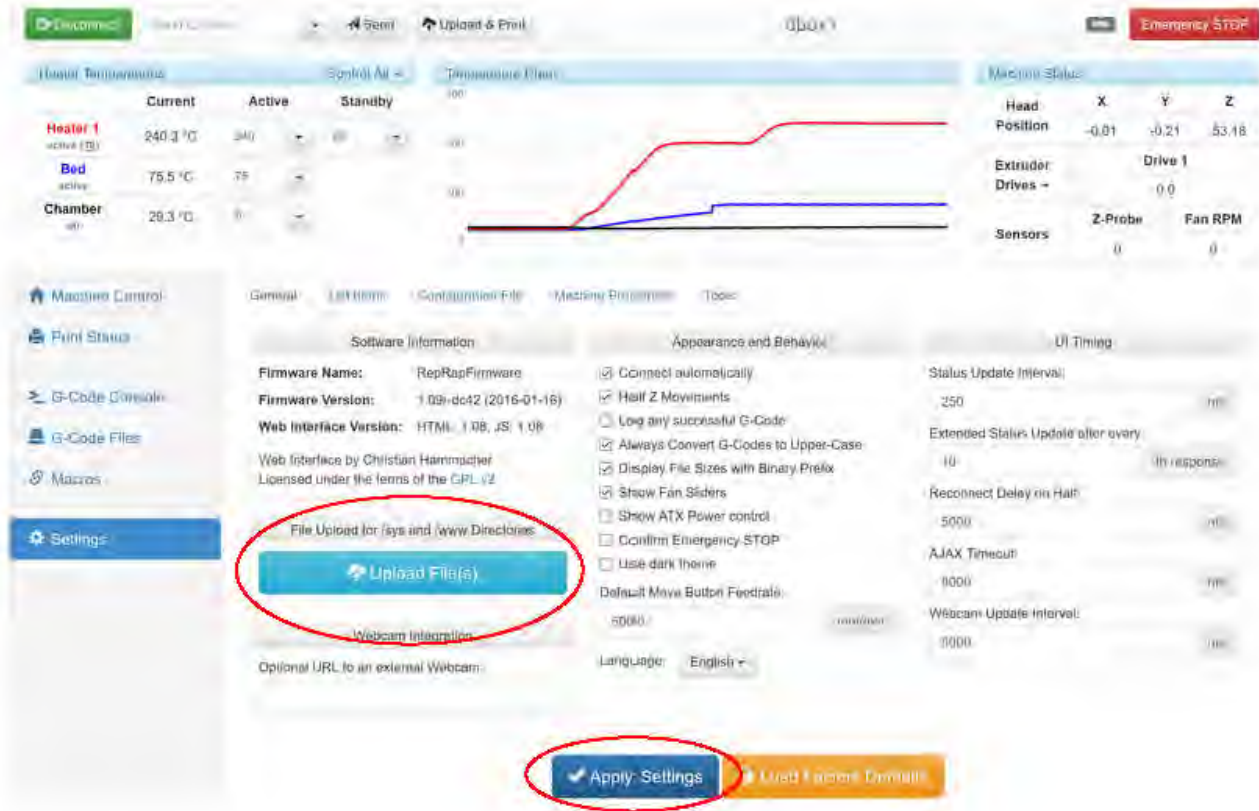
[< Back](#)
[Finish >](#)

11. Hit “Finish” and the following window will appear. These are all the files required to configure and run the Duet controller. Download the configuration bundle as a ZIP file.



12. Now, power up the 3D printer controller using either the 24V power supply or a microUSB connection. Plug in your Ethernet cable to both your computer and the controller. Go to your browser window and enter your controller's IP address: **192.168.1.100**. This will open the Duet Web Control user interface when your printer is powered. A full user's guide to the Duet Web Control can be found here: https://duet3d.dozuki.com/Wiki/Duet_Web_Control_Manual

In here, you may go to *Settings* and *Upload System Files*, circled in red below. Find and select the downloaded *config.zip* file. Once uploaded, confirm settings and save. You have now updated the printer controller's firmware to match your desired parameters. No recompiling is required.



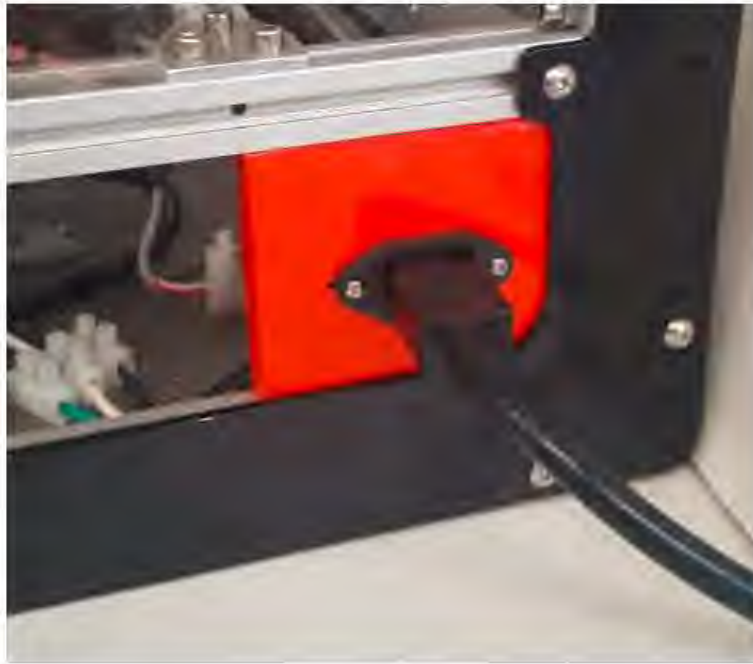
Note that these files may be viewed in a text editor if you take the controller's microSD card and connect it to your computer. *Config.g* under the *Sys* folder is the file to be updated to reflect your desired parameters. Please exercise care when changing these files – the Duet Wiki page offers many directions for using G-Code commands to change the printer's configuration to match your desired parameters.

Section 3 – 3D Printer Power-up and Safety Features

This section will cover powering up the 3D printer and using the Duet Web Control and Duet PanelDue touchscreen LCD panel. It will also cover the on-board safety features including fuses and switches that may need to be replaced in the event of an electrical failure.

Section 3.1 – Power-up

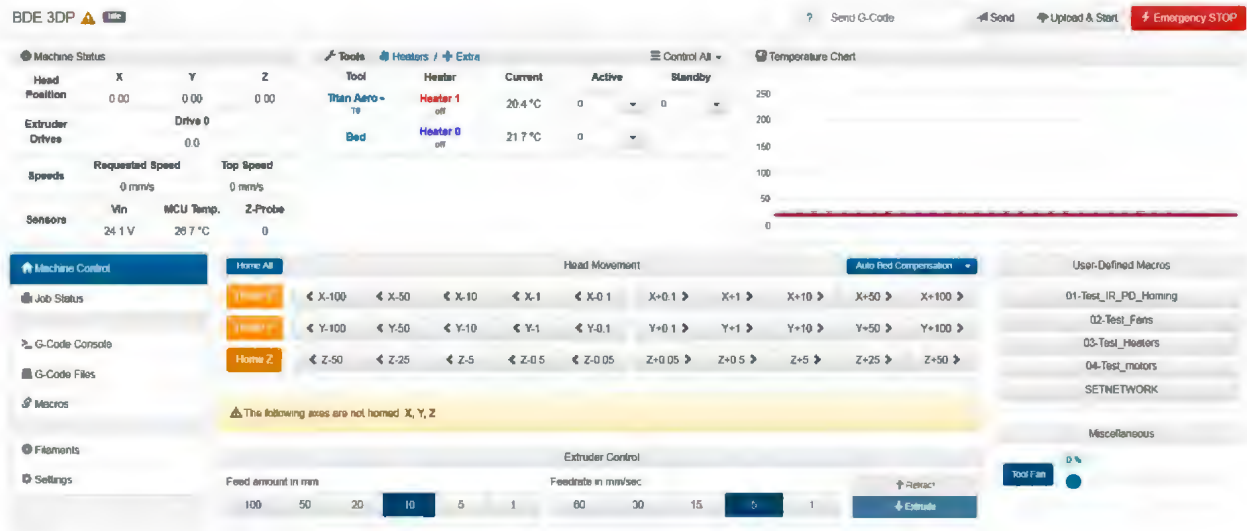
1. To power up the printer, use the provided 10' IEC cable and plug it in to the mating connector at the back right of the system.



2. To power the controller and touchscreen display, flip the leftmost switch at the front of the machine. This will allow you to access the controller through either the Duet Web Control application or the touchscreen LCD. The rightmost switch turns on the heated bed power and should only be used when preparing to make a print.



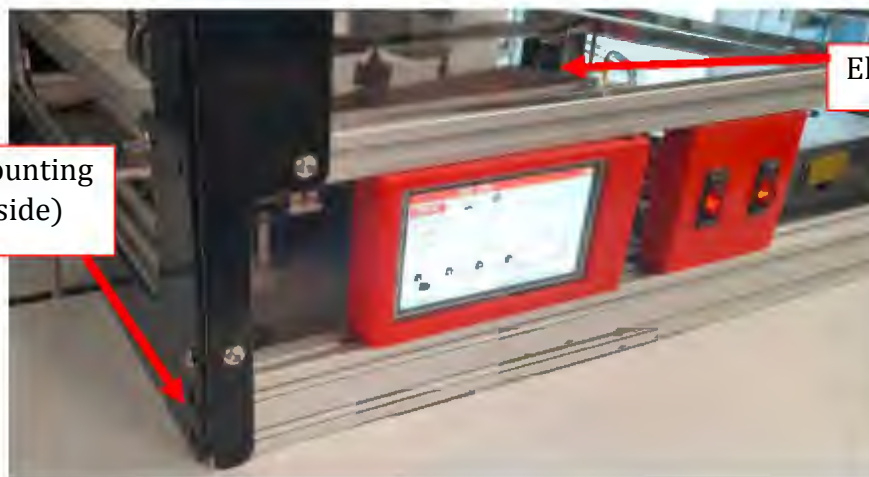
3. The Duet PanelDue and Duet Web Control application both offer similar control features with regards to jogging the print head, moving the bed, and changing heater temperatures. Between either user interfaces, the Duet Web Control offers more features including the ability to add user-created macros for pre-heating the bed, for example. For more information on Duet Web Control, consult this link: https://duet3d.dozuki.com/Wiki/Duet_Web_Control_Manual.



Section 3.2 – Safety Features

The printer’s electrical system incorporates several safety features that will protect components and the user from any potential short circuit situation. These features are built in with switchable fuses, glass fuses, and a thermal cutoff fuse. They can be accessed by removing the four m5 cap screws from the bottom front of the frame, as pictured below, and the tray can be slid forwards for ease of access.

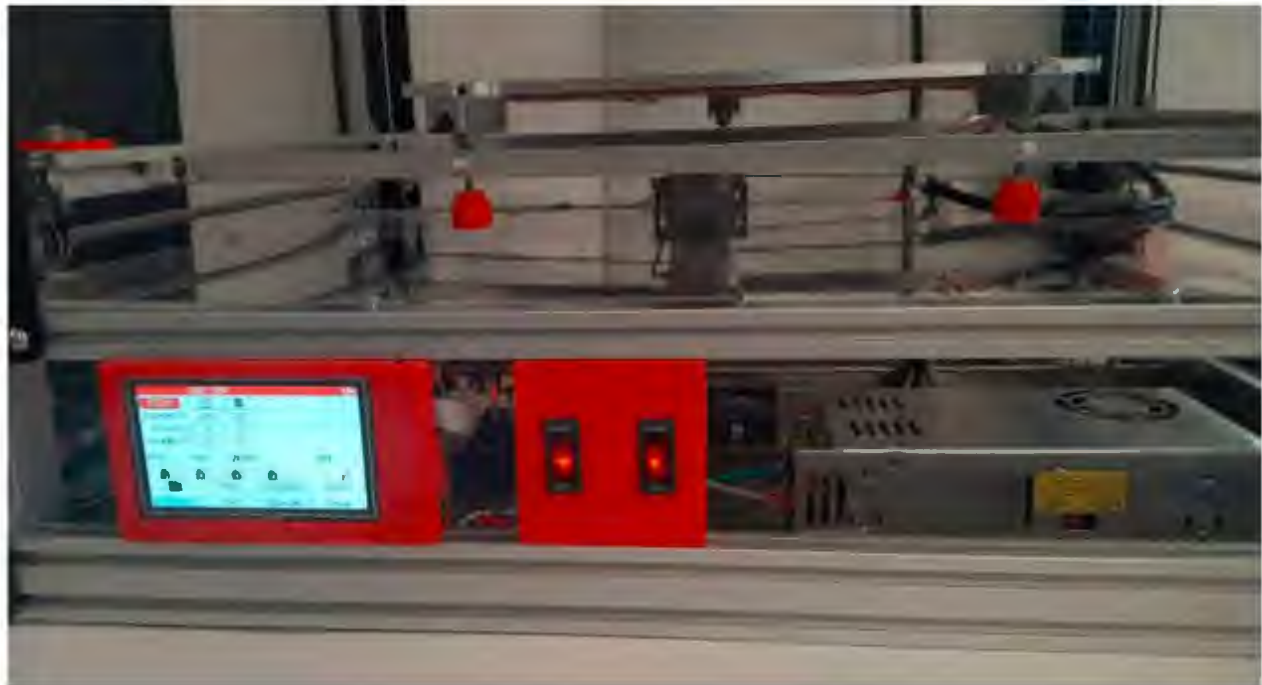
The electrical bay is covered by two acrylic covers which prevent hands from entering the system and plastic or metal shavings from falling on delicate electrical components. **If these are to be removed, ensure they are clear of debris that may fall into the machine.**



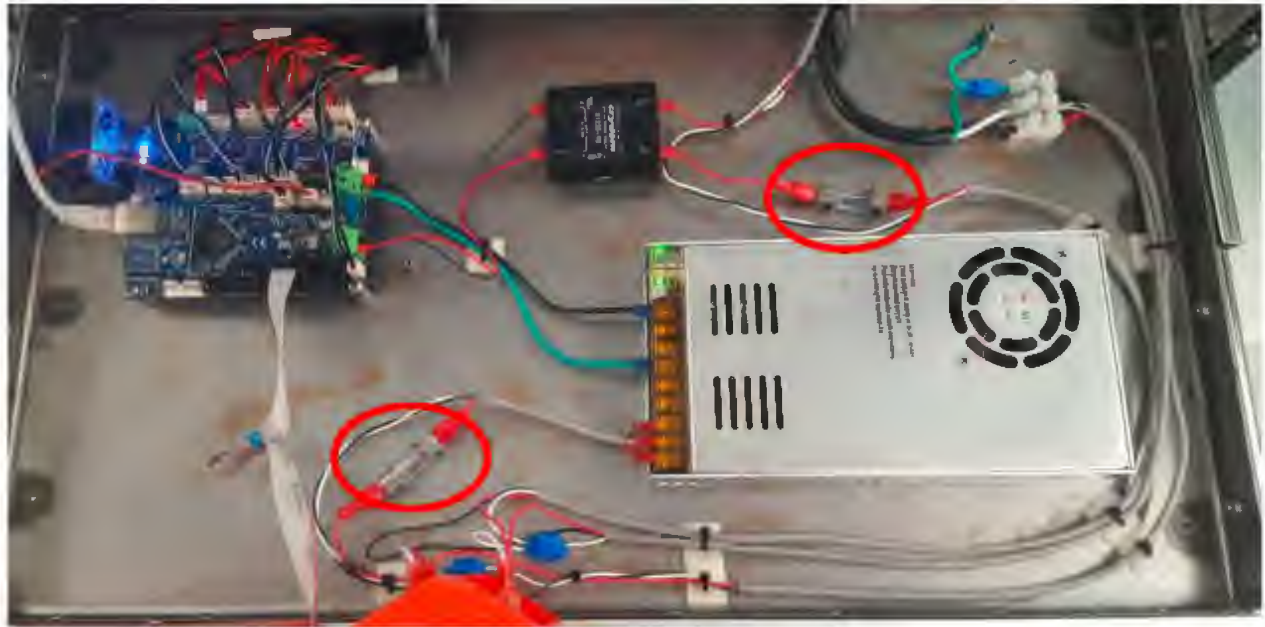
1. Firstly, the system is earth grounded on the bed. This protects the entire frame and provides a ground for any surface mounted electrical components.



2. The 10A switchable fuses are mounted for both the power circuit and bed heater circuit at the front of the machine. Just as they are fuses, they are also the system power switches.



3. The 10A glass fuses are mounted on the printer access tray. Additional fuses can be found with the printer's spare parts for easy replacement.



4. The thermal cutoff (TCO) fuse is mounted to the bed using a silver binder clip. This fuse is used to prevent rapid overheating of the bed in the event of the solid state relay failing. The TCO is a one-time use fuse so once blown, the fuse must be removed and a new one soldered in-line with the bed heater power cables. When soldering the fuse, be sure to heatsink the two leads to prevent the residual heat from the soldering process from prematurely blowing the fuse. **Be sure to wrap the entire TCO and its leads in 5 mil Kapton tape as its body is electrically live when powered.**

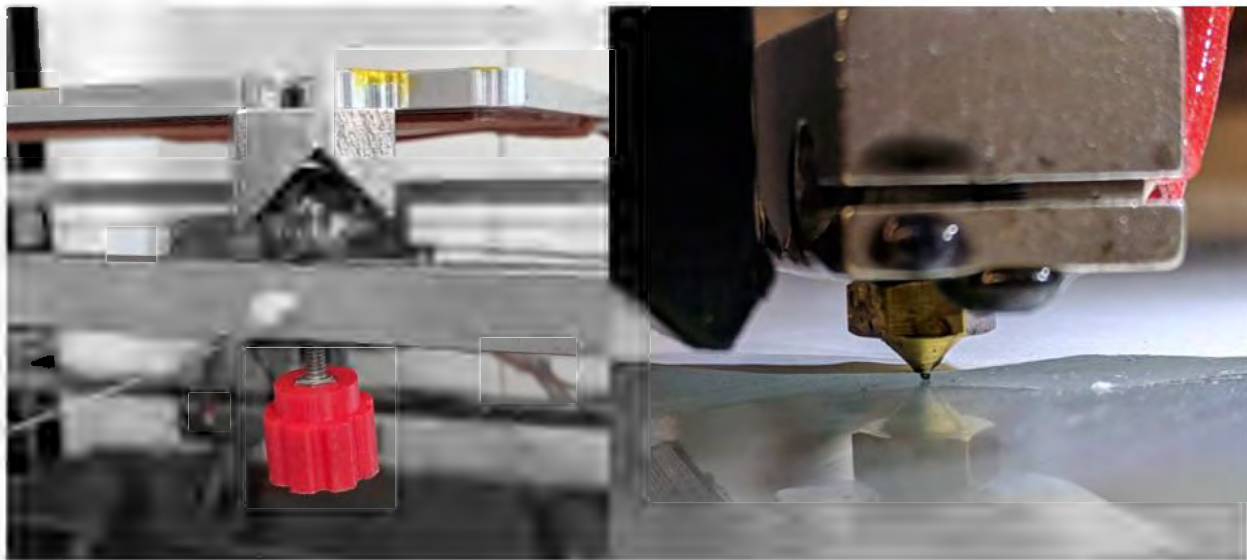


Section 4 – Bed Levelling Calibration

There are several aspects which go into the generic term of *bed leveling* for a 3D printer. These can refer to the height of the print bed in relation to the printer nozzle, the perpendicularity between the print bed and print nozzle, and the physical flatness of the printer bed, which may be warped or bowed. This section will outline a rough method for the first of these two categories (the height of the print bed in relation to the printer nozzle, and the perpendicularity of the nozzle to the bed), as the final category should be tackled by ensuring the build quality of the printer bed.

The bed height in relation to the print nozzle should first be set roughly using the Z-axis limit switch. This can be done by moving the limit switch along the T-slot rail to which it is attached. By doing this, the homed position of the print bed will be moved closer to or further from the printer nozzle. Extreme care should be used during this procedure to ensure that the bed does not ram into the nozzle while attempting to reach home position.

Once the limit switch height has been set, the leveling knobs below the printer bed can be used to finely adjust the height of the printer bed. To accomplish this task, the printer bed should be raised to the home position, then power to the printer turned off. After this, the printer head can be manually moved to different locations across the printer bed, first checking the four corners of the plate before testing a few points in the middle. A piece of paper should be placed between the printer nozzle and the print bed, and the bed height should be adjusted until the paper can move with only some slight friction due to the bed and nozzle height.



Upon completion of leveling the printer bed through the paper strategy, the printer bed will now be appropriately levelled to the extent which printing can occur. Fine adjustments can be made as the printer bed to optimally level the bed through creating prints and evaluating the first layer of the prints. A large, flat square can be printed on the bed to help evaluate the printer bed adjustments.

If prints are failing to adhere to the print bed, the bed height may not be the sole cause. Check the printer bed temperature and print speeds. If printing PLA, the bed temperature should be between 50-60°C for optimal adhesion. Second, ensure the first layer print speed is at or below 20mm/s to ensure adhesion. Finally, a glue stick, hair spray, or other adhesion promoter may be used to help.

If adhesion still fails, further software settings may need to be investigated such as the slicing software or controller implementing a first layer offset. This may be done to prevent the print head from hitting the printer bed on the first layer, which may damage both the nozzle and printer bed.

Section 5 – Printer Use

This section will briefly cover how to operate the printer, including start-up, print preparation, and print monitoring. It will entirely rely upon using the Duet Web Control interface for print monitoring once the printer is powered.

1. Power on the printer controller and bed heater using the two switches at the front of the machine. Connect this to the Duet Web Control interface by entering your printer's IP address into your web browser. Your initial page will be the "Machine Control" tab from which you can monitor current printer heater temperatures, the current head position, and run user-defined macros such as filament loading or heater preparation for printing (each is circled in red).

The screenshot displays the Duet Web Control interface for a printer named 'dbox1'. The interface is divided into several sections:

- Heater Temperatures:** A table showing the current, active, and standby temperatures for Heater 1, Bed, and Chamber. The values are circled in red.
- Temperature Chart:** A line graph showing the temperature of the heaters over time.
- Machine Status:** A table showing the current head position (X, Y, Z) and extruder status. The values are circled in red.
- Head Movement:** A set of buttons for moving the head in X, Y, and Z directions.
- Extruder Control:** A set of buttons for controlling the extruder, including retract and extrude.
- User-Defined Macros:** A list of macros that can be executed, such as filament loading and heater preparation. The macros are circled in red.

Heater	Current	Active	Standby
Heater 1 active (19)	241.0 °C	240	60
Bed active	75.3 °C	75	
Chamber	28.7 °C	0	

Head Position	X	Y	Z
	-0.01	-0.21	53.18

Extruder	Drive 1
	0.0

Sensors	Z-Probe	Fan RPM
	0	0

Machine Control

Print Status

G-Code Console

G-Code Files

Macros

Settings

Home All

Head Movement

Auto Delta Calibration

Extruder Control

Feed amount in mm: 100 50 20 10 5 1

Feedrate in mm/sec: 60 40 20 10 5

Retract

Extrude

User-Defined Macros

- __prepare_ABS
- __prepare_PETG
- __prepare_PLA
- _Load filament
- _Unload filament
- Allow_cold_extrusion
- bed_report
- bed4x11p

2a. Go to the “Print Status” page. From here you can print files by pressing the “Upload and Print” button at the top of any page.

The screenshot shows the 'Print Status' page of a 3D printer control interface. At the top, there is a 'Send G-Code...' input field, a 'Send' button, and a circled 'Upload & Print' button. The interface is divided into several sections:

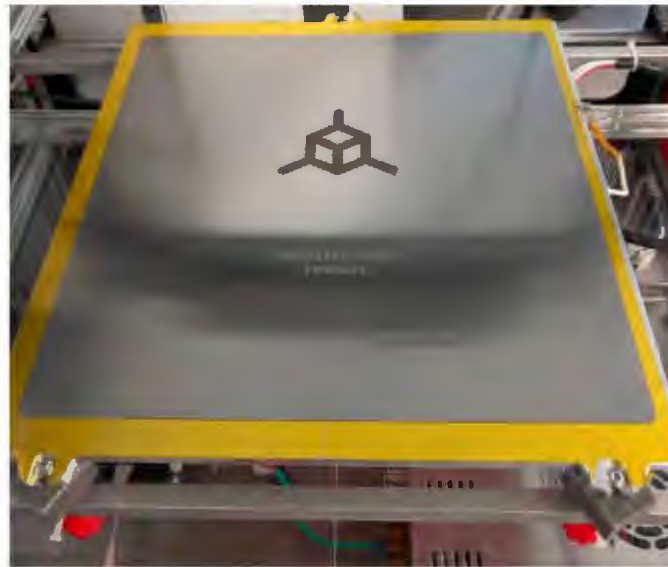
- Heater Temperatures:** A table showing the status of Heater 1, Bed, and Chamber.
- Temperature Chart:** A line graph showing temperature over time.
- Machine Status:** A table showing Head Position (X, Y, Z), Extruder Drives, and Sensors.
- Print Control:** A section with a 'Pause Print' button and checkboxes for 'Override Fan Value', 'Enable Auto-Sleep', and 'Speed Factor'.
- File Information:** A section showing details about the current print file, including size, object height, layer height, filament usage, and estimated end time.

2b. Files can also be uploaded to the “G-Code Files” tab. In here, they can be organized in directories on the console; however, it is recommended for the most up-to-date file used for printing to be uploaded using the “Upload and Print” button of Step 2a.

The screenshot shows the 'G-Code Files' tab of the 3D printer control interface. The 'G-Code Files' tab is circled in red. The interface displays a list of G-code files with the following columns: File Name, Size, Object Height, Layer Height, Filament Usage, and Generated by.

File Name	Size	Object Height	Layer Height	Filament Usage	Generated by
D-Box					
HXm					
100mm_calibration_block_255.g	1.9 MiB	6.11 mm	1 / 0.28 mm	3754.5 mm	Slic3r 1.2.9 on 2015-10-01 at 23:33:53
100mm_calibration_block.g	298.1 KiB	6.6 mm	0.35 / 0.25 mm	2983.3 mm	Slic3r 1.2.9 on 2015-10-09 at 13:42:29
3D-Benchy_255_025.g	3.8 MiB	49.1 mm	1 / 0.25 mm	6055.2 mm	Slic3r 1.2.9 on 2015-10-05 at 14:06:37
3D-Benchy_PLA_Fisher.g	1.9 MiB	48.7 mm	0.35 / 0.25 mm	4068.4 mm	Slic3r 1.2.9 on 2016-01-14 at 22:16:51
3D-BenchyPLA.g	2.7 MiB	48.55 mm	0.35 / 0.2 mm	4556.1 mm	Slic3r 1.2.9 on 2015-10-25 at 18:14:47

3. Once the files are uploaded, the flexible steel printing surface must be placed on the magnetic bed and cleared of any debris. If any printing surface adhesives are to be used, they should be applied now.



4. At the point when the bed and extruder have reached printing temperature, the printer is ready. User-defined macros which can be found online can automate this process. During printing, the “Print Status” window will provide feedback on heating element temperatures, time remaining, and the layer statistics. Here, the print may also be paused.

The screenshot displays the printer's control interface with the following sections:

- Top Bar:** Includes 'Disconnect', 'Send G-Code...', 'Send', 'Upload & Print', 'dbox1', 'Printing', and 'Emergency STOP' buttons.
- Heater Temperatures:**

Heater	Current	Active	Standby
Heater 1 active (T9)	240.2 °C	275	60
Bed active	77.6 °C	80	
Chamber off	30.3 °C	0	
- Temperature Chart:** A line graph showing temperature over time for Heater 1 (red), Bed (blue), and Chamber (black).
- Machine Status:**

Head Position	X	Y	Z
	-0.01	-0.21	53.18

Extruder Drives	Drive 1
	0.0

Sensors	Z-Probe	Fan RPM
	0	0
- Machine Control Panel:**
 - Print Status:** Shows 'Printing struct_bracket2.g, 0.0% Complete' and 'Layer: 0 of 66, Filament Usage: 0.0mm of 971.3mm (971.3mm remaining)'. Includes a 'Pause Print' button (circled in red) and 'Layer Statistics' (circled in red).
 - Speed Factor:** A slider set to 100%.
 - Extrusion Factors:** A slider for 'Extruder 1' set to 100%.
 - File Information:**
 - Size: 580.5 KIB
 - Object Height: 13.55 mm
 - Layer Height: 0.6 mm / 0.2 mm
 - Filament Usage: 971.3 mm
 - Generated by: Slic3r 1.2.9 on
 - Collected Data:**

Warm-Up Time	Current Layer Time	Last Layer Time	Print Duration
09s	n/a	n/a	09s
 - Estimations:**

Based on	Filament Usage	File Progress	Layer Time
Time Left	n/a	n/a	n/a
Est. End Time	n/a	n/a	n/a

5. Once the print is complete, the flexible print surface must be carefully removed from the magnetic bed surface. It can then be slightly bent to easily separate the part from the printing surface. The machine may now be powered down or used for another printing job.