Inyo National Forest Sign Maker
Final Design Report

Cal Poly Tree's Company

Brandon Mainini bmainini@calpoly.edu
Lauren Kirk lakirk@calpoly.edu
Alec Boyer aboyer01@calpoly.edu

Sponsor:
Lee McFarland

Mechanical Engineering Department
California Polytechnic State University
San Luis Obispo

2016 – 2017

Statement of Disclaimer

Since this project is a result of a class assignment, it has been graded and accepted as fulfillment of the course requirements. Acceptance does not imply technical accuracy or reliability. Any use of information in this report is done at the risk of the user. These risks may include catastrophic failure of the device or infringement of patent or copyright laws. California Polytechnic State University at San Luis Obispo and its staff cannot be held liable for any use or misuse of the project.

Table of Contents

1.Introduction

1.1. Problem Definition

Cal Poly Tree's Company has set out to improve the production rate of trail signs for the Friends of the Inyo. Paul McFarland has been tasked with manufacturing replacement signs for any and all of the damaged signs within Inyo National Forest. Presently, a single person cannot complete such a task in a time-efficient manner. The previous year's senior project team, Forest Friends, built a CNC machine to minimize time spent on producing replacement signs. Cal Poly Tree's Company has been enlisted with adding on several enhancements to more fully meet the sponsor's needs.

1.1.1. Objective

The senior project group will meet the sponsor's desired enhancements by refining the CNC machine's current design, implementing a more modernized build, and testing the sign-cutting device itself. The end goal of the project is to produce a CNC machine actively interfacing with Adobe Illustrator, outputting completed signs in under 2.0 hours, and remaining below the $5000 budget. By achieving these goals, the team hopes to deliver a product that will aid Paul McFarland and the Friends of the Inyo by increasing the production rate of producing trail signs.

- Revision 1/31/17 -

It was previously determined that Adobe Illustrator would be the main interface between user and machine when designing the final appearance of a trail sign. However, throughout the iteration process, the team has decided that Fusion 360 will be used in place of Adobe illustrator.

Fusion 360 is an open-sourced CAD/CAM designing software supplied by Autodesk, a leading developer in 3D design software. The tool is offered free to students, teachers, and non-profit organizations, which satisfies the team's need for a low-budget user-interface. Additionally, Paul McFarland, the main user of the team's CNC machine, has experience with the CAD software which will more easily integrate with the CNC machine to-be-designed.

1.2. Project Motivation

The Friends of the Inyo work hard to keep the forests well-maintained for visitors. Trails, signs, and markers are always under careful observation to prevent accidents or disorientation of visitors. Routed wooden signs, in particular, take a sizeable amount of skill, manual labor, and time to produce. Presently, the Friends of the Inyo create wooden signs by tracing letters onto a blank, wooden board. Then they proceed by cutting the stenciled letters and symbols using a palm router. Depending on a given board's size and the amount of content needing to be etched onto the board, the sign development process often requires two to three days for completion. Cal Poly Tree's Company aims to shorten the length of time it takes to create a sign with hopes that the Friends of the Inyo can replace worn trail signs quickly and allocate their time to other, urgent needs.

1.3. Scope

The main goal of Cal Poly Tree’s Company is to assist the Friends of the Inyo with expediting the trail sign production process. The team will refine the current design by enhancing the current build to an automated 3 axis CNC machine. Such a design will be completed in under 2.0 hours. The CNC machine which Cal Poly Tree’s company will work with is built entirely by the students. Using such a method ensure that at both the hardware level and the software level, Cal Poly Tree’s Company will be able to fully optimize the system under the constrained budget. At completion, the project will eliminate the majority of manual labor used to produce these large signs, will produce higher quality signs at a greater consistency, and deliver an increased production rate.

The scope of the project focuses on the design process which extends from analyzing and modifying the previous team’s design to fully refine and develop a functioning prototype. Intermediate steps, such as conceptual ideation, design development, fabrication, and prototype testing will be executed according to the requirements outlined within the ME Senior Project course layout. Any derivatives or improvements to the final prototype developed by Cal Poly Tree’s Company extends beyond the original scope of this project.

1.4. Stakeholders

The impact of the project extends beyond those directly involved in the production and operation of the Forest Sign Maker; hikers and civilians who visit Inyo National Park will be reading these signs and ultimately, they will benefit from the endeavors. A successful prototype will ensure these visitors are able to safely explore the Inyo National Forest. Having acknowledged the visitors as the ultimate end user, this project also impacts to The Friends of the Inyo, Cal Poly Tree’s Company, Paul McFarland, and Lee McFarland.

The Friends of the Inyo is a non-profit organization in California that works in tandem with the United States Department of Agriculture (USDA) Forest Service (FS) to maintain the Inyo National Forest. In particular, they are a "...conservation organization dedicated to exploration, preservation, and stewardship of the public lands of Eastern Sierra. They ensure the place is preserved for future generations..." (Friends of the Inyo). They manage the signs on all roadways and trails within the Inyo National Forest and thus will benefit greatly from increased sign production.

Cal Poly Tree’s Company is a team of three Cal Poly senior engineering students. Brandon Mainini (Mechanical Engineering), Lauren Kirk (Computer Engineering), and Alec Boyer (Computer Engineering). The first part of the team name, “Cal Poly”, serves as a reminder that the senior project will be designed, built, and engineered at California Polytechnic State University, San Luis Obispo. The second portion of the name, “Tree’s Company”, serves as a light-hearted reminder of the three individuals working together to promote and maintain the country’s national forests. In a broader scope, the project can serve as a foundation for encouraging other national forest organization to follow a similar method of generating replacement signs for the thousands of miles of forest trails within the United States.

Paul McFarland is an employee of the Friends of the Inyo. Paul works during the summer to help maintain the forest after the winter season has passed. At present, he uses a hand router to carve letters into a wooden board that will serve as a replacement sign. He spends two to three days on this process. Paul has requested the assistance of Cal Poly Tree’s Company to provide a faster and more consistent sign development process.

Lee McFarland, father of Paul McFarland, is the sponsor of the project. In addition to being the senior project advisor, Lee McFarland will assist Cal Poly Tree’s Company with communication between the co-sponsor, Paul, and the development of the project.

The visitors and hikers trekking through Inyo’s national mountain trails rely on indicator signs to safely explore the wilderness. Each year, 4 million people visit Inyo National Park. Wooden signs generated by the Forest Sign Maker will populate these wilderness trails. Visitors reading the signs will have the luxury to stop and read each sign up close. Following the trail sign guidelines provided by the United States Forest Service, Cal Poly Tree’s Company will help create easily understood signs such that visitors might continue with their exploration safely.

2. Background

2.1. Guidelines for Trail Signage

Due to the purpose of this project, it is essential to understand the human factors involved in the experience of an end user. To benefit the end user (hikers) the most, words must be easily read without detracting from the wilderness experience. An example of such a human factor considered in the trail sign design is letter height. One must consider if words are large enough for the average person to read with ease from a safe hiking distance. Unfortunately, quantifying such characteristics requires an exhaustive amount of metadata analysis on involved human factors.

Conveniently, the Forest Services (FS) has published standards for the creation of signs, specifying aesthetics and geometric constraints of signs. Refer to Figures 1,2 and 3 for extracts of said guidelines. These guidelines cover a wide range of signs, from highway road signs to small trail signs. The primary focus is clarity and readability. In addition, the speed of the viewer must be taken into account. For example, a road sign must have larger text than a trail sign because a driver has less time to read the sign than a hiker.

The scope of this project concentrates on wooden trail signs measuring from 1'x1' to 2'x4'. Guidelines published by the FS provide suggestions for the layout of the text, including font, stroke size, spacing, and symbol size. Since the wooden signs produced by the Forest Sign Maker are intended to be located in the "primitive" and "non-motorized" National Forest System Trails (NFSTs), solid wood is the only base material the Forest Sign Maker is required to accommodate, see Figure 2-1 below (Forest Service).

Item	Primitive	Semiprimitive Nonmotorized	Semiprimitive Motorized	Roaded, natural	Rural/urban
1. Sign materials	Solid wood (or appearing so)	Solid wood (or appearing so)	Solid wood, plywood, limited use of synthetics and metal	Wood, natural fiberglass, limited use of synthetics and metal	Wood, metal, fiberglass, synthetics
Color or finish	Natural or stained; preservative not evident	Natural or stained; preservative not evident	Natural, stained, or painted Retroreflective	Stained or painted Retroreflective	Painted, stained etched or decals Retroreflective

Figure 2-1. FS guidelines extract confirming sign material, color, and finish

The FS categorizes three different styles of trail signs, see Figure 2-2 (Forest Service). Due to the scope of this project, the Forest Sign Maker must only accommodate Trail Directional (TD) shaped signs, which are rectangular in design. It will not be required to handle an odd-shaped sign, such as those formatted in the Trail Directional & wilderness (TDW) style.

TD — Nonmotorized, primitive and wilderness use (routed)

TDW — Wilderness use (optional) (routed)

FRD — Motorized, bicycle and cross-country ski use (retroreflective)

Figure 2-2. FS Guidelines extract depicting various trail sign shapes

Furthermore, the FS guidelines indicate a minimum letter high of one-inch for the trail signs. This specification is in accordance with the American Standards Association (ASA) for non-motorized trails. The Federal Highway Administration (FHWA) has also adopted this standard for text sizes with different text "series", ranging from Series A (narrowest) to Series F (widest) letter spacing. Series C has been accepted as the norm for trail signing and will be used by the Forest Sign Maker in order to produce acceptable trail signs. The details for this style can be seen below in Figure 2-3.

Trail type	Sign face	Capital ASA Series C text	Color	Shape
Hiker/pedestrian pack and saddle	Typically routed	1 inch, routed	Unfinished wood with scorched or blackened legend or WPC material	TD
Wilderness	Routed only	1 inch, routed	May be unfinished wood with scorched or blackened legend	TD or TDW

Figure 2-3. FS Guidelines extract specifying the standard font to be used for routed signs

The final prototype will physically adhere to these standards. However, it is ultimately the responsibility of the operator to program the machine properly to produce signs containing text that adhere to the guidelines outlined by the FS. The Graphical User Interface (GUI) designed for the Forest Sign Maker will include built-in features to help enforce proper signage, such as defining a minimum text height and letter spacing.

2.2. Fundamentals of CNC Machinery

Computer Numerical Control (CNC) implements digital control algorithms which control the physical location of an object in three-dimensional space. Such a process can be performed without the use of closed-loop position feedback. However, doing so requires the use of stepper motors. If DC servo motors are the actuators of choice, then the CNC depends heavily on the measured position of an object in order to propel said object in the correct direction. To, accurately measure location, it is critical that the supporting mechanical components are sufficiently rigid and any deviation of the measured value will not be representative of the actual location of the controlled object. If there is a lot of compliance in a particular axis - in other words, if the system is not very rigid - then the motor controller will have a difficult time positioning the object accurately. A more rigid system facilitates accurate measurements of the controlled device.

Additionally, CNC machines tend to decompose the motion of the controlled device in two or three dimensions, normally represented as Cartesian coordinates. By providing controller actuation along three linear axes, it is possible to effectively control the three-dimensional location of the device. The orthogonality of each axis is essential to the location accuracy (CNC Concepts).

Cal Poly Tree's Company will be evaluating the rigidity and perpendicularity of the physical prototype while finalizing a detailed design of the CNC prototype for the Friends of the Inyo According to the scope of the project, stepper motors shall not be implemented. Doing so would require scrapping valuable materials, purchasing and programming unnecessary equipment, and consuming excess amounts of time and money. Such an action is not befitting the constrained budget of Cal Poly Tree's Company.

2.2.1. Stepper vs. DC Motor

In addition to the rigidity and other geometric constraints required by a CNC machine, the method of actuation is of great concern. The majority of CNC machines use DC motors connected to a power transmission unit to actuate a system appropriately. This is due to the fact that DC motors are relatively small and can provide continuous motion. Note, however, that the power transmission unit varies depending on the capacity and capability of the machine.

Despite this tradition, the designer of the CNC machine must decide between using stepper or servo DC motors. By identifying the differences between the two types of motors, it is possible to understand why servo DC motors were chosen.

Stepper motors are brushless DC motors that rotate incrementally based on a desired number of steps. Using two independent coils, the controller can send alternating pulses of voltage that alternate the magnetic field actuating the stepper motor. These steps are of a precise angle of rotation. They are also extremely repeatable without any accumulation of error. Steppers are commonly used in CNC machines because they provide open-loop position control at a relatively low cost, eliminating the need for feedback sensors. Despite their popularity, steppers must be oversized considerably in order to operate reliability. Since steppers operate in open-loop control, meaning the stepper motor controller cannot verify the actual position of a controlled object as there is not feedback information, there is the risk that the motor could be overloaded, stalled, or have skipped steps. These risks result in inaccurate and unacceptable performance degradation. Thus it is imperative that the designer must carefully size the stepper motors for desired application.

Servo motors are brushed DC motors that rotate continuously based on the applied voltage at the two motor terminals. They achieve accurate position control via closed-loop feedback information sent to the controller by an encoder. Servo motors only have one coil of copper wire wrapping the armature, meaning the motor voltage is the only input to the motor, unlike the two pulse trains seen in the stepper motors. DC servo motors are most commonly used for close-loop position control, ensuring the positional accuracy of the machine. Under this setup, the controller is able to detect if the motors are temporarily overloaded because of the encoder information, and in turn, help the motors push through obstacles, such as a dense knot. Furthermore, in comparison to stepper motors, the power dissipated by similarly sized servo motors. Whereas stepper motors operate at full power continuously, servo motors can be operated using Pulse Width Modulation (PWM) and consume less power.

As it pertains to the Forest Sign Maker project, the Cal Poly Tree's Company will consider the performance, control, and power requirements when working with control interfacing for the selected motor.

2.3. Microcontroller Basics

In the world of automation, computers are critical for making all the necessary calculations and decisions required. In many cases, these computers take the form of specialized microcontrollers, named as such for their small form factor and ability to control many peripheral components. Microcontrollers can be adapted to suit a limitless amount of needs, including CNC.

In this context, the term "microcontroller" references the printed circuit board assembly (PCB), and the term "processor" refers to the core computing integrated circuit (IC). Using the Arduino as an example, the Arduino itself is to be considered the microcontroller, and the processor it uses is the ATmega328.

2.3.1. Components

Microcontrollers are designed with practicality in mind: computing components are usually situated in the center of the PCB while interfacing peripherals are located on the edges where they can be more easily accessed.

Many processors have a plethora of built-in features such as analog-to-digital converters and general purpose input/output pins. However, other components are necessary to facilitate proper operation of the microcontroller within the CNC system. Some of the components that are necessary for CNC microcontrollers include a programming interface, a clock crystal, motor drivers, and communication ports.

- Revision 1/31/17 –

An additional component to the project will be the implementation and use of Fusion 360. Fusion 360 is a 3D CAD/CAM software design tool supplied by Autodesk. While this is not a physical component, it is as integral part to the system as Fusion 360 will be the main user interface with which the user shall design the actual sign. In earlier designs, the use of Adobe Illustrator was to be implemented. However, many of the necessary specifications provided by Adobe Illustrator were not made public knowledge and therefore the files were not modifiable. Thus, Fusion 360 was deemed to be the better option since it provided an easily modifiable file for the Raspberry Pi B+.

2.3.2. Power

An area of concern for the microcontrollers is the given power scheme, and consequently, the power dissipation scheme. For CNC purposes, the primary consideration is supplying the motor drivers with a sufficient amount of power while also sustaining the low-power processor and peripheral IC requirements. Unfortunately, DC motors operate at voltages much higher than what the given processor and other typical ICs can handle. DC motors require up to 24V, whereas the processor typically operates at a 5V range. Consequently, microcontrollers have independent low-voltage and high-voltage rails. In addition to separate rails, the microcontroller usually contains voltage regulators such that one low-voltage power supply can support all of the components regardless of a specific input voltage requirement.

As mentioned earlier, power dissipation must be considered to protect the microcontroller from overheating. There are various techniques in microcontroller board design that can aid in heat dissipation. However, such decisions are controlled by a board’s designer and if a commercial board is utilized, it removes any chance of applying such heat dissipation techniques. Aside from modifying the actual microcontroller, the most common method of increasing the heat transfer capacity of a board is to use force convection. In other words, the team will use a fan to force air over the components, inducing a forced convection to aid in the heat transfer process. As it pertains to the Forest Sign Maker project, the power dissipation rating of the microcontroller must be evaluated and modeled in order to determine whether or not an active heat dissipation scheme is necessary.

2.4. Traditional Solutions

With every design endeavor, it is beneficial to research current products or designs that satisfy the problem. If an appropriate solution already exists, then designing an equivalent product would be an inefficient use of time for all parties involved. After investigation, Cal Poly Tree's Company found that no existing CNC machine could meet our customer's needs at a reasonable price. However, three contenders that most closely match our sponsor's needs are the Rockler CNC Shark, the ShopBot Buddy, the Baileigh Industrial CNC Routing Table WR-48, and the KL-6090 Desktop CNC Router. The following is a description of each machine with the inclusion of why it is inappropriate for this project.

2.4.1. Rockler CNC Shark HD4

The Rockler CNC Shark HD4 has already been considered by the sponsor of this project. However, it is not appropriate for the project for one main reason, capacity. This machine can only accommodate boards that are 28"x36", which is too small to accommodate the largest trail signs. Furthermore, the router's precision of +-.0005 in. is far beyond the required tolerances of this project, resulting in unneeded features and higher, unnecessary costs.

2.4.2. ShopBot Buddy

Further research into CNC routers led to the discovery of another possible solution: the ShopBot Buddy. The ShopBot Buddy Model BT48 has a size capacity sufficient for the maximum sign dimensions defined in this project (2' x 4'). Unfortunately, this product is delivered pre-assembled with the company's proprietary version of CAD/CAM software, limiting the amount of personal modification which the sponsor of future engineering students might wish to perform. Not only are these features and services superfluous to the customer's needs, the machine is priced at the high cost of $15,954, which extends far beyond the budget constraints requested by the project's sponsor. It addition to the high cost, it also weighs roughly 600 pounds, which is beyond the desired weight for the system.

2.4.3. Baileigh Industrial CNC Routing Table WR-48

After continuing the search for alternative solutions, a third potential solution was discovered, the Baileigh Industrial CNC Routing Table WR-48. This beast of a machine was more than capable of matching the design size and output specifications. However, this product comes with a steep price tag of $14,000 and weighs roughly 2500 pounds. After further investigation, this company does produce alternative solutions that are cheaper in price, but they still exceed the designated weight and budget and are not capable of producing signs of the desired maximum size.

2.4.4. KL-6090 Desktop CNC Router

Lastly, on the search for viable alternatives, the KL-6090 Desktop Router was chosen. Although this $3,000 option fits within the scopes budget and fulfills a few of the user desired specifications, it is incapable of producing signs of the desired size, lacks the desired user interface, and is relatively importable.

2.5. Alternative Solutions

2.5.1. Outsourced Labor

National forests are able to contract woodshops to do their sign making for them. One such company is Wood Product Signs. Unfortunately, this avenue involves additional expenses such as shipping, labor, and meeting the shop's profit margins. Having a personal CNC machine, like the idealized Forest Sign Maker, to make replacement signs is a more economical approach to creating faster and cheaper replacement signs not meant for large volume production.

2.5.2. Laser Cutting

An alternative to producing trails signs using a wood router is implementing a high power CO_2 laser cutting system. Despite the high price tag and design implications of such a high power system, the laser cutter method may be more appropriate for the team's application. Laser cutting is naturally limited to a two-dimensional plane making it ideal for sign making. Most laser cutting systems have variable laser power levels, meaning that a laser cutter could also be used as a laser engraver - the laser does not have to penetrate the base material completely. It is easy to rationalize that this method does not produce as much debris during the "cutting" process, despite any charred edges that remain on the board. Additionally, laser cutters can operate on a wide range of soft materials. For example, a laser cutter may work with acrylic, medium density fiberboard (MDF), and other materials beyond wood. There are two main consequences when working with laser cutting systems: the high cost of materials and the low production rates.

The laser cutting system itself is an assembly of many optical components: a laser tube, an electron source, the focal mirrors, the CO_2 ducting, and then a cooling subsystem. All of these components are required to operate a high-power laser safely and efficiently for long durations of time. Unfortunately, the total investment of these features is steep. For example, a standard 40 watt CO_2 laser tube costs approximately $240 on Ebay. The lens and mirrors can cost an additional $120, reaching a total of $360 for just the machine's glassware. With the addition of refrigeration, CO_2 and ventilation systems, the entire cutting system would cost several hundreds of dollars. Such a high price-tag is unacceptable for the project scope when compared to the cost of a traditional wood router. It is important to note that the rough cost breakdown above is only for the cutting mechanism, not the entire CNC machine.

In addition to the immediate costs, power consumption and operating costs would also be steep. A high power laser consumes a large amount of energy. In addition, a majority of the power consumption also comes from the support system, i.e. the motors and pumps required for refrigeration, CO_2, and ventilation systems.

2.5.3. Two-Dimensional Printing

As an alternative to engraving symbols into wooden plank, one can instead print an adhesive label which they will then affix to the sign. Using adhesive material allows an individual to apply their symbols to a variety of materials extending beyond wood. However, the environmental conditions present during the lifetime of a wooden forest sign may cause wear and tear on the printed, adhesives. Such ravages of time will result in premature fading of letters and symbols on the sign. Using a material like metal makes a sign more durable, but it detracts from the natural aesthetic of the forest. Additionally, the National Forest Specifications for signage, metal signs are reserved for motorized trails while wooden signs are reserved for walking trails (Forest Service).

One may argue that the use of adhesive labels is a favorable option, despite the reduction of a sign's lifetime before replacement. However, the previous senior project group determined such a diminished lifetime was not favorable towards the causes promoted by the Friends of the Inyo. As such, the present team shall endeavor to continue working with the current, wood-carving CNC machine.

2.5.4. Chemical Etching

The last and unconventional option for putting letters onto a wooden plank uses a chemical etching process known to the paper industry as pulping. Pulping uses a complex chemical solution to degrade the cellulose and then eventually erode the wood. This widely used process has been optimized over the centuries and serves as a potentially valuable alternative to carving. Typically, pulping chemicals are used in large batches to dissolve all grain structures within the wood. Using chemicals to dissolve specified regions of a board to create letters may be an impractical endeavor as the grain pores act as capillary tubes. These tubes will allow the pulping chemicals to disperse around a general area rather than remaining in the expected deposited area. Another uncontrollable factor deals with grain density. The density of the grain has a great influence on the time it takes to dissolve wood. Due to these reasons, chemical etching may not serve as an acceptable solution.

2.6. Performance Risks

There are considerable risks involved with any high-speed cutting device. With a wood-cutting machine, one must be mindful of wood chip management (among other debris), structural rigidity, knot densities, and climate various. These risks are detailed in the subsequent sections.

2.6.1. Wood Chip Management

With all woodworking processes, the production of wood chips is inevitable and it tends to become a performance issue with routing applications. For a CNC machine that is powered by precision lead screws and uses ball bearings for guide rod support, it is critical to address the presence of wood chips. The main concern regarding wood chips is that they will clog the threads and bearings, increasing power consumption and exerting additional wear on the machine.

It is important to note that wood chips, which are relatively heavy, are accompanied by sawdust, which conversely is small and lightweight. Sawdust particles have a tendency to float in the air, coating hard-to-reach areas that larger wood chips might not usually reach. Therefore, it is essential that the non-enclosed components of the Forest Sign Maker must be able to operate despite exposure to sawdust.

The Forest Sign Maker design will combat the issue of wood chip management through three methods. Firstly, the linear ball bearing and lead screw nuts will be located underneath the workpiece surfaces so that they are protected from wood chip accumulation. Secondly, by enclosing the electronics and motors in a mental encasing, sawdust will be prevented from clogging the internal components. Thirdly, the foundation for the work surface will be designed to contain the wood chips on the bed of the CNC machine, which will utilize either manual cleanup or vacuuming.

2.6.2. System Rigidity

The system rigidity is essential to the accuracy of the CNC machine. If the components have excessive compliance, the feedback information gathered by the measurement sensors will be inaccurate. As such, the CNC controller will not be able to locate the cutting device within the required tolerance range. Furthermore, a rigid system is necessary to cut high-quality text that matches the desired image and tolerances.

Rigidity will be achieved through a mostly metal construction and careful designing of supporting components. For each component, the mechanical loading will be considered and an optimal geometry will be implemented. For example, long horizontal members will be required to have high bending moments about their neutral axes in order to sustain a high level of rigidity.

Not only is a rigid construction necessary for accurate cuts, it is also beneficial when pushing the cutting device through knots in the board where the grain density is greater. With such irregularity in the density, it poses a potential safety hazard while the rigidity of system will contain the motion of the CNC machine during these instances. Routers are especially prone to gouging and tearing the wood, exerting very high forces on the support mechanism. Thus, securing all the moving components is essential.

2.6.3. Knot Density

The presence of knots in the blank signs act as a potential performance risk due to their increased grain density. These regions will exert a much higher resistive force on the Forest Sign Maker. They also pose the threat of dislodging themselves and being flung by the cutter at high speeds. Therefore, the system mechanisms must be heavily overrated in terms of stiffness and power in order to physically cut through the knot. Similarly, all components must be able to withstand the impact of a knot projectile without failure. These risks will be addressed by oversizing the support and actuator components of the Forest Sign Maker on top of shielding sensitive equipment with impact resistant covers.

2.6.4. Climate Variation

Another unique consideration that must be made for the Forest Sign Maker is that of climate variation. Normally, CNC machines operate in closed, stable environments such as machine shops or warehouses. However, the Forest Sign Maker will operate in Paul McFarland's personal work shed in the Sierra Nevada Mountains where exposure to the environment is greater and more drastic. This exposure could adversely affect the performance of the machine.

The implication of this performance risk is that the machine must be able to operate in a temperature range of 0-100°F. The selected materials and system design must accommodate this temperature range such that operation remains consistent during all seasons.

2.7. Enhancement

Although the current motor setup is operable, there still is much room for improvement in both efficiency and performance. These areas of improvement are listed in the following subsections.

2.7.1. Power Control

The function of a motor driver is to take a low-current control signal and convert it into a high-current signal to drive a motor. The current motor controller board is outfitted with three VNH3SP30 motor drivers, each with the capability to handle peak amperages and voltages up to 30 A at 40 V. This is appropriately oversized for the selected Pittman gear motors that draw a stall current of 9.6 A at 24 V maximum. However, after testing the current drivers, their outputs do not come close to their manufacturer specifications. At approximately 16 V, destabilization with the current drivers occurs. The end result of this discrepancy is an inaccurate carve on the wooden sign. To resolve this, alternate drivers and controllers will be tested, reviewed, and utilized to accommodate the system's power requirements.

2.7.2. Vibration Isolation

When in operation, the current design produces unwanted vibrations that not only reduces the quality of the product but also contributes to unnecessary wear on the current system. To mitigate these vibrations, the three following industry add-on solutions may be explored or design changes may be implemented.

The first add-on method utilizes of anisotropic bars with specifically assigned orientations of the stiffness axes. This is based on the theory that if a specific orientation of stiffness relative to the cutting forces is utilized, it can reduce chatter and significantly increase the dynamic stability of the system.

The second, and most common, add-on approach utilizes dynamic vibration absorbers (DVA). DVAs are spring-mass systems that oscillate in such a way that counteracts any vibrations or imbalances produced by the system. The catch with these systems is they are tuned to specific frequencies and lose effectiveness as the frequencies change.

The third, and most effective, solution is active vibration dampers. Similar to the previously mentioned DVAs, these dampers work by producing oscillations to counteract any machine produced vibrations. However, unlike the passive spring-mass system, these dampers use actuators to generate opposing oscillations based on multiple vibration sensors throughout the system.

However, in addition to the implementation of add-on vibration isolation solutions, design modifications may also be used to limit unwanted movement. These design changes range from material selection, material thickness, and material size. Although design changes may be time consuming and expensive, modifications to these design parameters in specific, critical locations can have significant benefits in reducing system chatter, vibration, and instability.

- Revision 1/31/17 –

When redesigning the Forest Sign Maker's x-axis, the team took special consideration to eliminate excessive noise and vibration. To achieve this goal, the team removed the second linear lead screw, thus also removing the chain and tensioning system. Once accomplished, it was determined that no further vibration isolation was necessary.

2.7.3. Output Speed

The current method of cutting signs is performed manually with the use of a palm router. Such a process can cause a sign to take up to three work days to create. Not only is this process highly labor intensive, it is incredibly time-consuming. Utilizing a fully automated system will not only increase the current production time to less than 2.0 hours, it will also increase the consistency of product quality and reliability.

2.7.4. Output Performance

Although the current configuration is superior to the manual labor methods that were used previously, there is still much more room for improvement. The objective for Cal Poly Tree's company is to enhance the quality of the outputs, specifically increasing the control and quality of organic curves, shapes, and diagonals while being able to consistently reproduce such figures.

2.7.5. User interface

The current user interface involves direct-user-interaction with the router. To operate the machine, the user must manually move the router over an outline plank. This procedure is intensive and inadequate for the desires of the sponsor. To better satisfy the sponsor's desires, efforts have been made to create an easy-to-understand interface that takes an Adobe Illustrator file and converts the following design into motor signals, which the CNC will then follow.

The current user interface decodes images through a custom designed motor-signal translator. Illustrator, though a proprietary commodity, can be included in the current application through several potential methods.

First, Adobe Illustrator provides software development kits (SDKs) which allow an individual user to design modifications for the existing program. Following such a direction will allow users to access the extra-feature and interact with the CNC machine.

A second solution would leave the Adobe Illustrator software untouched. However, this secondary option would make a user save his or her images as an encapsulated postscript (EPS) vector file. With this vector file, the user can upload it to the existing user interface where it will generate a corresponding motor-signal code and then determine if the motor-signal code is a valid application for wood-carving. If the signal code is verified, the user interface will proceed to send these motor signals to the CNC machine and the sign will begin developing. If the motor-signal file does not satisfy the dimensional constraints of the CNC machine, an instructive error message will be sent to the user. The user will receive this message until all dimensional constraints are satisfied and the machine will then begin developing the sign.

A third solution would involve a hybrid of the previous two solutions. This hybrid would remove the current web-interface and allow a user to simply "print" a sign. After "printing" the sign, the CNC machine will begin operations to develop the sign. This method of approach was taken from the existing laser-cutting machine found in the Mustang 60 Machine Shop.

- Revision 1/31/17 -

Previous design choices opted to use Adobe Illustrator on a workspace desktop which would be interfaced with a Raspberry Pi B+ to communicate with the mechanical motors attached to the Forest Sign Maker. As mentioned in the 1.1.1 Objective Revision, the team has decided to use of Fusion 360, an open-sourced CAD/CAM designing software.

On the Fusion 360 software available to Paul McFarland, several sign templates will be provided with which he can simply add textual content and designs. The user will access Fusion 360 through a personal laptop, which is networked to communicate with a Raspberry Pi B+. From these CAD designs, a corresponding G-code will be generated and sent to the corresponding Raspberry Pi B+ for analysis of appropriate dimensional features. Once the Raspberry Pi B+ has interpreted the supplied G-code, the Raspberry Pi B+ will inform the user of the successful status and will deliver the appropriate motor signals to the controller in charge of driving the machine's motors. Additionally, if the supplied G-code fails to meet any of the system's required parameters, an informative error message will be returned to the user for improvements to the G-code design.

2.7.6. Three-Axes Capability

Currently, the machine operates under a 2½ axes configuration meaning that although the machine can operate fully in the XY plane, it can only operate at one level along the z-axis. Reconfiguring the Forest Sign Maker to operate in a three-axis configuration promotes two major benefits. First, under the current configuration, the machine has no coordinate regulation along the z-axis. Consequentially, as the Forest Sign Maker engraves its features, the drill bit wanders unregulated causing undesired fluctuations in depth. However, if the Forest Sign Maker is configured to operate with three axes of control, the depth of every coordinate will be monitored and kept within the specified tolerance, eliminating any wander or fluctuations. Second, three-axes control enables the Forest Sign Maker to perform multidimensional cuts, thus allowing for more intricate and complex sign designs.

3. Objectives

3.1. Overall Project Goals

Over the next nine months, this senior project team will attempt to achieve the following eight goals:

1. Build, design, and test a CNC device for producing signs in under 2.0 hours
2. Be able to produce quality signs of various sizes of redwood planks
3. Must have programmable X, Y, and Z axes
4. Must be affordable
5. Must be portable
6. Must be easy/simple to use
7. Must operate safely
8. Minimize any unwanted movements and vibrations

The final prototype for the project, the Forest Sign Maker, must satisfy all of the customer requirements mentioned above to be considered a successful endeavor. Any additional requests made by the sponsor, or any stakeholders during the developmental process are considered to be beyond the scope of the project and Cal Poly Tree's Company is under no obligation to satisfy such requests. However, any reasonable request will be discussed and evaluated by the team such that it may deliver the best possible product to the customer in return for their sponsorship.

3.1.1. Build, Design, and Test

The team will be using the sign cutter built by the previous senior project team, Forest Friends. As such, a large portion of the build phase has already been completed. However, as the team begins to implement the newly requested features, it will enhance the current designs, modify the existing components, and embody the problem solving and creating thinking aspects typical of any design process. As design augmentations undergo implementation, the team will test each implementation and iterate the design process until a CNC device capable of consistently producing quality signs in under 2.0 hours is produced.

3.1.2. Production Capabilities

The final product must be able to rout letters and symbols on a flat, rectangular plank of redwood or any piece of lumber of equivalent density. The maximum size of these planks is specified at 2’ x 4’ x 1.5”, while the minimum size specified is at 1’ x 1’ x 0.75”. In addition to handling different sizes of planks, the product must also be able to handle knots and other internal deformities on a blank sign while creating a sign faster than any single individual could manually.

3.1.3. Programming

Presently, HTML5 and JavaScript are used to design the front-end service of the web application. This implementation will be maintained and any improvements shall be designed solely in HTML5 and JavaScript. Documentation will be created and provided to explain the functionality of the front-end as well as inform the user how to improve and edit this side. Although no unit testing is required, visual checks shall be run to confirm the expected output is indeed present on the page. CSS may also be used to improve the styling and image of the front-end display. However, this falls in line with understanding HTML.

When looking at the backend, Java is currently used to convert sign specifications into a list of coordinates, which the device’s router will then follow when cutting out the design. This implementation will be maintained. Any improvements shall be designed in Java. However, unlike the front-end, unit tests will be designed to verify that the interpreted coordinates are correct. Once completed, visual tests will be performed to confirm the outputted coordinates are correct. Documentation will be created and provided for future modifications.

Currently, the motor controller board runs on C++ and receives coordinates while also tracking the position of the router. This portion of the project was not correctly implemented in the previous year. Thus it is the task of this year’s team to include this implementation to handle a different, off-the-market, higher-powered board.

As of now, Adobe Illustrator interactions are not directly involved with the process of using the CNC machine. Research will be done to find potential solutions for Adobe Illustrator integration into machine signals. Currently, machine signals are output directly by a Java-based image interpreter. Part of the scope of enhancing the programming portion of this project will be to assess the value of implementing a more common, open-source machine language (such as G-Code or SVG). The best solutions will be implemented and tested for potential defects or issues. The best solution with the best testing results will be implemented at that time.

- Revision 1/31/17 -

With the choice to implement the project Fusion 360 rather than Adobe Illustrator, an HTML5 and JavaScript-based web application will no longer be required. Fusion 360 will supply the bulk of direct user-to-machine interactions. When the user generates the appropriate G-code files, it will be sent to Raspberry Pi B+ for analysis. To initiate analysis, the user will execute an on-device program written in both

Python and Objective-C to determine whether or not the supplied G-Code satisfies the CNC machine’s dimensional requirements. Once this requirement has been satisfied, the Raspberry Pi B+ will decode the G-code and deliver the motor-related instructions to the controller in charge of driving the CNC Motors.

3.1.4. Affordability

Since the team is designing something that already exists to some degree in today's market, it is important that the budget is kept reasonable lower than the price of comparable CNCs. Most products on today’s market that are capable of satisfying most of the customer’s requirements cost anywhere from $15,000 to $35,000. With that said and taking into account the current statutes of the machine, the budget should remain under $5,000.

3.1.5. Portability

The first component of portability is the device must be able to fit inside a standard doorway, therefore the device may be no wider than thirty inches. Second, the design must be able to sit on standard eight-foot-long workbenches while providing ample clearance on each side, thus is may be no longer than six feet. Third, it must never come in contact with ceilings, thus it may be no taller than four feet. Lastly, it must be reasonable to carry and move the device with the help of others, thus it may weigh no more than 150 pounds.

3.1.6. User Simplicity

A good design is not only focused on the output of the product itself, but also the experience between the user and the product. To achieve this goal, the system will utilize an integrated computer system to store and load electronic files. The interaction between the user and the mechanical system will be kept to a minimum for convenience and ease of use. The simplicity of the system would be such that any user without previous experiences would be able to understand how to operate the product after fifteen minutes of minimalistic training. Not only does this encourage a highly intuitive system, it also streamlines the process to increase the product’s overall effectiveness and efficiency.

3.1.7. Operation Safety

It is of paramount importance that this design produces high-quality signs not only in an effective manner but also safely. These signs must also be produced in such a way as to ensure the safety of the user. To achieve this goal, the user must be able to shut off the machine in less than half a second. Also, all moving components must not be exposed during operation. In addition, Cal Poly Tree's Company must target and minimize the quantity of pinch points or any other locations where the user may be placed in the line of fire. Additionally, it is required that an operator wears proper safety equipment, which includes but is not limited to safety glasses, hearing protection, and a dust mask during the machine's operation. Lastly, the user must also be aware of the basic format with which to operate the machine before usage.

3.1.8. Vibration Isolation

Unfortunately, the current condition of the machine produces excesses unwanted vibration and chatter. To ensure that the machine will operate relatively smoothly and quietly, the machine in motion without the router running must maintain a sound level less than 80 dbas.

3.2. Specifications Table

Table 3-1. Formal Engineering Requirements

Index	Parameter Description	Requirement or Targets	Tolerance	Risk	Compliance
1	System Weight	200 lb.	Max	H	T
2	Width	30 in.	Max	H	T
3	Length	6 ft.	Max	L	T
4	Height	4 ft.	Max	L	T
5	Cost	$5,000	Max	H	A
6	Sign Production Time	2.0 hrs.	Max	L	T
7	Max Blank Size	2 ft. x 4 ft.	± 0.25"	L	T, I
8	Positional Accuracy	Target dimension	±0.03125"	H	T
9	Cutting Depth	Target dimension	± 0.03125"	L	T
10	Graphical User Interface	Fusion 360	--	L	S
11	Local Operation	No network connection necessary	--	L	T
12	Multi-platform Capabilities	Function on Chrome, Firefox browsers	--	L	T
13	Tool Path Errors	Zero out-of-bounds errors for the tool path	Max	L	T
14	CNC Design Input	Interface hardware can function with sawdust present	--	H	T, I
15	Vacuum Capabilities	50% of total debris vacuumed	Min	L	T, I
16	Clamp Rigidity	0.012 in	Max	M	T, S
17	Cutting Tool	Holds stock Bosch Colt Router	--	L	I
18	Mounting Feature	Securely fasten CNC machine to table	--	L	T, I
19	Shutdown Time	0.5 sec	Max	L	T, I
20	Electronics Temperature	60 °C	Max	M	T
21	AC-DC Power Supply	300 W	Min	L	A

- Revision 1/31/17 -

Revise such that where is says (10) the Graphical User Interface will *not* be a web application, but instead will be a software-based CAD/CAM tool supplied by Autodesk known as Fusion 360.

3.3. House of Quality

Through the embodiment of the Quality Function Design (QFD) principles, Cal Poly Tree's Company was able to determine the appropriate specifications for the Forest Sign Maker design. Throughout the process, the team was able to utilize a tangible approach to translating the customer requirements into concrete, testable engineering specifications. This process can be depicted in following steps which all come together to form the QFD house of quality, which is provided in Appendix B.

3.3.1. Who

The first step in the QFD process is identifying the customers for the project. However, when referring to the "customer", it should be noted that that is not simply just the end user, but rather anyone who is affected by the product. As mentioned previously in the *Stakeholders* section (1.4), this broad term would apply to The Friends of the Inyo, Cal Poly Tree's Company, Paul McFarland, Lee McFarland, and the visitors of Inyo National Forest.

3.3.2. What

The second component of the QFD process is determining the customer requirements. Here, the team was able to create the following list of both the customers' implicit and explicit requirements:

- Operate Safely
- Produce Signs of Multiple Sizes
- Produce Signs Quickly
- Produce High-Quality Signs
- Produce Limited Sound and Vibration
- Utilize a Quality Motor Controller
- Be Affordable
- Utilize a Simple User Interface
- Utilize Easily Replaceable Parts
- Maintain a Portable Weight
- Maintain a Portable Size
- Cut Dense Woods
- Embody a Quick Learning Curve

3.3.3. Who vs. What

In the third stage of the QFD process, all of the customer requirements are weighed and prioritized. Here, each customer will individually weigh the different requirements formulated in the *What* sub-section (3.3.2), and then the results will be prioritized to determine which requirements are most important. For this project, it was decided that the capability to produce signs of multiple sizes and to produce signs how high quality was of top priority among all the customers. Thus, those requirements will be of paramount importance for the project. However, it is important to note that although certain requirements may not be important to one customer, it still may be a necessity for another. For example, although the visitors of the forest are not directly affected by the safety aspects of the Forest Sign Maker, those aspects are crucial to Paul McFarland and the Friends of The Inyo. Thus, it has been decided that all requirements should be met to some degree to ensure the satisfaction of all customers.

3.3.4. Now vs. What

The fourth and fifth stages of the QFD process are benchmarking processes current market alternatives are explored and analyzed on how well they satisfy the customers' requirements. In this stage, the team's Forest Sign Maker was compared with the Rockler CNC Shark HD4, the ShopBot Buddy, the Baileigh Industrial CNC WR-48, and the KL-6090 Desktop CNC and after the initial review, the Cal Poly Tree's Company product was considered best fit for achieving the customers' requirements.

3.3.5. How

The sixth aspect if the QFD process focuses on providing measurable and testable specifications to the customer requirements. The following list of specifications will help to determine how the team's design will satisfy the customers' requirements:

- Max Sign Dimensions
- Shut Down Time
- Minimal Pinch Points
- File Input Format
- Uncluttered Graphical UI
- Low Cost
- Low Weight
- Desired Dimensions
- Quiet and Smooth
- Desired Speed
- Minimum Speed
- Cuts Desired Woods
- Minimal Training
- Handles Peak Currents and Voltages
- Easily Purchased or Sourced
- Path Deviation Tolerance

3.3.7. **What vs. How**

The seventh step of the QFD process connects the customers' requirements directly with their relative engineering specifications. This process shows how strongly connected each engineering specification is with the customer needs. For example, in order for a machine to meet the safety requirement, it must be able to have a sufficient shutdown time and minimal pinch points. These are not necessarily the quantitative values required but simply the measurable tests.

3.3.8. **How Much**

The eighth and final component of the QFD process quantifies all the previously defined engineering specifications with the following numbers and targets:

- Takes Board Dimensions Up To 2' x 4'
- Emergency Shut Down in Less Than 0.5 Seconds
- Contains Zero Pinch Points
- Utilizes Adobe Illustrator Files as the Input
- Interface Contains Less Than Ten Interactive Components
- Final Product Costs Less Than $5,000
- Weighs Less Than 150 lbs.
- Maximum Machine Dimensions of 30" x 6' x 4'
- Produces less than 80 dbas (Without the Router Running)
- Desired Production Rate of 2.0 Hours/Sign
- Minimum production Rate of 8 hours/Sign
- Cuts Through Redwood Density Woods
- Requires Less Than 15 Minutes of Minimal Training
- Handles Peak Currents of 30A and Voltages of 24V
- Parts are Available for Purchase (Yes/No)
- Path Deviation Tolerances Less Than 0.03125 in.

- Revision 1/31/17 -

Machine will no longer utilize Adobe Illustrator files as input. Instead, the machine will make use of G-code files produced through Fusion 360. Reasons for doing so are more deeply described in the 1.1.1. Objective Revision and 2.7.5 User Interface Revision.

4. Design Development

4.1. Method of Approach

Cal Poly Tree's Company will follow the provided method of approach throughout the design development process, which will take place over the next nine months. This process is depicted in the Figure below and will be further explained in the following subsections.

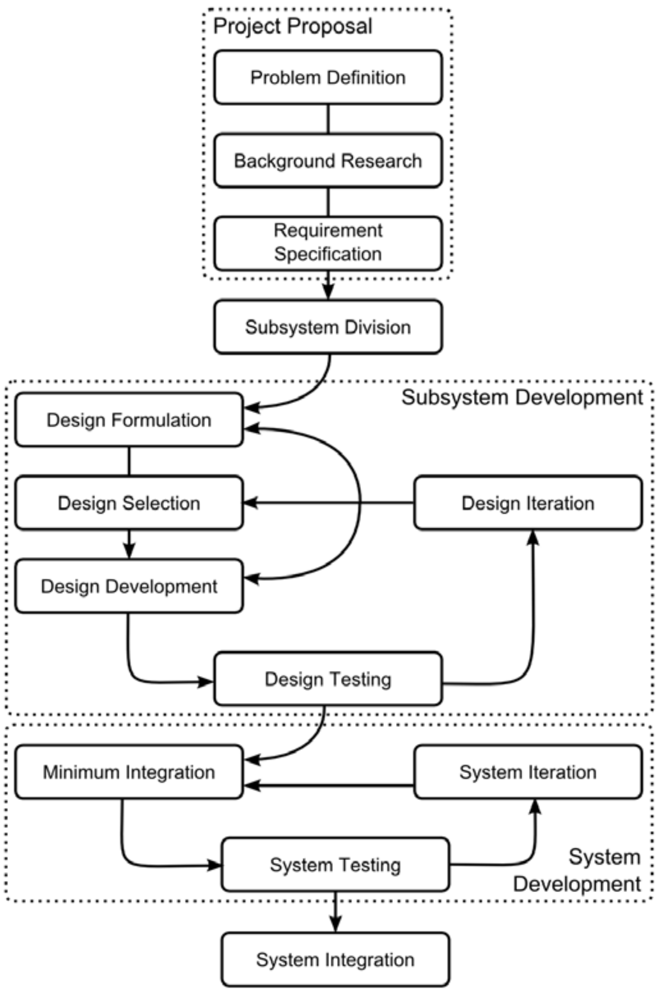


Figure 4-1. Method of Approach Flow Chart

4.1.1. Problem Definition

The first step in the team's approach to solving a problem was defining the problem. Although it might have seemed intuitive, it was crucial that the team fully understands and addresses the problem. To further this understanding, the team formulated a set of eight reasonable and achievable goals that satisfied the customer's desires, which can be seen in the *Objectives* section (3.1).

4.1.2. Background research

The background research necessary for this project was divided into three categories: research into needs of the problem, into current solutions, and methods, and into the characteristics of the current device

Research into the problem needs and current methods are presented in *Background* section. This component of the background research was motivated by the need to further understand the problem. Here, the limitations of each current solution were explored to further understand the particular needs of the customers. Additionally, concepts fundamental to CNC machinery were discussed to promote future discussion of design challenges.

Research into the current device was crucial, as the current limitations of the device directed the development efforts of the design process. Cal Poly Tree's Company had investigated the general operating characteristics of the device, the overall performance of the device, and the general layout of its control structure.

Cal Poly Tree's Company had also communicated with the previous design group responsible for the first development cycle. The previous team had supplied reference material, design documents, and source codes for the current device, as well as performed demonstrations of the device.

Additionally, the previous team had also discussed multiple design issues they encountered while developing the device, and how those evolved into the limitations currently seen. This initial research provided a stable base from which Cal Poly Tree's Company directed their subsequent investigations.

4.1.3. Requirement Specification

Cal Poly Tree's Company had combined the general design goals in the *Objectives* section (3.1) and the research performed in the *Background* section to create a set of engineering requirements and specifications, which were presented in the *How* and *How Much* subsections of the *Objectives* (3.3.5 & 3.3.7). These specifications were testable and measurable details describing how the team plans to address and qualify the customers' requirements. Then the requirements were quantified into specific metrics. These were then used to direct the team's Forest Sign Maker design and benchmark how well the team's solution, as well as alternative market solutions, met the customers' specific requirements.

4.1.4. Subsystem Division

The team's device is a fully capable CNC machine, containing dedicated motor controllers, a full user interface, and associated power and mechanical systems. To organize the development process, the system was divided into separate subsystems, as seen in Figure 4-2. Each subsystem represented a part of the device that was relatively self-contained where work could be performed without necessarily affecting another system.

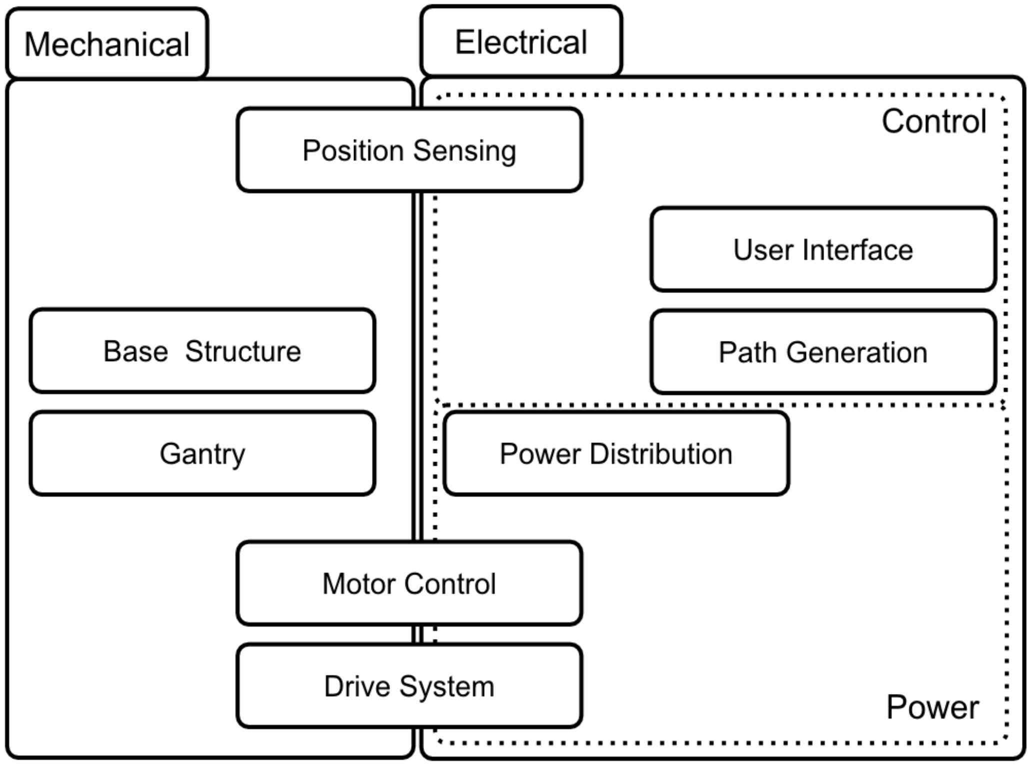


Figure 4-2. System Tree

The overall system was divided into two general categories: mechanical and electrical. Electrical devices were further categorized as either control or power. Categories were not mutually exclusive; several subsystems were members of multiple categories.

The mechanical system consists of the base structure, gantry, and drive system, which is a mechanical-electrical device. The base structure consisted of the aluminum base upon which the device is built. The gantry contained the moveable secondary axis, including the slider bars upon which it rests. The drive system included all motors and their associated gears, chains, and subsystems.

The electrical system consisted of the user interface module, the path generation module, the motor controller module, the position sensing module(s), and the power distribution system.

Subsystems were modeled as black-boxes; a subsystem was characterized by what inputs it received and the corresponding outputs it produced. Mechanical systems received and produced loads or movement, and electrical systems received and produced signals and power. Systems with multiple categories were able to send and receive multiple types of input-outputs. All subsystems were described by their inputs, outputs, and specifications that described their characteristic signals. The design team worked carefully to ensure that all inputs and outputs are described. For example, a software system might take input files as well as power and sensor signals from the CNC table, and produce coordinates.

Also, subsystems were able to receive engineering specification that its input-output behavior could completely satisfy. Certain engineering requirements lent themselves well to being addressed by one subsystem alone. For example, specifications for a user interface were safely assigned solely to the user interface subsystem. Under this format, black-box specifications were used to direct design formulation and create design tests. By doing so, the design team ensured that the specifications were kept closely linked to every step of the design process and that work was not done on a design which was not projected to meet its requirements.

Engineering specifications which did not fall under a single subsystem were examined individually. If they could be divided into rules that both clearly added up to the specification in question and could be assigned to individual subsystems, then they were divided and assigned as such. Otherwise, they were assigned to the system as a whole. Testing of such specifications was deferred to final system testing.

Additionally, the formation of a detailed black-box specification for each device helped to direct the design process by abstracting complicated systems away from one another. Furthermore, it assisted in the production of tests, as well as the final assembly of the device. Because the device combined many different types of systems, Cal Poly Tree's Company decided that a black-box model was best suited for the subsequent organization.

4.1.5. Design Formulation

Ideas for the design and performance of each subsystem were formulated and collected. The use of black-boxes to model the subsystems allowed ideas for a single system to be considered without any system integration, communication, or compatibility difficulties. Generally speaking, a design was modeled as a specific implementation that satisfied the input-output requirements of that design’s black box. A model consisted of either a high-level system model or a low-level implementation model that discussed the specific details of higher level concepts. This method ensured several ideas for one particular model can be discussed. Candidate final designs required both high-level and low-level model implementation.

Furthermore, strong designs required research into details of its function or implementation, and then small prototypes of an idea (particularly for software) were constructed to test their usefulness. This research was limited in scope to each subsystem and will not attempt to explain the entire device. Additional design resources included mathematical models of the subsystem in question or computer models and simulations of a proposed design. These resources assisted in the subsequent selection of a candidate design by providing useful data against which competing ideas can be compared.

4.1.6. Design Selection

Naturally, Cal Poly Tree's Company will seek the optimal solution for each subsystem. Because the design team will be working with a preexisting device, possible solutions could involve improving a subsystem, replacing an implementation, or redesigning an entire subsystem from the ground up. It is expected that most software subsystems will be at least partially, if not fully, redesigned, due to the relative ease of developing and testing new code. Mechanical subsystem designs will focus on enhancing existing structures and implementing improvements rather than focusing on redesigns, although it has been acknowledged that component redesigns may be the most effective solution.

Each final design candidate, consisting of high-level models and low-level implementations, will be ranked according to a series of selection criteria. Selection criteria will include the corresponding engineering specifications of its respective subsystem. These criteria will have the highest priority. Any candidate solution unable to fulfill these criteria will be discarded. Criteria will also include internal metrics determined by the design team, such as the ability of an interface to connect to different subsystems or the amount of code a program requires. Internal metrics will have an associated priority representing the importance of that metric to the overall design. Once each candidate had been ranked, the optimal solution was determined. The optimal solution satisfied all engineering specifications and maximize all internal metrics.

4.1.7. Design Development

With the optimal design chosen for each subsystem, work will begin on the implementation of each design. Specific mathematical analysis, code development, and mechanical design will be performed as a part of this process. Total redesigns will involve the construction and evaluations of prototypes; improvements to existing systems are able to move straight to unit testing. While it is desired that subsystems be developed independently of others, the design team acknowledges the inconvenience in building fully dedicated test rigs for every system. As a result, the pre-existing CNC device may be used as a prototyping rig with the understanding that the changes implemented at this stage are still subsystem changes and not final changes.

4.1.8. Design Unit Testing

This stage will test the ability of each subsystem to produce the input-output behavior of its respective black-box model. Thus, each subsystem will be subject to comprehensive unit and integration tests.

Unit tests examine the smallest possible component of a particular subsystem. An example unit test for a motor controller would test if one command for a single motor drive is working properly. An example of the user interface would test if a certain button properly closes the program. Unit tests are intended to expose any flaws in the execution of the subsystem and will be developed according to the low-level models.

Integration tests establish the ability of a subsystem to properly interface with another. This type of testing is crucial for the black-box model, as the power of that design approach lies in abstracting complicated subsystems to interfaces. Interface tests will be designed according to the black-box specifications developed during subsystem partitioning. The tests will confirm that each input creates its expected output both without error and within an acceptable time. For example, an integration test will analyze the current flow rate to a motor and its response time when the motor control provides a new positioning coordinate.

Since the machine has the capability to injure or maim its user, testing of low-level motor control and drive systems will focus in particular on a timely response to unsafe signals. The signals from a stop or end switch should quickly produce a halting of the machine.

Interface testing is particularly important for the software subsystems, as they will each be receiving complicated signals and messages from one another. Here, timely responses are not as important as accurate outputs. User interface and path generation should be able to translate a line or curve in the design to the correct sequence of motor movement needed to reproduce it. For other systems, the focus will be placed equally upon timing and correctness.

4.1.9. Minimum System Integration

Once the correctness of each subsystem is verified, the full system will be assembled into a functional state. That is, all subsystems will be connected, but only with the minimum connections necessary for the operation of the device.

Electrical subsystems will be connected with temporary wiring to facilitate removal of subsystems. Control systems will be installed, but any debugging or testing harnesses will be left intact. Little to no focus will be given to wire management or subsystem housings, aside from those needed to facilitate operation.

Those mechanical systems which were prototyped upon the device will not require any installation. Any mechanical system which was developed outside of the existing device will be installed here.

4.1.10. System Testing

The system will now be tested to ensure that, as a whole, it meets the engineering specifications presented in *Objectives.* Using these specifications, a comprehensive testing plan will be developed; each specification will receive a suite of tests intended to verify the design's ability to deliver those specifications in any circumstance. Engineering specifications which were assigned to black-box models of subsystems will be tested again, to ensure that a connected subsystem did not modify their behavior. Engineering specifications which were assigned to the device overall will also be tested. Once the device had passed all engineering specifications, it will be examined for any issues, not just in the scope of the customer requirements, but any that could be reasonably inferred to cause a problem currently in the near future. If none are found, the design team will verify the system as correct.

4.1.11. Iteration

No design process is perfect, and Cal Poly Tree's Company anticipates that problems will naturally arise during work on various steps. Each testing step is designed to catch both new flaws as well as reoccurring flaws from the previous steps. Thus, the team expects to encounter plenty of failed tests. But, problems can arise during the design or implementation of an idea as well. If an idea is not easy to implement or not conceptually clear to the design team, clarification and iteration will occur. Additionally, it is possible that subsystems pass all their unit and integration tests, but the overall design does not meet a certain specification. Regardless of the cause, these problems will be addressed by a cycle of iteration. Throughout this process, the team will return to an earlier step and pursue an alternative solution. Failures in a testing stage will be addressed by returning to the design development, design selection, or design formulation as appropriate. One or several unit tests failures might only require a modification to the low-level implementation, while a failure of many integration tests might require that an alternate design is chosen. If it is necessary, the subsection partitioning step could be revisited as well, although the design team does not anticipate that this will be necessary. Once a step has been revisited, development will carry on, with as many cycles as necessary until the offending step is successfully passed.

4.1.12. Final System Assembly

At this stage, the design is functionally complete. Finalizing the project will involve the installation of the assembly into its final housing, and the installation of permanent wiring and connections between subsystems. Debugging and testing equipment will be removed from the internals. The team will complete assembly by adding decals, safety information, and other visual touches to the frame.

4.1.13. Contingency Plan

Should the project fail to meet its overall requirements and engineering specifications, a contingency plan will be developed, with the full participation of all involved parties affected by the failure. If the cause of the failure can be determined and its solution can be worked into the scope of the project, it will be incorporated into it and an additional cycle performed. If the cause of the failure cannot be determined or it falls out of the scope of this project, the contingency plan will recommend a course of action that is acceptable to all parties.

Using this method of approach, Cal Poly Tree's Company will be able to develop a fully functional and safe version of the CNC device, which will fix the limitations identified by the previous team, and fully meet the overall needs of the Friends of the Inyo.

4.2. Design Concepts

4.2.1. Movement

The team has defined movement as the action of moving a cutting tool relative to the fixed board. The movement subsystem options detailed in the subsequent sections reflect various operations of high-level cutter movement schemes. The proposed concepts vary from linear motion to rotational motion. Although it may not significantly affect the mechanical decision process, it should be noted that these movement configurations will govern future programming commands of the CNC controller. For example, linear motion systems lend themselves to programming a Cartesian coordinate system while rotational motion lends itself to the programming of cylindrical-based coordinates. Therefore, the ultimate goal of this design component is to produce programmable movements of three-axes directions while also maintaining the desired output quality and tolerances.

4.2.1.1. Gantry

The gantry design would utilize a rigid bridge that moves horizontally along the x-axis while suspending the cutting tool, as seen in Figure 4-3. In addition to the horizontal movement of the x-axis, an additional actuator on the side of the gantry will move the cutting tool in the y-axis direction. Additionally, a third actuator on top of the y-axis structure will allow for movement in the z-axis direction. Such a three-dimensional setup is the industry standard for CNC routers as it allows for simple linear motion while reaching every point on the workpiece without sacrificing rigidity.

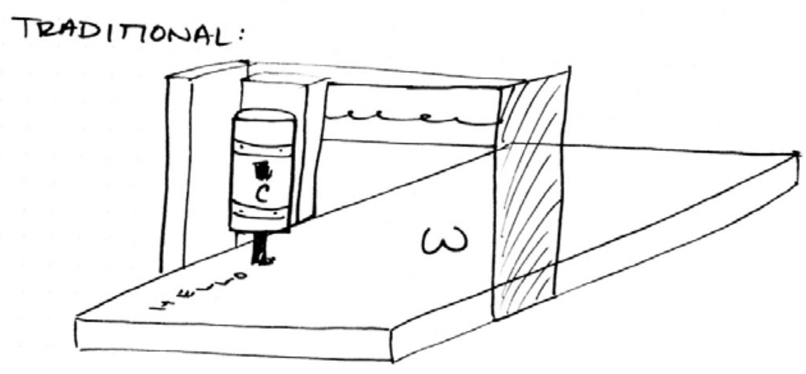


Figure 4-3. Traditional Gantry Layout

4.2.1.2. Drawstring

The drawstring method suspends the cutting tool above the workpiece using a network of cables attached to pulleys. These pulleys would be located on the edge of the Forest Sign Maker. Such a setup may be seen in Figure 4-4. The drawstring design is inspired by the aerial cameras used on football fields. By pulling cables towards one direction, the suspended cutting tool will follow the direction of increased tension. It is important to note a few of the major drawbacks of this system. The lack of control in the vertical height of the tool, lack of stability of a drill-bit in motion, and the potential for undesired sag in a drilling device all lend themselves to a potential decrease in output quality of a carved sign.

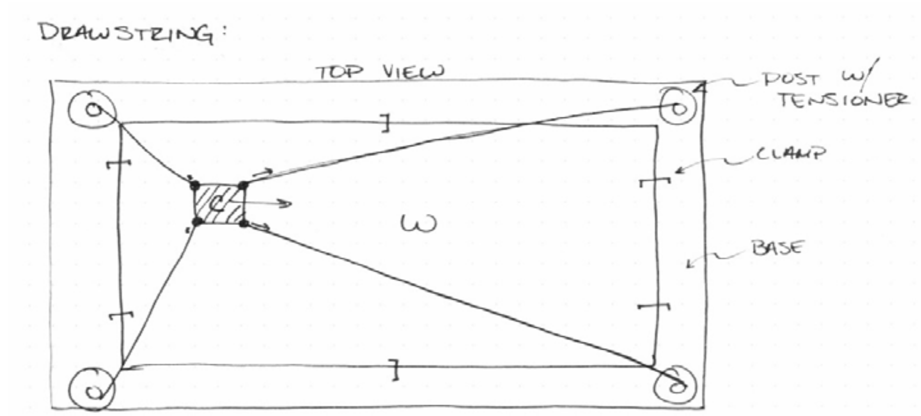


Figure 4-4. Top-Down View of the Drawstring Layout

4.2.1.3. Tower

The tower design is similar to the gantry option. However, instead of the positioning the workpiece horizontally, it is positioned vertically standing up, as depicted in Figure 4-5. Such a design will save floor space, but potentially limits the feasibility of workbench mounting. The drawback of this method is the effect of gravity when the cutting tool is moving or even simply positioned in the vertical position. Since the tool head will constantly experience the effects of gravity, this will require motors to draw extra power to constantly counteract these negative effects.

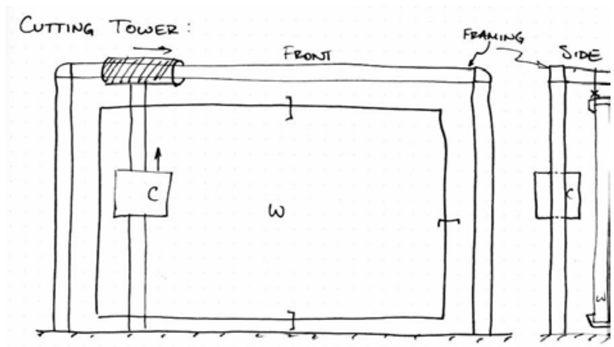


Figure 4-5. Front and Side Views of the Tower Layout

4.2.1.4. Strong-Arm

The strong-arm design utilizes a two-bar linkage with the cutting tool installed at the end of the second linkage. Such a setup can be viewed in Figure 4-6. The two pivot points in the linkage provide enough range to reach every point of the fixed wooden board. The major advantage of a strong-arm setup is that only two motors are required (one motor per pivot point). The disadvantage is that the arm system must be heavy enough to support its own weight across the body of the workpiece, thus requiring larger motors. While only two motors are needed for this configuration, the motors would need to be larger in order to support the weight of the system

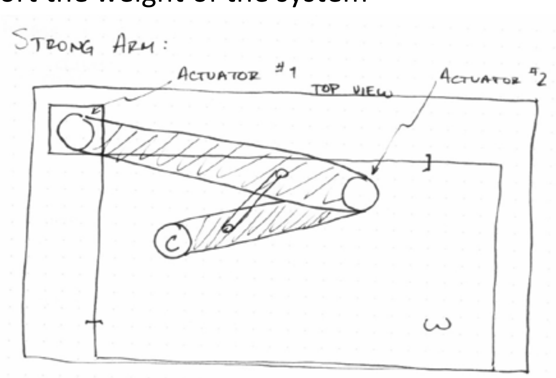


Figure 4-6. Top-Down View of the Strong-Arm Layout

4.2.2. User Interface

A user interface is the means by which an individual (a "user") is able to interact with a computer or computer system. Cal Poly's Tree's Company has determined three broad categories with which to research for future construction of the Forest Sign Maker's user interface. Of these three categories are the tablet computer, personal computer, and custom/on-board display. Each apparatus comes with pros and cons, which are detailed in the immediate subsections. The intended implementation of the device involves the use of a specially designed web-interface interfaced by a personal computer attached to the machine. This computer accepts uploaded files from an external USB device which will be translated into machine code for the CNC machine to use. Current implementation involves direct communication with a Unix console to deliver direct text characters and offers very little flexibility in symbols and fonts of the text carved on the wooden signs. It is the goal of Cal Poly's Tree's Company to implement a more user-friendly, design-flexible means of sign-development. Such flexibility will introduce a variety of fonts and vector-based image files to be carved.

- Revision 1/31/17 -

Diverging from the current implementation of the User Interface (A web-interface linked to a personal computer and USB file-transfer), the modified interface will interact solely with Fusion 360 to produce and design a suitable CNC file. The G-code will then be supplied to the Raspberry Pi B+ for further processing and finally sent to the motor controller to generate the physical sign.

4.2.2.1. Tablet PC

A tablet is defined as a portable, lightweight workstation that is easily transported between locations, as shown in Figure 4-7. In particular to the Forest Sign Maker, a tablet PC will provide high-level interaction between the user and the machine without risking a blockage within the mechanics due to sawdust accumulation. As a tablet PC is a fully-enclosed, touchscreen-based device (one that does not make use of physical buttons or open, internal cavities), where the internal hardware will not be at risk of deterioration caused by sawdust buildup. Through this implementation, the PC will function as a digital designing tool adjacent to the Forest Sign Maker set up in Paul McFarland's workshop. Making use of a tablet will aid in creating a more modular and easily transportable product

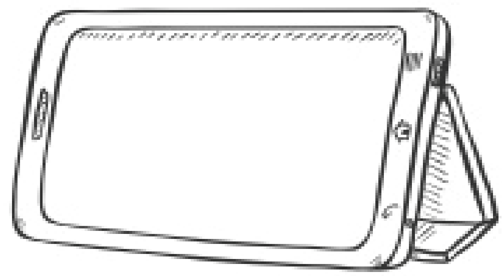


Figure 4-7. Tablet PC Set-Up

4.2.2.2. Personal Computer

A personal computer may be a traditional laptop or desktop. The main components of a personal computer are a keyboard, a mouse or trackpad, a monitor, and the computer itself. Such a display can be seen in Figure 4-8. Modern PCs are built with enough power and memory to perform general, everyday tasks such as processing and interpreting Adobe Illustrator files or Fusion 360 files, as well as design other programs to output CNC-based instructions. A few shortcomings of this approach involve the personal computer's susceptibility to dust and the space requirement.

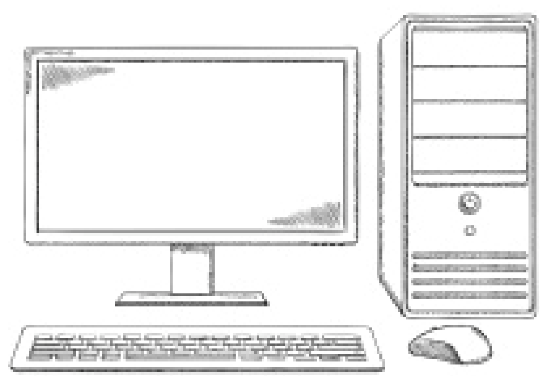


Figure 4-8. Personal Computer Set-Up

4.2.2.3. Custom Display (Onboard Computer)

A custom display would require Cal Poly Tree's Company to design, build, and test a non-keyboard method of inputting data. Custom displays limit buttons and options, making the purpose of the display precise, as seen in Figure 4-9. A custom display is designed specifically for the purpose of the Forest Sign Maker and would be simple and intuitive to any new user. Examples of other custom displays are the microwave's timer and buttons or a car's navigation system. A custom display can be thought of a simple control panel constructed for a specific device.

4.2.4. Controllers

Controllers are simple, versatile, lower-powered computer processors that can execute programs and produce voltage and signal outputs. They are small in size and relatively inexpensive, enabling them to be a good starting point for different projects. For this project, the team will utilize different types of controllers to interpret information, produce motor signals, and ultimately regulate the Forest Sign Maker.

The motor controller is responsible for the translation of program instructions into motor movements. It is a complex device which combines high-level interpretation with low-level power control. Additionally, the motor controller must be able to accept movement instructions and configuration from the user interface. This entails a common communication interface, as well as a method of parsing instructions. Also, the motor controller must be able to output voltages appropriate for the motors, as well as modulate motor speed: either through Pulse Width Modulation (PWM) or voltage level shifting.

Within these black-box esque constraints, there exist many potential solutions. In general, however, the implementation of these solutions will be limited to specific classes of devices, with the freedom to choose different devices left available.

The motor controller will employ an H-bridge topology for the switching of motor voltages. This configuration is so named for its four switches, arranged in an H-pattern, which allows each lead of the motor to be connected to either VCC or ground, in any particular order. This allows rotation in either direction, as well as motor breaking. The H-bridge can also be employed to control the speed of rotation, by means of PWM control. This control scheme involves the rapid switching of the H-bridge switches to create a series of on/off pulses. While the frequency of each pulse is fixed (on the order of milliseconds for motors), the time that each pulse spends on can be varied, in relation to the time that each pulse spends off. The natural inductances and momentum of the motor smooth out the varying pulses into a constant velocity. In this way, varying amounts of power can be delivered to the motor with longer run times corresponding to higher speeds (up to a maximum speed for a constantly running signal).

There are two main options to be considered for the H-bridge: an integrated circuit, or a discrete H-bridge. Because of the high currents and fast switching times needed for controlling motors with PWM, either option will use power metal-oxide semiconductor field-effect transistors (MOSFETS) as switches. A discrete H-bridge assembles four independent MOSFETs in separate packages (Integrated circuits, or ICs), along with their drive circuitry. An integrated circuit combines all four MOSFETs and their circuitry in a single package.

Benefits of the discrete H-bridge include maximum configurability, as there are thousands of power MOSFETS available, each with different parameters. The downside to this approach is that all sub-circuits must be directly implemented: Overcurrent protection, thermal shutdowns, and current sensing are all crucial to safety but increase the complexity of the final bridge. The integrated circuit drastically reduces complexity at the cost of being constrained by what chips are available on the market.

To control these H-bridges, interpret sensor data, and sending and receiving communications from the user interface, the team has investigated the following three microcontrollers.

4.2.4.1. Arduino Uno

The Arduino Uno is an open-sourced microcontroller which takes very little power to function. It is a powerful tool for developing small maker-space projects and popular among hobbyists. An image of the device can be seen in Figure 4-9. Advantages of the Arduino Uno include low cost, open-sourced software, publicly available hardware diagrams, and is a USB powered device. As a minimalistic board, the Arduino Microcontroller board lacks a graphical user interface (GUI). Another shortcoming of the device, as it is inexpensive and small, is that it falls short when implemented in more complicated projects that require significant amounts of computing power.

Figure 4-9. Arduino Uno Microcontroller Board

4.2.4.2. Raspberry Pi B+

The Raspberry Pi B+ is a tiny, low-powered computer that runs Linux from an SD card. The Raspberry Pi B+ can run a variety of projects that require a graphical interface or the Internet, see Figure 4-10. Its advantages include an HDMI port, 4 USB ports, and Internet connectivity. Since its origins lie in education, it's also best suited for beginners looking for a low-cost, educational computing project. While the Raspberry Pi B+ is as powerful as any personal computer, the operating system has to be manually installed and it does not have as many options to interface with external sensors or buttons compared to other microcontrollers on the market.

Figure 4-10. Raspberry Pi B+ Microcontroller Board

4.2.4.3. BeagleBone Black

The BeagleBone Black is a combination of a Raspberry Pi and an Arduino Uno, seen in Figure 4-11. The BeagleBone Black is best suited for projects that are too complicated for the Arduino Uno but don't require the complex graphics of the Raspberry Pi. Additionally, the BeagleBone Black can connect to the internet but unlike the Raspberry Pi, it may also connect to external sensors. As the BeagleBone Black isn't as popular compared to the Arduino Uno or the Raspberry Pi B+, fewer open-source ideas and materials exist to reference.

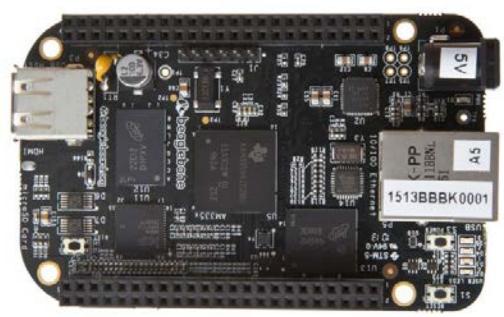


Figure 4-11. BeagleBone Black Microcontroller Board

Both the H-bridge and the microcontroller will require additional support circuitry in order to function. Microcontrollers generally run on 3.3-5V, whereas the motors are run at 24V. For safety purposes, they must be connected to separate power supplies, which demand two separate input headers and distribution lines on the controller board. The microcontroller will additionally require power line filtering, to insulate against fluctuations caused by motors switching on and off.

Signal lines between the H-bridge, microcontroller, and (if used) user interface should also be filtered to prevent signal noise from inducing unwanted motor movement commands. Signals from any sensors, including rotary encoders, current sensors, and temperature sensors, must also be filtered and potentially translated to voltage levels that the microcontroller can accept. If an integrated H-bridge is used, it will most likely require its own circuitry, as set forth by the manufacturer for that particular chip. If a discrete H-bridge is used, MOSFET drivers will need to be included, as the microcontroller alone is not powerful enough to switch the large MOSFETS.

4.2.5. Cutting Module

The cutter is the tool used to engrave the wooden board. The markings will be used to differentiate the letters against the background wood. While the traditional form of generating these markings is by routing them into the wooden sign, there may be other options that are more appropriate for this situation.

4.2.5.1. Router

A palm router, as seen in Figure 4-12, is a power tool that uses a high-speed routing bit to remove material from the workpiece, typically wood. Routing is the most common and cost effective method for cutting signs. However, routing produces a lot of debris and wood chips, which may interfere with the performance of the router and diminish the quality of the finished cut. In addition, the high speed of the routing bit produces a significant amount of noise and exerts a lot of force on the tip of the router bit. Based on the type of wood being cut, a router's feed speed should be adjustable.

Figure 4-12. Wood Router

4.2.5.2. Laser Cutter

For detail on the construction and investment required to assemble a high power laser cutter, please refer to the *Background* section (2.5.2) of this document.

The intent of the laser cutter is to produce a high-powered laser directed perpendicular to the workpiece in order to burn away, or melt, the material. An example of said machine may be seen in Figure 4-13. Laser cutting requires a substantial amount of electrical energy in order to produce the required flow of electrons for laser production. Additionally, it must also generate sufficient ventilation for safe operation of the laser. As lasers are also complex by nature they are also expensive.

Since the laser cutter appears to be a valid option, the Cal Poly Tree's Company believed it was warranted to investigate the laser cutter in the Mustang '60 machine shop on the university campus. However, after talking to one of the Industrial Manufacturing Engineers that was responsible for setting up and creating the user interface for the on-campus laser cutters, it was determined that it would be incredibly difficult to use a laser cutter to fulfill the sponsors' desires and requirements.

Additionally, when looking at the process, Laser cutting also burns the wood, producing a burnt odor and an inconsistent quality of cut. Thus, this process can be very dangerous and must be closely supervised when in operation. Also, due to the nature of wood fibers, the depth of woodcuts may vary slightly, produce a rough texture. Lastly, in addition to the high rate of energy consumption, laser cutters are also relatively slow, thus requiring significantly more energy and time to complete a sign.

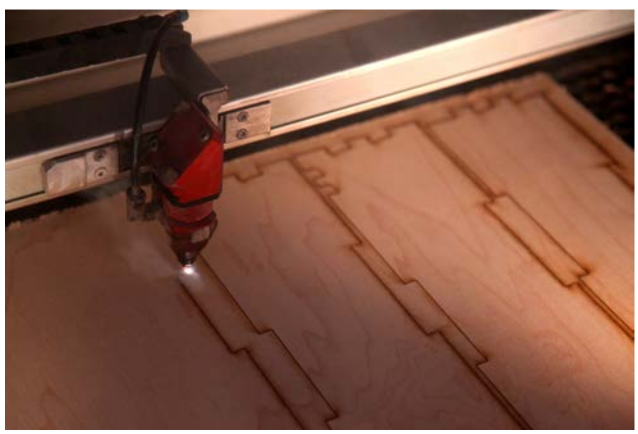


Figure 4-13. Laser Cutter

4.2.5.3. Chemical Etcher

Chemical etchers, as seen in Figure 4-14, deposit chemical solutions to eat away exposed regions of the workpiece material. By carefully applying chemicals on specified areas of the workpiece, the surface will erode and reveal the desired image. To properly perform the etching process, very specific machinery must be used to accurately apply chemicals in desired locations. One must also ensure that the used chemicals will not negatively affect the machine. Additionally, since harmful chemicals may be used, these machines must ensure the safety of the operator and the surrounding environment since harmful chemicals will be used. A few of the chemicals that dissolve wood include sodium hydroxide and sulfuric acid. Each of these substances will negatively affect the user's health if an exposure occurs.

Then, once the letters are dissolved away, the board must be washed of debris and dissolving agents. The result is a significant production of chemical waste that must be safely and properly disposed of.

While chemical etchers produce beautifully intricate designs, these machines come at a steep price, are extremely dangerous, and take up large amounts of room.

Figure 4-14. Chemical Etcher

4.2.6. Actuation

The actuation subsystem will define the method used to move the cutting module and control its location in three-dimensional space. The chosen actuation subsystem must consider the presence of wood chips, the limited space, and the required accuracy of the system.

4.2.6.1. Belt and Pulleys

For this option, the system uses pulleys to generate tension in the belt which will pull the attached payload, as seen in Figure 4-15. The payload for this project will be the cutting tool and gantry mechanism. Even though this option allows for a cost effective transfer of power across a large physical distance, it also introduces some error in the accuracy of the position due to slack in the belt. The belt and pulley system will have to implement additional belt tensioners in order to minimize backlash in the system and accommodate belt stretching due to temperature variations. The belt stiffness is a concern considering its CNC purpose, so belt sizing must be carefully executed.

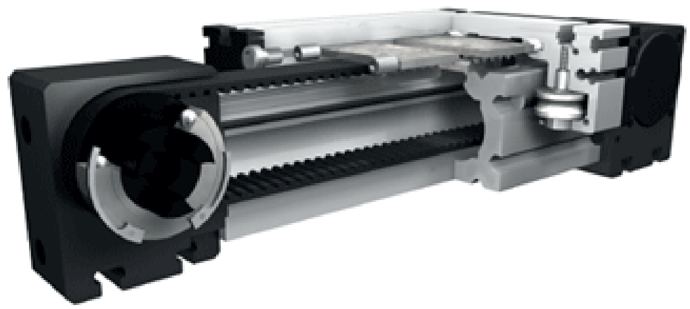


Figure 4-15. Belt and Pulley Actuator

4.2.6.2. Power Screw

The power screw, which can either be a lead screw or a ball screw, translates rotational motion into linear motion of the attached payload, as shown in Figure 4-16. By rotating the screw, the object attached to the nut will move across the screw, creating linear motion. This method of motion is accurate and has relatively little backlash. A consequence of this method is that the power loss due to friction, especially if multiple screws are used. To maximize the efficiency of the lead screw, thread profiles other than standard ACME thread could be investigated.

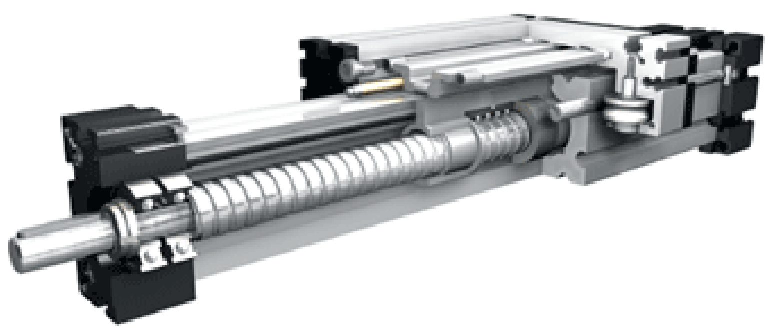


Figure 4-16. Power Screw Actuator

4.2.6.3. Rack and Pinion

The rack and pinion actuation method uses a set of gears and a rack to translate the rotational motion of the gear into linear motion along the length of the rack, as seen in Figure 4-16.1. The rack will be set stationary in relation to the Forest Sign Maker, while the gear will move along the designated axis. Even though this method of actuation is accurate, it would be difficult to manufacture due to its limited tolerance range. The teeth of the rack and pinion need to be in very close alignment in order to operate properly, and such tolerances will difficult to abide by while machining the components on campus.

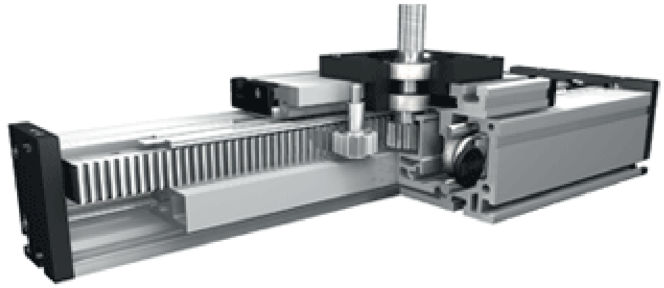


Figure 4-16.1 Rack and Pinion Actuator

4.2.7. **Tensioners**

Tensioners are devices that apply a force to a chain (or belt) creating a tensile force in the system. By applying the proper force to the chain, one can eliminate excess slop in the system as well as increase the precision of the system. It is important to note that there must be a proper balance between tensile loading and tolerable slop. After the system reaches its optimal loading configuration, any increases in tensile forces throughout the chain/belt system will decrease the motor performance and efficiency. With this in mind, the ultimate goal of the tensioners is to apply an effective amount of force to the chain/belt system to eliminate slop while also minimizing any system losses.

4.2.7.1. Ultra-Low-Profile Tensioners

The objective of ultra-low-profile tensioners is to apply a tensile load to a system in the simplest way possible. Due to their “ultra-low profile”, these tensioners have very few parts and take up a minimal amount of space, as seen in Figure 4-17. They are relatively cheap and very simple to install. The major downside to the simplicity of the low profile is the lack of moving parts for the chain to rotate around. Instead, the chain simply slides along the guide rail, resulting in large frictional forces and excessive loads on the motor.

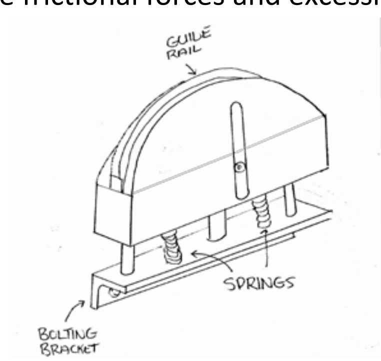


Figure 4-17. Ultra-Low-Profile Chain Tensioner

4.2.7.2. Spring-Loaded Adjustment Arm Tensioner

Spring-loaded tensioners with an adjustment arm utilize a lever arm with a built-in spring to apply a continuous tensile force in a chain and automatically account for any slack or slop in the system, as seen in Figure 4-18. These tensioners are very effective and produce minimal loads on the system. However, due to the complexity of the multiple moving components, this is a moderately expensive solution.

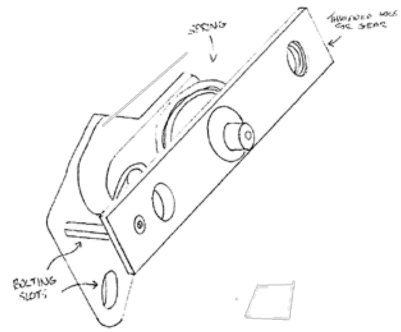


Figure 4-18. Spring-Loaded Adjustment Arm Tensioner

4.2.7.3. Adjustment Screw Tensioner

Adjustment screw tensioners are a fairly low profile type of tensioner that utilizes an adjustment screw to set the tension in a chain system. There are minimal moving parts on this system. Unlike the ultra-low-profile tensioners, these models utilize a free spinning gear rather than a friction system to maintain tension, as seen in Figure 4-19. The major downside to this results from the lack of spring loaded tension. As such, the user must manually set the tension with the adjustment screw. It should be noted that while this may be viewed as an inconvenience to the user, it does provide the user the ability to adjust the tension to a desired level, which the user would not be able to achieve with a preloaded spring system.

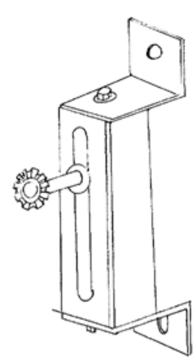


Figure 4-19. Adjustment Screw Tensioner

4.2.8. Foundation

The foundation of the CNC machine will serve three main purposes. First, it must provide a structural base for the cutting mechanism. Second, it must be able to securely support the sign. Third, it must protect all of the mechanical and electrical components under it from any debris or dust. With those goals in mind, it will feature clamping spots for the workpiece to hold on to. It will also include mounting features for fastening the entire system to a workbench.

4.2.8.1. Wooden Board with T-Slots

For this foundation, a wooden board slightly larger than 2' x 4' will be assembled and then grooves may be routed to situate the T-slot extrusions flush with the top surface, as seen in Figure 4-20. The simplicity of the design will facilitate fabrication and assembly. However, a wooden foundation will not be incredibly durable and may break down prematurely or warp due to any moisture in the air.

Figure 4-20. Wooden Board With T-Slots

4.2.8.2. Metal Plate with T-Slots

This concept is similar to the previously mentioned design. However, in efforts to increase the durability of the design, the wood will be replaced by metal (most likely aluminum), as seen in Figure 4-21. Unfortunately, due to the board's size, the quality of the aluminum plate, such as flatness, perpendicularity, and the final dimensions of the board are not controllable and will be governed by the fabrication process. It should also be noted that although a metal plate may be more durable than the wooden plate, it is also significantly heavier and costlier.

Figure 4-21. Metal Plate With T-Slots

4.2.8.3. Prefabricated Bed

Similar to the wooden board with T-slots option but instead of manufacturing and developing a 2' x 4' board, a prefabricated board may be purchased to save the time and effort required to build one. However, after researching prefabricated beds, finding one at least 2' x 4' large is fairly difficult and very expensive. Although a prefabricated bed is an easy solution, it may not perfectly satisfy the design requirements or budget constraints set by the project.

4.2.9. Safety

Due to the nature of moving parts, wood cutting devices, and high-power electrical devices, there is the risk of accidental injury to the user. For the general well-being of the user, safety features and considerations have been deliberated to reduce the risk of injury. Also, since safety is of paramount concern, all the following design considerations will also be implementations, thus there will not be a *Safety* sub-section following.

- Revision 1/31/17 -

Drawings have been added throughout the following safety subsections to help the viewer.

4.2.9.1. Vacuum Capabilities

To help mitigate any performance and safety issues that may arise from sawdust and debris, there will be a permanent vacuum tube attached to the router mounting plate in order to maximize the amount of wood chips a sawdust consumed by the shop vacuum, as seen in figure 4-22. As discussed previously, wood chips are relatively heavy and will not pose much of any issue as far as hazards or performance malfunction. However, the sawdust produced during the routing process has the potential to be inhaled (risking the operator's health) and can coat the rotating parts in a film of dust.

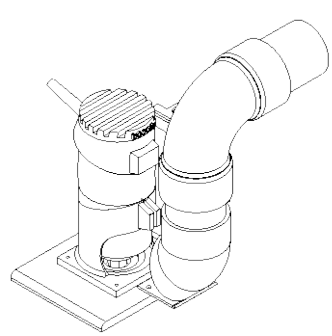


Figure 4.22 Permanent Vacuum Design Possibility

In addition to having a permanent vacuum duct connected to the mounting plate, the ducting will be joined with a standard shop vacuum nozzle. Such a construction provides the user the ability to detach the vacuum nozzle after a sign has been routed, and vacuum the remaining pieces of wood chips and sawdust manually.

4.2.9.2. Emergency Shutoff Switch

The emergency shutoff switch is an easily accessible big, red, mushroom button on the machine, as seen in Figure 4-23. When pressed, the button will shut down the entire machine. In the event of a malfunction or if the user wishes to turn off the machine, the button may be pressed and any electrical power flowing through the system will be terminated. Such a feature will eliminate the potential for accidental injury if something goes awry during the cutting process.

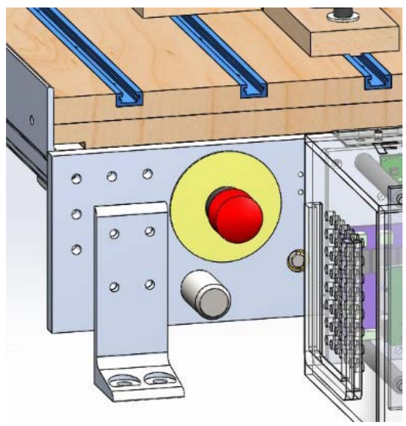


Figure 4-23. Emergency Shut-Off Switch

4.2.9.3. Limit Switches

To prevent the motors from ever forcing the gantry past its physical parameters, limit switches will be installed at the minimum and maximum dimension of each axis. If triggered, these switches will send a signal to controller to cease any movement and prevent the machine from experiencing any physical damage.

4.2.9.4. Electrical Power and Conduits

Another field of concern is protection against the electrical power of the system. All wires and cables will be hidden from direct access. The copper material will be completely shielded. Additionally, these wires will be comprised of stranded cores rather than solid cores to prevent any fatigue due to periodic flexing and vibration. Furthermore, all electronics will be protected from direct finger access due to the shielding of the impact cover. The high voltage power supply and grounding scheme will be linked directly to the workshop AC main via a rated power cord. Lastly, all lengths of cable will have strain reliefs near the terminal locations to mitigate fatigue stress and cracking of the copper.

4.2.9.5. Overheating

Overheating of any electronic component or hardware raises much concern because it often leads to component failure if not addressed properly. Any device which shall conduct a significant current must be appropriately designed so as to handle the heat naturally generated during operation. Additionally, the device must be able to detect, prevent, or otherwise mitigate high temperatures caused by abnormal operation. The presence of sawdust and wood chips threatens to make even a minor electrical fire a large disaster. Even high temperatures which are not sufficient to start fires shall not be acceptable, as they shorten the device's lifespan and hasten the failure of moving parts.

The motor driver H-bridges and motors themselves are most sensitive to high temperatures. The H-bridges must be able to rapidly switch high current loads; the parasitic resistance present in all electronic devices means that they will produce a significant amount of heat. The motors, which appropriately sized for normal operation, can overheat if they encounter high loads or stall.

While other components, such as wires and microcontroller logic, could potentially suffer from overheating, conditions which would induce failure in those parts would have caused catastrophic failure in the two previously mentioned systems long before any other failures would be noticeable. Thus, strategies for mitigating overheating will be centered around the motor H-bridges and motors.

The H-bridges, either discrete or integrated, must be sized to properly handle the heat that normal operation will produce. Their packages must be able to tolerate and conduct heat away from the electronics within. The controller board will serve as a heat sink, thus conducting heat away from the packages. While a large ground plane might be suitable for some designs, others might require discrete heat sinks or forced air cooling to maintain their proper temperature.

During normal operation, the motors should not need any special consideration with regards to heat, as they are inherently designed to handle the loads produced therein.

Motor stalling or high loads presents high currents to both the motors and the motor drivers. This high current, while tolerable by the electronics themselves, will quickly produce destructive heat levels if not mitigated. The motor controller must be able to detect periods of unacceptably high current and disable the offending motors before high temperatures accumulate. If such event were to occur, a signal would be sent to inform the user that an over-temperature situation has occurred. Subsequent behavior will depend on the nature of the stall. If the motors are able to continue making a cut, they will do so. If the motors are stuck firm and the device cannot free itself without stalling, the program will be halted and inform the user of the problem.

These strategies will help to prevent any thermal failures from occurring within the electronic subsystems. Thermal failures within the physical subsystems are not predicted to be a problem as the speeds of the drive systems are not particularly high and the router has been professionally designed and will handle its own cooling.

4.2.9.6. Enclosure

To ensure the safety of the operator and other bystanders in Paul McFarland's workshop, it is essential to minimize the quantity of pinch points present on the machine. A pinch point is a location where gaps close quickly, sometimes forcefully. Unfortunately, designing an exposed system with moving parts containing absolutely no pinch points is impossible. In attempt to completely eliminate any potential harm to the user, a Plexiglas enclosure will encircle the entirety of Forest Sign Maker. Not only will this prevent the user from being exposed to any moving parts, it will also eliminate the spread of any saw dust and debris beyond the machine. Additionally, the design will be made to prevent the machine from being operated if the enclosure is not sealed.

4.2.9.7. Personal Protection Equipment

Despite all efforts to make this machine as safe as possible, it should be acknowledged that no design is perfect. To augment the safety of the Forest Sign Maker's operator, the team insists on proper use of personal protection equipment being utilized. Such equipment may consist of but is not limited to safety glasses, hearing protection, and a dust mask, as previously mentioned in the *Operation Safety* sub-section (3.1.7).

4.3. Design Selection

4.3.1. Movement

After evaluating the four potential movement options, the team determined the Gantry method best meets the customers' requirements and the team's design specifications, as seen below in Table 4-1.

Table 4-1. Movement Pugh Matrix

Subsystems	Potential Options	Benchmark	Handles Planks Up to 2' x 4'	Shuts Down In Less Than 0.5 sec.	Contains No Pinch Points	Takes Desired Input File	Costs Less Than $5,000	Weighs Less Than 150 lbs.	Dimensions Smaller Than 30" x 6' x 4'	Produces Less Than 80 dbas.	Produces Signs In Less Than 2.0 Hours	Produces Signs In Less Than 8 Hours	Cuts Redwood Density Planks	Requires Less Than 15 Minutes Of Training	Handles Up To 30A and 24V	Replacement Parts Available For Purchase	Produces Minimal Tolerances of 0.03125 in	Total Score
Specification Weight			8	10	5	5	10	10	5	5	8	10	10	7	8	8	8	
Movement	Gantry	Gantry	S	S	S		S	S	S	S	S	S	S			S	S	**0**
	Drawstring		S	-	+		S	S	S	S	S	S	-			-	-	**-31**
	Tower		S	S	-		-	-	+	S	S	S	S			S	S	**-20**
	Strong-Arm		-	S	+		-	-	S	S	S	S	S			-	S	**-31**

Using a gantry allows for a strong, stable, and relatively simple way to move the cutting tool. By allowing motion in 3 directions, this maximizes the potential and control for building signs of multiple sizes and dimensions.

Additionally, when comparing the gantry to the other three options, it is the only option capable of three-dimensional cutting, arguably the simplest design, and is the industry standard. The gantry design may be seen in Figure 4-24.

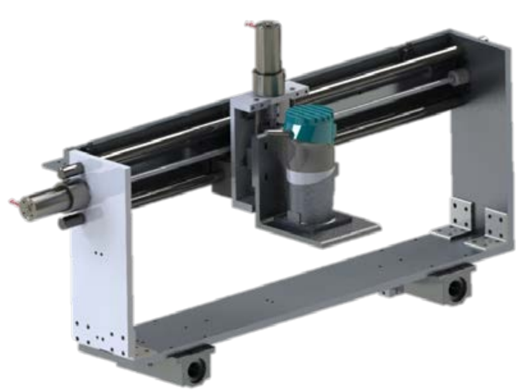


Figure 4-24. Rendered Gantry Design

4.3.2. User Interface

After evaluating three potential user-interface options (tablet, personal computer, custom display), the team resolved that the personal computer serves to best meet the needs of the customers' requirements and the team's design specifications. The final analysis can be seen in the Pugh matrix detailed in Table 4-2.

Table 4-2. User Interface Pugh Matrix

Subsystems	**Potential Options**	**Benchmark**	Handles Planks Up to 2' x 4'	Shuts Down In Less Than 0.5 sec.	Contains No Pinch Points	Takes Desired Input File	Costs Less Than $5,000	Weighs Less Than 150 lbs.	Dimensions Smaller Than 30" x 6' x 4'	Produces Less Than 80 dbas.	Produces Signs In Less Than 2.0 Hours	Produces Signs In Less Than 8 Hours	Cuts Redwood Density Planks	Requires Less Than 15 Minutes Of Training	Handles Up To 30A and 24V	Replacement Parts Available For Purchase	Produces Minimal Tolerances of 0.03125 in.	Total Score
Specification Weight			8	10	5	5	10	10	5	5	8	10	10	7	8	8	8	
User Interface	Tablet PC	Personal Computer				**S**	**-**	**+**	**+**					**S**		**-**		**-3**
	Personal Computer					**S**	**S**	**S**	**S**					**S**		**S**		**0**
	Custom Display					**-**	**-**	**-**	**S**					**-**		**-**		**-40**

The implementation of a personal computer allows for an easier transition from the sign's design on various digital media to the sign's development on a CNC machine. The user interface designed by Cal Poly's Tree's Company will include several data input methods which predominantly involve a third-party graphical user interface (GUI) known as Fusion 360. Fusion 360 is a digital prototyping software produced by Autodesk which encapsulates the design of a two-dimensional image, such as a vector file produced by Adobe Illustrator, the conversion of that vector file image into appropriate and CNC-applicable G-code (Autodesk). The Forest Sign Maker will make use of an individual's personal computer and Autodesk's Fusion 360 software. While deviating from the customer's requirements for interfacing with Adobe Illustrator, the sponsor has agreed to make use of Autodesk's CAD-based software to help facilitate the sign's development. Subsequent to the user's direct interface with a computer, a USB connection is included between the user's main personal computer to the machine's existing Raspberry Pi B+ interface that will ultimately communicate to the controller in charge of directing the cutting module.

4.3.3. **Microcontroller**

After analyzing the few different boards, as seen below in Table 4-3, the team determined that the ideal microcontroller would be an ARMv8-A family device, exemplified by the Raspberry Pi.

Table 4-3. Microcontroller Pugh Matrix

Subsystems	**Potential Options**	**Benchmark**	Handles Planks Up to 2' x 4'	Shuts Down In Less Than 0.5 sec.	Contains No Pinch Points	Takes Desired Input File	Costs Less Than $5,000	Weighs Less Than 150 lbs.	Dimensions Smaller Than 30" x 6' x 4'	Produces Less Than 80 dbas.	Produces Signs In Less Than 2.0 Hours	Produces Signs In Less Than 8 Hours	Cuts Redwood Density Planks	Requires Less Than 15 Minutes Of Training	Handles Up To 30A and 24V	Replacement Parts Available For Purchase	Produces Minimal Tolerances of 0.03125 in.	Total Score
Specification Weight			8	10	5	5	10	10	5	5	8	10	10	7	8	8	8	
Micro-Controller	Arduino Uno	Arduino Uno		**S**		**S**	**S**				**S**	**S**				**S**	**S**	**0**
	Raspberry Pi B+			**S**		**+**	**S**				**+**	**+**				**S**	**+**	**31**
	BeagleBone Black			**S**		**+**	**-**				**+**	**+**				**S**	**+**	**21**
	Other			**S**		**+**	**S**				**+**	**+**				**-**	**+**	**23**

The processing power provided by the ARMv8-A architecture gives the most flexibility in regards to control and translation algorithms. Because the device is not battery powered, higher power consumption is not a concern. Furthermore, the relative lack of hardware peripherals can be adequately resolved by using software replacements, easing development at the cost of precision.

The team has also elected to use an integrated H-bridge IC because the previous device used such chips (the feasibility of this approach is established). Furthermore, the team has identified chips whose tolerance are well above what they will encounter in the motor controller. The VNH series of controllers also include offerings with integrated current sensing. Temperature and overcurrent protection come standard on all offerings. Such a board configuration significantly reduces the complexity of the final motor driver by offloading its functionality to the motor driver ICs.

Thus, the designs have been selected to maximize flexibility while minimizing complexity. This combination of microcontroller and H-bridge should permit the most challenging design to be done in software, which is significantly easier than hardware.

- Revision 1/31/17 -

Description of the controller as a 'micro-controller' is a misnomer, and this component of the device is more aptly described as a 'motor controller.' The role of the controller has been clarified in regards to the user interface and the motor system.

The new motor controller consists of four independent modules: one logic controller device and three separate motor driver devices. This is a new design representing the decomposition of the original device into separate sub-devices. Each device has a separate PCB and is fully self-contained, possessing all the supporting circuitry needed to support its own functionality. The full motor controller is thus the four separate modules, each on a separate PCB, and the physical interconnects made between them. Note that no changes in actual device functionality have been made.

The 'micro-controller' originally discussed in this section is the focus of the logic controller device, which has been named to reflect its role in handling communications and processing instructions to send to the motors. Its board shall contain the microcontroller chip, as well as voltage regulation and signal debounce circuitry. The main purpose of this new board is to support the microcontroller; it does not contain any motor driver circuitry, as that has been moved to the separate devices. This device is a custom PCB board, to be designed and manufactured by the team.

The three motor driver devices are third-party components available from a commercial robotics supplier. They control the actual voltages to each motor, although they contain no logic themselves. Each driver PCB contains a single H-bridge chip, of the same type originally to be used in the controller.

The decision to separate the controller into separate parts was made after reviewing the scope of the original controller plan, which called for an entirely new, custom-made controller board. This board would have placed all components, including microcontroller and H-drivers, onto the same board. This design quickly evolved into a daunting design challenge. The production of a PCB board involves many steps, from part selection to trace routing to actual assembly. The mixed-signal nature of the original board further complicated the design, as high-current power signals tend to drown out digital signals in close proximity to themselves, calling for a degree of expertise uncommon even in industry.

The team has determined that development of a completely new board isinfeasible based off the time, cost, and expertise required. Thus, the team has made the decision to outsource as many of the components as possible to commercial suppliers. In exchange for a decrease in design flexibility, the team can access high-quality designs for entire systems that would otherwise need to be redesigned.

The motor driver boards, as mentioned, have been sourced from a commercial robotics supplier. The controller board, while still custom-designed, has been simplified by the removal of high-current signals and the large H-bridge chips. It is now within the means of the team to design a high-quality controller board, as it now only needs to support a microcontroller, and a few simple power components.

4.3.4. Cutting Module

The final decision on the cutting module that will be used for the Forest Sign Maker is a wood router. This decision was made prior to the project being initiated by the sponsor. However, after further analysis, the team also concluded it was the best option with respect to the customers' requirements and the team's design specifications, as seen below in Table 4-4

Table 4-4. Cutting Module Pugh Matrix

Subsystems	**Potential Options**	**Benchmark**	Handles Planks Up to 2' x 4'	Shuts Down In Less Than 0.5 sec.	Contains No Pinch Points	Takes Desired Input File	Costs Less Than $5,000	Weighs Less Than 150 lbs.	Dimensions Smaller Than 30" x 6' x 4'	Produces Less Than 80 dbas.	Produces Signs In Less Than 2.0 Hours	Produces Signs In Less Than 8 Hours	Cuts Redwood Density Planks	Requires Less Than 15 Minutes Of Training	Handles Up To 30A and 24V	Replacement Parts Available For Purchase	Produces Minimal Tolerances of 0.03125 in.	Total Score
Specification Weight			8	10	5	5	10	10	5	5	8	10	10	7	8	8	8	
Cutting Module	Router	Router	**S**	**S**	**S**		**S**	**S**	**S**	**S**	**S**	**S**	**S**	**S**		**S**	**S**	**0**
	Laser		**S**	**S**	**+**		**-**	**-**	**-**	**+**	**-**	**-**	**-**	**-**		**-**	**S**	**-58**
	Chemical		**S**	**-**	**-**		**-**	**-**	**S**	**+**	**-**	**-**	**-**	**-**		**S**	**-**	**-73**

To accommodate a wood router into the gantry movement design, the team as selected to use the Bosch Colt Palm Router, as seen below in Figure 4-25. It is not required to consider mounting other style routers since Lee McFarland has stated that if the router were to burn out, they would simply replace it with the same model router. With that said, the router mount will be a flat plate with a particular hole pattern, which could easily lend itself well to future modifications if need be.

Figure 4-25. Botch Colt Palm Router

4.3.5. **Actuation**

After evaluating the different modes of actuation with respect to the customers' requirements and the team's design specifications, as seen below in Table 4-5, it was decided that the power screw was the best option for this project.

Table 4-5. Actuation Pugh Matrix

Subsystems	**Potential Options**	**Benchmark**	Handles Planks Up to 2' x 4'	Shuts Down In Less Than 0.5 sec.	Contains No Pinch Points	Takes Desired Input File	Costs Less Than $5,000	Weighs Less Than 150 lbs.	Dimensions Smaller Than 30" x 6' x 4'	Produces Less Than 80 dbas.	Produces Signs In Less Than 2.0 Hours	Produces Signs In Less Than 8 Hours	Cuts Redwood Density Planks	Requires Less Than 15 Minutes Of Training	Handles Up To 30A and 24V	Replacement Parts Available For Purchase	Produces Minimal Tolerances of 0.03125 in.	Total Score
Specification Weight			8	10	5	5	10	10	5	5	8	10	10	7	8	8	8	
Actuation	Belt and Pulleys	Power Screw	**S**		**-**		**S**	**+**	**S**		**S**	**S**	**-**			**S**	**-**	**-13**
	Power Screw		**S**		**S**		**S**	**S**	**S**		**S**	**S**	**S**			**S**	**S**	**0**
	Rack and Pinion		**S**		**-**		**-**	**-**	**S**		**S**	**S**	**S**			**-**	**S**	**-33**

Power screws, which can take the form of a lead screw or a ball screw, provide accurate positioning, which is required for the ±0.03125-inch tolerance in letter positioning. Belts and pulleys were considered, but through testing and experience, they were not accurate enough. They stretch over time, perform unreliably under extreme seasonal weather, and any slack in the belt will manifest itself as backlash in the motor controller. Similarly, with the rack and pinion, it would be very difficult to achieve the desired tolerance and the system will wear down over time. Conversely, despite the expense of power screws, their positional accuracy and reliability are worth the investment. The power screw actuation assembly for the x-axis may be seen in Figure 4-26.

Figure 4-26. X-Axis Power Screw Actuation Assembly

- Revision 1/31/17 -

Unlike the design shown above, the team has decided to peruse a single lead screw to actuate the x-axis of the Forest Sign Maker. This modification was the largest mechanical design change the team made and was focused around four main ideas: simplicity, efficiency, reliability, and alignment.

To start off with simplicity, the original, double lead screw design required two lead screws, two gear sets, two tensioners, a chain, 4 ball bearings, and 2 worm gears. However, after switching to a single lead screw, the entire actuation system only required one lead screw, two ball bearings, and one gear. However, it is important to realize than not only did this change clean up the actuation system, it also decreased the system losses and loads.

When looking at the efficiency of the original system, not only did it contain over twelve contact points resulting in frictional losses, it also contained a tensioning system that was putting excessive torsional and shear loads on the motor and components. To express this matter further, these loads were so large that is was nearly impossible for the oversized motor to actuate the machine. However, after redesigning to a single lead screw, the contact points were reduced from twelve to five and the systems loads were significantly reduced.

With regards to durability, the life-span of the system is proportional to the system's efficiency and simplicity. As the number of parts in a system increases, the likelihood of something breaking also increases. Thus, by switching from a double lead screw system to a single lead screw system and eliminating all the unnecessary parts previously mentioned, the reliability of the machine greatly increases. Similarly, as the loads on a system decrease, their life cycle increases.

Lastly, the last aspect the team analyzed was alignment, which was actually the reason a double lead screw design was originally picked. When originally analyzing the alignment of the system, the team thought that a double lead screw system would help stabilize the gantry and prevent any tilting or misalignment. However, since the chain and tensioning system was unideal, the double lead screw design actually had the potential to force the gantry out of alignment if there was any slop in the system. Although the single lead screw does not provide the support the double system potentially could provide, it is not capable of forcing the gantry out of alignment, but taking all other things into account, the team has determined that the single lead screw is the best option and will be implemented.

4.3.6. **Tensioners**

After reviewing the different modes of tensioning with respect to the customers' requirements and the team's design specifications, as seen in Table 4-6, it was decided that the adjustment screw tensioner was the best option for this project (based of the double lead screw design).

Table 4-6. Tensioner Pugh Matrix

Subsystems	**Potential Options**	**Benchmark**	Handles Planks Up to 2' x 4'	Shuts Down In Less Than 0.5 sec.	Contains No Pinch Points	Takes Desired Input File	Costs Less Than $5,000	Weighs Less Than 150 lbs.	Dimensions Smaller Than 30" x 6' x 4'	Produces Less Than 80 dbas.	Produces Signs In Less Than 2.0 Hours	Produces Signs In Less Than 8 Hours	Cuts Redwood Density Planks	Requires Less Than 15 Minutes Of Training	Handles Up To 30A and 24V	Replacement Parts Available For Purchase	Produces Minimal Tolerances of 0.03125 in.	Total Score
Specification Weight			8	10	5	5	10	10	5	5	8	10	10	7	8	8	8	
Tensioner	Ultra-Low-Profile	Ultra-Low Profile			**S**		**S**	**S**									**S**	**0**
	Spring-Loaded Adjustment Arm				**S**		**S**	**S**									**S**	**0**
	Adjustment Screw				**+**		**S**	**S**									**S**	**5**

When looking at the result from the Pugh Matrix, the scores of all three tensioners were roughly the same. This is because such a small component of a subsystem has very little effect on the overall system's ability to meet the customers' requirements and the team's design specifications. However, where this adjustment screw method does excel is in its mode of creating tension.

The adjustment screw's design simplicity makes it a comparable option to the ultra-low-profile tensioner. However, since the adjustment screw tensioner utilizes a free spinning pinion rather than a rubbing surface, as seen below in Figure 4-27, it minimalizes the frictional losses on the system and reduces the overall load on the motors.

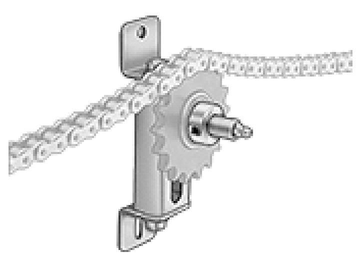


Figure 4-27. Adjustment Screw Tensioner

Since the team has decided to use a single linear lead screw to actuate the x-axis, the Forest Sign Maker no longer requires and chain and tensioning system.

4.3.7. **Foundation**

Through direct comparison of the foundation surface options, as seen in Table 4-7, the team decided to design a wooden work surface with T-Slots. Such a design may be seen in Figure 4-28.

Table 4-7. Foundation Pugh Matrix

Subsystems	**Potential Options**	**Benchmark**	Handles Planks Up to 2' x 4'	Shuts Down In Less Than 0.5 sec.	Contains No Pinch Points	Takes Desired Input File	Costs Less Than $5,000	Weighs Less Than 150 lbs.	Dimensions Smaller Than 30" x 6' x 4'	Produces Less Than 80 dbas.	Produces Signs In Less Than 2.0 Hours	Produces Signs In Less Than 8 Hours	Cuts Redwood Density Planks	Requires Less Than 15 Minutes Of Training	Handles Up To 30A and 24V	Replacement Parts Available For Purchase	Produces Minimal Tolerances of 0.03125 in.	Total Score
Specification Weight			8	10	5	5	10	10	5	5	8	10	10	7	8	8	8	
Foundation	Wooden Board	Wooden Board	**S**				**S**	**S**	**S**							**S**		**0**
	Metal Plate		**S**				**-**	**-**	**S**							**-**		**-28**
	Prefabricated Bed		**S**				**-**	**S**	**S**							**-**		**-18**

Even though the wooden board is not the most durable solution, it has many other positives that make it the desired choice. First, it is relatively lightweight and inexpensive, which satisfy two important design requirements. Second, using a wooden board will provide the user the flexibility to modify the board in the future, if necessary. Third, due to its low cost, it is significantly easier to replace if any problems arise in the future.

Figure 4-28. Wooden Board With T-Slots

4.4. Preliminary Construction Plan

Construction of each subsystem will be initially independent of the others. Because of the varied nature of each subsystem, they will generally require different construction approaches regardless of whether they are combined or not; thus, independent development is the natural approach.

4.4.1. User Interface

The physical components of the user interface (the personal computer) are ubiquitous consumer products and will not need to be constructed. Furthermore, the use of commercial software to perform sign design and CAD/CAM file construction spare the effort of constructing path-geometry software. Thus, the primary avenue of development for the user interface is the software upon the device with which the user will control its operation.

The user interface will reside upon the onboard Raspberry Pi B+ and control its operation through a simple application, which will accept files and basic control of the device. The interface itself should then be constructed and tested using resources that are available to the lightweight Raspberry Pi B+. The preexisting device uses a rudimentary GUI devised using the Python scripting language; this is suitable for an improved version, although a full application designed with a graphical toolkit such as GTK+ is also feasible.

While the interface will eventually reside on the Pi, its development does not need to be limited to the Pi itself. In fact, it is preferable that development take place on a full-sized computer, as the Pi has limited resources for compilation and debugging. The interface will be developed separate from the Pi, and then loaded onto it for testing.

To this extent, it is most likely that some form of network interface will be installed onto the Pi to facilitate easy transfers of development resources. Barring this, frequent uploads to the device will be required.

- Revision 1/31/17 -

To connect the user's personal computer to the Raspberry Pi B+, the device will be linked through a private network which will make use of either a standard Ethernet or Wi-Fi-based connection. In considering the final construction, opting for a Wi-Fi-based connection will allow the Raspberry Pi B+ to exist within a closed environment, protecting it from sawdust, and prolonging the part's life-expectancy. Using Wi-Fi will also free the laptop from being constrained to a distance within an Ethernet cable's length from the Forest Sign Maker. A point of contention with this construction design is the chance of foreign devices entering the network and tampering with the machine. To prevent this, a private network must be designed. If this issue cannot be resolved with a privatized Wi-Fi-network, and Ethernet cable will be used such that only the designated laptop can talk to the Raspberry Pi B+ (and thus, the Forest Sign Maker).

4.4.2. Motor Controller

The motor controller has two main aspects: electronics and control software. Each will be developed independently before being combined and tested together.

The first phase of the electronics construction is a block diagram of the components. Since the controller is fairly simple, this diagram is not anticipated to be complex. Nevertheless, it is important for expanding into more detailed circuit models, which show actual connections between components. Circuit simulation and parameter calculations, again, should not be complex, since most of the complexity of the controller is abstracted away within the microcontroller or motor controller ICs, but power and signal line filtering will still need to be developed. These steps are crucial for the protection of data against transients which can be introduced by the large currents being switched on and off by the drivers. Even lines which never directly meet can be influenced by electrical and magnetic fields generated by the other.

At this stage, components will be selected according to the parameters identified during design. Compromises may need to be made according to what parts are available with particular parameters; any modifications that need to be made to the design will be made and noted. At this stage as well, circuit layout will be planned with particular attention being given to the trace layout of the circuit board. Because it does carry significant amounts of power, the board must not only be able to carry high currents but dissipate large amounts of heat as well. Attention should also be given to the EMF emissions of high-current traces, and how that will affect the digital signal lines present elsewhere.

Once design and layout are finished, the device will be assembled.

The driver software will initially be developed on a separate board as well. Because the microcontrollers used are fairly common, options for control strategies and operating systems can be tested for functionality using a separate microcontroller before the controller board has even be constructed. Once the motor driver board is finished, however, the software should be moved onto it immediately, as any motor control algorithms must be designed with the characteristics of the board in mind.

The revised motor controller simplifies elements of controller construction, while adding other new requirements. Construction can be now roughly divided between the design and procurement of the logic controller board, and the assembly of the motor controller proper.

Though the logic controller board has been greatly simplified, it will still require careful design. Functionality has not been changed, although part selection could vary depending on the ability of the current chip to work properly with three separate boards. A new board must be designed and its layout constructed. This, however, has been greatly simplified by the lack of high-power currents on the board; most signals are now 3.3V digital logic signals, at low (> 10kHz) frequencies. Thus, traces can be routed simply from point A to point B without excessive worry about crosstalk or EMF interference.

The physical construction of the logic controller board will be outsourced to a commercial PCB fabrication service. The team will assemble the components on the board; this is again made much simpler by the lack of the power electronics on the design, which required sophisticated soldering techniques. The team will attempt to utilize the Cal Poly IME department’s PCB oven for assembly, although hand soldering is possible now that the power electronics are removed.

Once the logic controller board is complete, the team will assemble the controller proper. This will require some mechanical preparation as well as electrical: the electronics components box will need to be revised in order to support the mounting of four separate boards instead of a singular board. The team will install the four controller modules, and then route signal and power connections between them, and the rest of the system. It is anticipated that certain existing wires will need to have new headers installed in order to interface with the new controller.

4.4.3. Drive System

Owing both to the extra work needed to construct a test rig, and the preexisting structure of the device prior to modification, efforts to construct the drive system will take place on the device itself. Because the drive system is robust and can be isolated from the other systems, it is not anticipated that this should affect development in other areas. Thus, all new mechanical systems and improvements will be constructed on the current device.

4.4.4. Other

The other systems not specifically mentioned have been constructed and tested by previous efforts to develop the device. They are generally assumed to be correct;

any development on their behalf will only be performed if made necessary by changes to the three main subsystems of development.

4.5. Testing

As outlined in the *Method of Approach* section, testing will come in two flavors: unit/integration and system. Of the two, the unit and integration tests are anticipated to be the most involved. Each subsystem is modeled by its ability to accept inputs and produce outputs; thus, testing must establish each subsystem's ability to properly perform its duties. Batteries of tests will be devised, with each aiming to test a different aspect of a subsystem to its fullest extent.

The user interface will be tested to ensure that the user cannot manipulate it into an unstable state by improper use. General stability tests will also evaluate its robustness. On the output side, tests will ensure that the files sent to the controller from the user interface are correct and that it accepts and properly displays messages back from the controller as well.

The motor controller will be tested to ensure that no combination of commands from the user interface sends it into an unstable state. Furthermore, the internal structure of the controller must be tested, to ensure that it itself does not enter unstable states during the course of its operation. Because the controller must respond to time-sensitive events, its ability to correctly respond to a variety of inputs at conflicting times must be tested as well. Finally, the signals sent to motors in response to commands must be verified. On the hardware side, the construction of the board itself should be tested for physical faults, such as shorts and open leads.

The drive system, and specifically the tensioners, will be tested to ensure that it puts adequate pressure on the drive chain while reducing the strain on the drive motors. Testing here will be tightly integrated with the construction of the tensioners, as they will be installed in-situ at their final resting place.

System testing will test the ability of all systems to integrated and perform the machine's full duties. It is here that the device will be evaluated against the engineering specifications. These tests are intended to expose any shortcoming not exposed by unit and integration testing, as the device can produce input conditions in much more complexity and far more variety than individual tests can accomplish, simply as a consequence of normal operation.

4.6. Design Safety Hazard Identification Checklist

Table 4-8. Design Hazard Checklist (Part 1 of 2)

Yes	No	Design Hazard Checklist
X		Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and shear points?
X		Can any part of the design undergo high accelerations/decelerations?
X		Will the system have any large moving masses or large forces?
X		Will the system produce a projectile?
	X	Would it be possible for the system to fall under gravity creating injury?
	X	Will a user be exposed to overhanging weights as part of the design?
	X	Will the system have any sharp edges?
	X	Will any part of the electrical systems not be grounded?
X		Will there be any large batteries or electrical voltage in the system above 40 V?
	X	Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	X	Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	X	Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
X		Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
X		Can the system generate high levels of noise?
X		Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
	X	Is it possible for the system to be used in an unsafe manner?
	X	Will there be any other potential hazards not listed above? If yes, please explain on reverse.

Table 4-9. Design Hazard Checklist (Part 2 of 2)

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
1. Moving Drill bit / Movement of Drill	**Plexiglas surrounding machine**	N/A	
2. Movement of Drill bit	**Plexiglas surrounding machine**	N/A	
4. Projectiles from loosened wood knots or from broken drill bit	**Plexiglas surrounding machine. Plastic Goggles**	N/A	
9. High Voltage	**Grounding Switch - cuts all power to each source of machine.**	N/A	
13. Hazardous byproducts of sawdust and woodchips	**Facemask. Vacuum.**	N/A	
14. High levels of noise	**Ear Plugs on User. Redesign of machine to reduce level of noise.**	N/A	
15. Extreme Weather Changes - Workshop located in mountain. Machine subject to cold temperatures	**Durable Materials**	N/A	

- Revision 1/31/17 -

It is important to note that in the preliminary design, Tree's Company considered the inclusion of a Plexiglas casing to be placed around the machine to protect the user from projectiles (loosed knots) launched from drilling through the wood, as well as contain any dust and debris produced while cutting signs. While this design is still under consideration, it is a low-priority addition to the general construction and successful execution of the wood cutting machine. If time does not permit, Plexiglas will not be included in the project but left in the documentation in case the client wants to make use of a Plexiglas encasing modification.

5. Final Design Details

5.1. Functional Description

To create a sign, the Forest Sign Maker follows the system flow, depicted in the functional diagram seen in Figure 5-1.

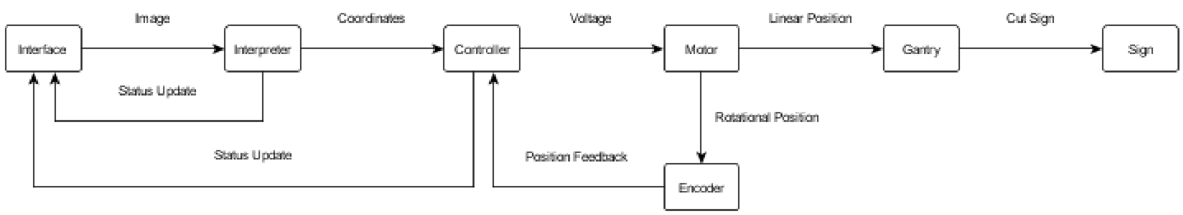


Figure 5-1. Functional diagram for the Forest Sign Maker

To begin designing the sign, the user must first access his or her personal computer and enter the pre-downloaded Fusion 360 software. Fusion 360 is a cloud based CAD/CAM 3D Modelling software. The product is provided free to students, educators, hobbyists, and small businesses. The software is perfect for Cal Poly Tree's Company's senior design project as it incorporates a familiar CAD software for mechanical designs. The end-user, Paul McFarland, has experience in this area and the interface of Fusion 360 makes the design process both efficient and manageable. A set of templates for sign cutting which maintain the correct height-width-length dimensions of several differently sized rectangular signs will be provided on the user's personal computer will be . Through these templates, the user can decide what image or text will be carved on the surface of the sign. If the dimensions of the wooden signs deviate from any of the given templated structures in Fusion 360, the use will simply have to copy a template and adjust the dimensions of the sign accordingly. Once the user is satisfied with their design drawings, the user will save the design to a G-Code file. This will create a G-Code-based design file read to be sent to the wood carving machine for analysis and, eventually, production.

The first step in operating the Forest Sign Maker will be to power on the wood cutting machine and allowing the connected Raspberry Pi B+ to utilize and load it's pre-existing OS. Once the OS has fully loaded and the Raspberry Pi B+ begins to run, said laptop will be connected to the Raspberry Pi B+ in a private network (designed to function in either Wi-Fi or Ethernet based environment). Both the personal computer and the Raspberry Pi B+ will be preloaded and configured to work with VNCServer, a virtual network computer server. Through this method, the personal computer will be able to see and interact with the contents of the Raspberry Pi B+ as though the user was directly interacting the Raspberry Pi B+ itself. Having accepted the G-code file, the Raspberry Pi B+ program will do a preliminary analysis of the maximum x-, y-, and z- dimensions of the sign. It will validate the G-code design as falling within the maximum dimensional constraints or reject the design if these constraints are not satisfied. If the design is rejected, an error message will be presented to the user detailing the source of failure such that the user can re-design the file and submit a new G-code.

When the Raspberry Pi B+ detects a valid G-code file, it will inform the user and proceed to deconstruct said G-code file into smaller packets which will then be delivered to the motor controller. Through the utilization of smaller code packets, the motor will be able to focus on translating said G-code into corresponding machine signals which will then power the connected x-. y-, and z-axis motors. Had the entire G-code file been uploaded to the motor controller, risk of exhausting the controller's existing memory to store said G-code would cause slower performance and execution at the hands of the controller.

The motor controller accepts G-code instruction sections from the user interface, along with general commands (run, stop, report, etc.). From these, it will eventually produce the timed motor signals necessary to make each cut. Figure 5-2 shows the internal operation of the controller necessary to perform this complex transformation. In particular, it shows the four software components of the logic controller, implemented via microcontroller.

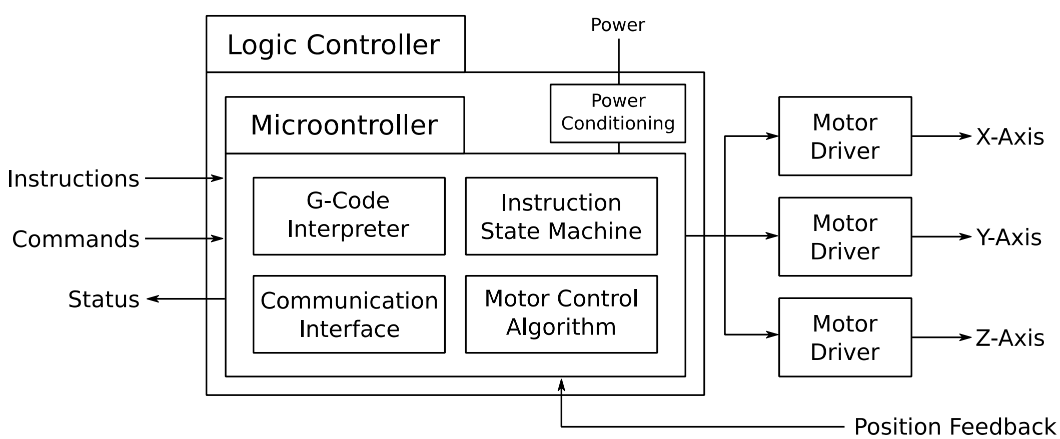


Figure 5-2. Controller Functionality Diagram

The communications interface, as expected, handles communications with the user interface. This module is not very large, as much of the low-level signaling (USB or UART) is handled by the microcontroller's built-in peripherals. This module accepts packets of instructions and commands for the controller to take. The module also sends status messages, either on demand or in response to some event (motor stalls, next instruction, program done, etc.).

From the communications interface, commands and signals are fed into the instruction state machine, which tracks the current instruction, and the current position of the device. The state machine passes each instruction into the G-code interpreter, which translates the instructions into explicit motor positions and paths. These are then fed into the motor control algorithm, which works closely with the state machine to move the motors along the right paths at the correct rate. The motor control algorithm passes direction and speeds to each individual motor driver, which in turn pass along power to the motors. Feedback in the form of position and end switches are accepted from various sensors positioned around the device.

When a motor receives a voltage from the controller, it responds by producing rotary actuation to a shaft. Each motor shaft will be coupled with a lead screw that is responsible for the gantry actuation in its designated axis. As the lead screw rotates, a threaded coupling is actuated along the lead screw, thus resulting in the linear movement of the gantry component. To provide a locational feedback back to the controller, an encoder is attached to the end of the lead screw to track the rotational position of said lead screw. Each encoder will send their rotational information back to the controller. Then by combining this feedback with the rotational pitch of the lead screws, the controller is able to accurately locate the position of the cutter and move it to its desired location. This feedback loop is performed throughout every line of positional code to ensure that each cutting point is within its desired tolerance, and when completed, a sign should be produced.

Errors can be produced at any point in the system flow, from the motors to the user interface. A critical error is any condition from which the machine cannot easily recover or which is an immediate risk to machine or user safety. Examples of critical errors include motor stall conditions, bad G-code instructions, and hitting a limit switch. The general response to any critical error is to stop the machine execution, and to pass the error up the system flow to the user, who can then determine the appropriate action to take. The motor controller is able to detect errors in the motor system by monitoring current usage; higher than expected currents generally represent motor stalls, motor overheating, or shorts. Any such error will result in an immediate shutdown of the machine, to avoid damage to components. The controller passes these, and any critical errors that itself encounters, to the user interface, which presents them to the user.

While it is feasible that the system could recover from some types of critical error, such as overheating, these will still produce a system halt, giving the operator a change to confirm that the error can be recovered from.

Note that individual sections of the system flow can also encounter errors that they can recover from. The controller, for example, encounters constant error between the desired motor position and the actual motor position: this is not a problematic condition, but rather a natural part of any control algorithm. Recoverable errors can also happen between system components: a packet of communication between the user interface and the controller can be lost, but the system can detect this and simply resend the package. These errors are not reported back to the user, and do not produce a system halt.

5.2. Material and Component Selection

5.2.1. User Interface Selection

5.2.1.1. Raspberry Pi B+

The Raspberry Pi B+ is a high powered micro-computer capable of handling the extensive memory and power requirements for a hobbyist project as large as a CNC. The Raspberry Pi B+'s exposed General Purpose I/O connections as well as its surplus of USB ports allows it to easily interface a personal computer to a more dedicated, unique piece of electronic equipment. In the case of the Forest Sign Cutter, the Raspberry Pi B+ must allow the user to interact with his or her own personal computer while at the same time being able to communicate with the motor controller of the CNC which will power a majority of the sign carving.

- Revision 6/06/17 –

As part of the overhaul of the control systems, a new control interface has been installed on the Raspberry Pi, specifically bCNC. This is a free and open source (FOSS) program, written in the Python language, which is specifically designed for comunicating with the redesigned motor controller. bCNC was selected for its easy installation (the Raspberry Pi comes with a Python environment already installed) and its large range of functionality.

5.2.1.2. Fusion 360

Another tool utilized in the user interface is the use of Fusion 360. Fusion 360 provides a clean and sophisticated means of creating and saving multiple sign designs. Several templates will be provided on the pre-downloaded Fusion 360 software which fall within the maximum x-, y-, and z-axis dimensions of the Forest Sign Maker. Deciding to use a personal computer to run Fusion 360 removes the risk of overloading the Raspberry Pi B+ with too much unnecessary software. As such, Fusion 360 and the personal computer serve as the main point of contact for the user to begin sign creation while the Raspberry Pi B+ facilitates communication between the personal computer files and the motor controller which will instruct wood carving machine.

5.2.2. Control Systems Selection

- Revision 6/06/17 –

The control system has undergone a major change, the most notable being swapping brushed DC motors for bipolar stepper motors. As the control system is tightly integrated, most of its components required adaptation in order to support the new motors. The control of these devices is fundamentally different from that of the brushed motors; however, many of the new parts are existing free and open source (FOSS) or commercially available components; all are specifically designed to work with one another.

The move to steppers is motivated by difficulties encountered with the brushed motors and the complexity of constructing a controller suitable for them. The sections below detail specific changes to each part. The initial development plan called for a custom controller algorithm to be written for the brushed DC motors. This is theoretically the best option; servomotors of this type are like what are used on professional-class CNC machines. However, the control algorithm proved to be a challenge: for each motor, position, velocity and acceleration would have to be tracked. Then, each of these three parameters would have to be moved precisely in time and in relation to one another, to create shaped cuts.

Thus, the second plan involved the use of Grbl, adjusted for use with brushless motors. However, Grbl is designed with steppers in mind: it operates by stepping individual motors in small, precisely timed steps. Brushless motors are not designed with short halting motions in mind, and this style of control caused motor stalling and overheating, while not producing any semblance of precision movement at all.

Thus, it was determined that the benefits of steppers outweight the mechanical inconvenience of fitting them to the machine. Steppers are naturally suited to positioning; in addition, they are widely used in the hobbyist sphere, and so a great deal of accessible resources are available. These resources include fully designed hardware and software controls, many of which could replace chunks of the original, custom designed controller with little to no issue.

While the underlying changes are complex, the use of existing solutions greatly streamlined the development of the controller, while solving the problems that had arisen with the first design.

5.2.2.1. Logic Controller

The movement of the motor drivers to separate modules has greatly simplified the selection of the logic controller microcontroller. Nevertheless, the microcontroller must still be powerful enough to support the four main software components detailed in Functional Description. This translates into two selection criteria: a fast execution speed and a large program memory.

The microcontroller must also have a specific set of peripherals to interface with the motor drivers and user interface. On the motor side, the chip must have a PWM output, three digital outputs, and one analog input for each motor driver. It must also have 12 digital inputs for the various sensors mounted on the machine. On the interface side, the chip must have a UART and USB communications port for transfer of G-code instructions.

The team has selected Atmel's AVR microcontroller family as a starting point for chip selection, owing to its good performance and company’s history of documentation and support for small teams and individuals. The ATxmega128A1U is a member of Atmel’s high performance XMEGA line of chips. This chip offers a huge selection of peripherals and a 128k memory space, which should be more than sufficient for a large program. Crucially, the chip is offered in a 100-pin TQFP package; this package is able to be hand soldered.

The microcontroller will require a small selection of additional parts, including a regulator and some power conditioning capacitors. These are not subject to strict selection criteria since they are merely acting as generic components.

The logic controller will also require a PCB to be made. The construction of a PCB is beyond the means of the team; thus, an outside PCB fabrication service will be contracted to construct the board. The team will order a standard PCB - that is, 2 layer, FR408, 1 oz copper, and ENIG finish: the default selection for industrial PCB boards. It is not expected that the final design will make use of advanced features like inner layers or blind/buried vias. The finished board is not expected to exceed 9 square inches.

OSH Park is a community-based collective PCB ordering service, which accumulates orders from a large network of small makers and sends them to a fab service, passing the savings down to its members. The team has selected OSH park as the primary PCB fab service for its good history of quality boards, as well as low price and quick turn around time.

- Revision 6/06/17 -

The microcontroller has been changed from a custom XMEGA device to a comercially available microcontroller, specifically an Arduino Uno. In addition, the custom software has been replaced by a free and open source (FOSS) equivalent, specifically Grbl v0.9. Grbl is a three-axis motion control platform designed specifically to control stepper motors and to run on an Arduino Uno. It is widely used in the hobbyist/maker communities, and enjoys healthy support from an active userbase. The use of Grbl vastly simplifies the development of the controller software: Grbl is ready to run immediately after downloading, and tweaking settings is easily done by sending commands to the device.

5.2.2.2. Motor Drivers

The motor controllers are responsible for switching the drive motors on and off; they must be able to handle the current demands of each motor, as well as provide enough accuracy to produce small toolhead movements. Each motor is a 24VDC brushed motor, drawing about 10 amperes of peak current and about 3 amperes at constant (unloaded) speed. The previous driver used three STMicroelectronics VNH3SP30TR-E motor drivers, which are automotive H-bridge drivers rated at 5.5V - 36V and 30A peak. The new design uses an evolved version of these drivers, the VNH5019 motor driver, rated for 5.5V - 24V and 30A peak. Because the system already possesses a regulated power supply, the lower supply voltage is not projected to be a concern. More importantly, these new chips offer integrated current sensing, which the old chips did not. This condenses an entire subsection of the old design, which previously used separate current sense chips. The new design relies upon integrated current sensing for simplicity.

The VNH5019 is offered on a populated carrier board from a commercial robotics supplier, Pololu. The team will source three of these boards for use in the motor driver.

- Revision 6/06/17 -

The brushed DC servomotors originally powering the machine have been replaced by bipolar stepper motors. The supply voltage (24V) has not changed; however, the motor drivers have been swapped for ones that support steppers. As with the controller, a commercially available device has been selected (the gshield v5 by Syntheos), designed specifically to work with Grbl and an Arduino Uno. This decision again simplifies development: the hardware is assumed to be fully functional (as it is tested by the manufacturer) and is simply plugged into the Arduino.

5.2.2.3. Other Parts

The final assembly of the controller will require assorted minor components.

Connections will naturally require high-quality wire. These will be attached to boards either through screw-terminals, or by locking pin headers, which will need to be ordered along with the rest of the components. The boards will also need to be mounted to the electronics box with plastic mounts to prevent electric shock.

- Revision 6/06/17 -

Bipolar stepper motors require four wires, two for each pole; brushed DC motors require only two. Power lines for each motor have been re-run through the machine, with four leads per motor instead of two. New braided cable wrapping and heat shrink has been applied. New jumper cables are used to connect the different parts of the control system to one another.

A simple filter network has been applied to the limit switches to prevent bouncing. A simple level shifting IC has been added to facilitate communication between the Raspberry Pi and the new Arduino, since they operate at different voltages.

5.2.3. Mechanical Systems Selection

5.2.3.1. Foundation

One of the most important design selections for the mechanical system was the wooden foundation because this was the surface where the Forest Sign Maker interfaces with the part. As mentioned previously in section 4.3.7, a wooden work surface with T-Slots was chosen to be the system's primary foundation due to its cost, durability, and light weight. However, to enhance the structural rigidity of this foundation, sidewall stiffeners and custom end plates were implemented.

When designing the side stiffeners, three important considerations were taken into account. First, they were sized to hold both wooden surfaces, the work surface and the support board. To accomplish this goal, the lengths of the stiffener legs were designed to be long enough to fully encase both wooden boards. Second, the length of the stiffener legs must have also provided a lip that extends higher than the top surface. This extension allowed the work surface to contain some of the wood chips produced during the cutting process, which additionally assisted in protecting the dynamic components from becoming clogged with debris. Third, the side stiffeners also provided anchoring features for fastening the wooden work surface onto the foundation, which in turn provided a solid surface onto which the blank trail signs can be loaded. This solid surface is designed to experience very little deflection under maximum load. In other words, designing for a solid, rigid foundation ensured that the router position tolerance will meet the engineering specification.

5.2.3.2. Guide Rods

Continuing in the design selection for performance and precision, the guide rods are the second critical component group that facilitates smooth and accurate performance of the Forest Sign Maker. The guide rods serve two distinct purposes: to restrict the motion of each subassembly to its respective Cartesian axis, and to provide rigid support for these subassemblies.

The guide rods are case hardened ANSI 1556 steel shafts, sized to provide the appropriate rigidity for the machine, as seen in Appendix F for the supporting analysis on guide rod sizing. These shafts have a straightness tolerance of 0.002 in per foot, which are well within the total tolerance of 0.125 in, hence it is considered negligible in the model calculations. To accommodate the curvature of the guide rod while sagging under high load, it is required to use linear bearings that are flexible to approximately 1° of misalignment. The bearings that have been selected from McMaster-Carr are sealed linear ball bearings that can accommodate such misalignment. These bearings will ensure that the motion of the subassemblies are restricted to one dimension, while also considerably reducing the friction load on the actuators.

Despite the functionality of the linear ball bearings, it was necessary to apply the engineering principles of beam deflection to optimize the diameter of the guide rods. By modeling the deflection under maximum load and constraining the guide rod deflection to 0.125 in, it is possible to calculate the minimum allowable diameter. With this result serving as a baseline, a standard, oversized shaft diameter could be selected to minimize cost and machining time, while maintaining robustness of design.

5.2.3.3. Structural Plates

The third major structural selection focused around system rigidity is comprised of the structural plates that construct the major mechanical subassemblies. These plates are aluminum 5 inch wide 6061-T6 flat rectangular. When looking at each major subassembly, both the End Plate and Face Plate utilize ½ inch thick bars. Then the gantry structure for the y-axis is comprised of four ½ inch thick aluminum plates to ensure sufficient rigidity for router accuracy. Lastly, the z-axis has two ½ in thick bars as end plates, and a 3/8 in vertical back plate.

5.2.3.4. Fasteners

The fourth and final major component selection focused around system rigidity was fasteners. Due to the size of the Forest Sign Maker, a large quantity of threaded fasteners was required to hold the components together with sufficient rigidity. By using fasteners to adhere all the necessary components, the criticality of each individual piece was reduced, thus providing a final product that was easily serviceable. Furthermore, alternative methods of bonding, such as welding or brazing, do not lend themselves well to high accuracy components. It would be possible, but very risky since the opportunity for error is absent. Only one final prototype of the Forest Sign Maker was to be built, so it was is critical to eliminate as many uncontrollable processes as possible.

Despite the benefit of modularity and increased accuracy, threaded fasteners are highly susceptible to vibration loosening of the joints. To combat this phenomenon, every threaded connection in the Forest Sign Maker will have a locking nylon patch present in either the screw threads or on the machine nut.

The second important issue that was the complexity of the purchase list. Only two screw sizes were used for fastening the subassemblies of the Forest Sign Maker, aside from the plastic screws used to mount the electronic components (Note that there are multiple lengths of identical screw sizes). This greatly reduces the quantity of parts in the Bill of Materials, and facilitates servicing and replacements, if necessary.

5.2.3.5. Power Screws

The next set of selections focuses more around the actuation of the forest Sign maker. As previously discussed in section 4.3.5, each axis of the forest Sign Maker will be actuated by a power screw, which could be further categorized as a lead screw or ball screw. Ball screws have larger, rounded grooves that serve as channels through which the mating nut ball bearings can roll. Lead screws usually have ACME profile threads that mate with the nut via sliding surface contact. Due to the presence of sawdust and wood chips, and due to the budget of the project, ACME lead screws are the power screw of choice. The thread callout for these screws designates the screw outer diameter and the thread lead. For simplicity, thread selection was limited to single start threads.

5.2.3.6. Motors

The second set of components associated with system actuation are motors. With the lead screw thread defined, it is now possible to proceed with determining the necessary motor torque and power required to satisfy the performance requirements. Each subassembly has been isolated for this analysis as to decompose the loading on each individual motor. The complexity of this design issue is presented when considering the two-step power transfer within this machine. First, electrical power is transformed into rotational motion via the dc motors. Second, said rotational energy is then converted into linear translational dynamics. The conducted system dynamic analysis focused on reflecting the linear translational loads into the rotational domain so that it would be possible to determine the transfer function between a voltage input to the motor and the corresponding movement of the motor shaft. This transfer function aides in selecting the appropriate motor to satisfy the performance requirements. For such an integral component of the Forest Sign Maker, high-quality motors from Pittman Motors are preferred. After conducting the necessary engineering analysis provided in Appendix F, a Pittman gearmotor with a continuous power rating of 25 W, outputting approximately 50 in-lbf at 663 RPM was selected to actuate all three axes of motion.

5.3. Fabrication and Assembly

5.3.1. User Interface Assembly

The user interface has a straightforward assembly. First and foremost, the computer must be built to house Fusion 360 and a virtual connection to the Raspberry Pi B+. Adding Fusion 360, it is a fairly simple process. In order to add the software to the laptop, one must go to the AutoDesk website and apply for a student, educator, hobbyist, or small business account. As of February 3rd, 2017, this information is located at:

http://www.autodesk.com/products/fusion-360/students-teachers-educators

Any individual seeking to recreate Cal Poly Tree's Company project must create an AutoDesk account and obtain a free license to download the software. Having downloaded the software to a personal computer, Cal Poly Tree's Company will design several templates to be utilized in the Forest Sign Maker. Creating these templates is a simple matter of drawing a three-dimensional rectangle which satisfies the dimensional constraints of the Forest Sign Maker. Several templates of varying rectangular blocks will be created and provided on the user's personal computer to be copied and modified for any signs need in the future. Following these templates, a sign will be created by using the Fusion 360 CAD/CAM software to add text or images to the virtual wooden board. For an individual familiar with CAD/CAM software, the download of Fusion 360 and utilization of Fusion 360 to create several sign-templates will take about 1 business day. For the less knowledgeable individual, creating several CAD/CAM templates for the purpose of carving a sign can take up to 3 business days.

Subsequent to the installation of the Fusion 360, the personal computer must be able to interface with the Raspberry Pi B+. To do this, two methods will be applied: first, the creation of a wire-based network and second, a Wi-Fi based network. To communicate with the Raspberry Pi B+, the personal computer and Raspberry Pi B+ will be built with a virtual network computing server. This type of software is readily available in a variety of forms on numerous open-source websites. Installation of the VNC on both devices and the setup of a privatized, personal network between the two devices will take up to four business days. After about a week's worth of work, the Cal Poly Tree's Company shall have preliminary functionality the front-end user interface.

After the personal computer is able to talk with the Raspberry Pi B+, the user must be able to submit a G-code from the supplied and modified Fusion 360 templates. The Raspberry Pi B+ will need software that is able to translate G-code into readable dimension. It is key that the software on the Raspberry Pi B+ is able to ascertain the maximum x-, y-, and z-dimensions requested on the G-code file. On top of this, the Raspberry Pi B+ must be able to inform the user of a bad G-code file (one that fails the dimensional constraints of the Forest Sign Maker) or a good G-code file. Creating a piece of software to manipulate and analyze a G-code file will take up to 7 business days. On detecting a bad file, the software should be able to inform the user as to why a file has failed inspection. On detecting a good file, the software should be able to re-construct the G-code file into a number of small packets which are to be sent sequentially to the motor controller for processing. These two additions will take up to five business days.

After about two-and-a-half weeks' time, Cal Poly Tree's Company will have a user interface capable of decoding a G-code file, detecting a good or bad G-code design, and an informative means of user response after detecting a G-code design with dimensions exceeding that of the Forest Sign Maker's physical cutting dimensions.

The last major step in the construction of the user interface is eliciting communication between the G-code packets and the motor controller itself to actually begin the process of physically carving the machine. The motor controller and the Raspberry Pi B+ will be connected using standard USB connection. Similar to USB connection between a USB drive and standard computer. However, the USB shall be a wired connection between the Raspberry Pi B+ and the motor controller. Through this wired connection, the Raspberry Pi B+ will be able to deliver packets of data for the controller to interpret. Further programming must be done on the end of the motor controller to retrieve information from the USB to the motor controller. The process of interfacing the Raspberry Pi B+ and motor controller will take up to ten business days. In conclusion, the entire design of the user interface will take up to six business weeks to complete.

5.3.2. Control Systems Assembly

Assembly of the motor controller is divided into two parts: hardware assembly and software development. Hardware assembly is dependent upon the sourcing of all four individual driver modules, as well as the necessary wiring and headers. Of these, the assembly of the logic controller is expected to be the most significant milestone. As previously explained, this component will require a PCB, sourced from an external fab service, and electrical components. Assembly proper begins with the construction of the logic controller after all parts have been sources. There exist several techniques for soldering components to PCB's; the team will work with Cal Poly's IME department to use their PCB oven and other equipment. It is also anticipated that certain components (headers, large capacitors, etc.) will have to be hand-soldered. The team has access to soldering tools such as soldering irons and hot-air guns through Cal Poly departments and as personal possessions. The team will also select parts that are sufficiently large to allow for manual soldering. All components must be soldered to the boards, including terminals for connecting wires. Assembly of the board is projected to take a week, including the testing of all components and allowing for time to correct soldering errors.

Assembly is completed by mounting the modules inside of the motor controller box. Because of the changing footprint (one board to four), the existing box will need to be slightly modified. A new metal baseplate will be installed with mounting screws that match the existing ones: the new components will be mounted on this baseplate. This will help to reduce the number of superfluous holes in the electronics box. The boards are mounted with nonconductive plastic screws to prevent electric shock.

Finally, the various systems are connected with the appropriate wires. Power connections to and from the motors are secured using thick wire, secured with screw terminals rated for high currents. Digital signals are mounted using locking pin headers. All connections are intended to be easily unconnected for any future maintenance, and the connection location for each input or output will be clearly labeled on each board.

Some preexisting machine wires will need to be modified. Any wires which are expected to move during the course of machine operation will be replaced by stranded-core wire (all current wires are solid-core), which is more flexible and resistant to breaking. Additionally, the wires to the limit switches and rotary encoders will have pin headers installed to interface with the locking pin headers on the new boards.

While the controller software must eventually run on the logic controller, it can be developed on a separate device during early stages to facilitate testing. The team will use several open-source software libraries in their implementation. The base of the software will be FreeRTOS, a real-time operating system for microcontrollers. Upon this, a G-code library such as GRBl will be added, abet with reduced capabilities to reflect the abilities of the machine. Unnecessary instructions such as 'change tool' and 'turn on coolant' will be removed to save space. Atmel offers several software stacks which implement common microcontroller features; an appropriate library will be used for the communications interface. The instruction state machine and glue logic will be developed to tie these components together.

Overall, software development will take some time, due to the complex nature of the controller and the inherent challenges in developing and testing embedded software. The team estimates that at least two months will be required to fully develop and test the software, including installation onto the controller board and testing in-situ.

5.3.3. Mechanical Systems Assembly

As far as the mechanical assembly goes, only the x-axis needs to be built. The team will be utilizing the y- and z- axis assemblies designed by the previous team with the exception of replacing the wiring and potentially the shaft couplings. With regards to the assembly of the x-axis, the assembly will begin with the face and end plates. Each plate will be constructed out of the 6061-T6 aluminum plates previously discussed in section 5.2.2.3. Any cuts along the face and back of each plate will be performed on a CNC to ensure their tolerances are met. Any holes along the sides of the plate will be fabricated personally on a manual mill. Said face plate may be viewed in Figures C-4, C-5, and C-6 found in Appendix C (all referenced Figure C-# will be found in Appendix C). Similarly, said end plate can be viewed in Figures C-7 and C-8. When all said and done, this step should take about one whole work day to complete.

The second set of steps focuses on assembling the guide rods and attaching the gantry to the x-axis assembly. To start loosely fasten the guide rod supports, Figure C-13, to the face and end plates. Then place the gantry in the middle of the x-axis assembly so its bearings line up with the guide rod holes. Next slide the guide rods, Figure C-14, through the holes and supports in the end plate, continue sliding them through the roller bearings in the gantry, and then slide them through the supports and holes in the face plate. When completed tighten the guide rod supports so that the guide rods are orthogonal with each other, and insert the set screws into the bottom if the guide rod supports to prevent any future movement of the guide rods. Excluding all shipping times, this set of steps should only take a few hours to complete.

The third set of steps focuses on assembling the lead screw and auction components of the x-axis. To start off insert the end plate ball bearing, Figure C-16, into the end plate while having the flat side against the back of the plate. Then mount the encoder the opposite side (exterior) of the end plate so that its shaft is sticking out through said end plate ball bearing. Next slide the lead screw, Figure C-15, through the face plate hole until it meets the threaded coupling on the bottom of the gantry. If down correctly, the end that contains the stepped groves should be on the face plate side. Thread the lead screw through the coupling so that the gantry is now located roughly in the middle of assembly. When completed, take the ½ inch diameter side of the flexible shaft coupling, Figure C-26, and slide it on the lead screw. Next slide the lead screw down so that the encoder shaft slides into the ¼ inch diameter side and then insert both set screws to secure the shafts inside the coupling. Once the lead screw is secured, slide the face plate ball bearing, Figure C- 17, onto the lead screw and cover it with the bearing retainer, Figure C-18. Similar to before, ensure that the flat side of the bearing is against the bearing retainer. Excluding all shipping times, this set of steps should only take a few hours to complete.

The fourth set of steps focuses on assembling the assemblies support structures. The Forest Sign Maker will consist of two foundation braces, as seen in Figure C-9. Said foundation braces will be purchased from McMaster-Carr at a stock length of five feet long and then cut down to size. Once cut down to length, two thru holes will be drilled into each end so that each brace may be fastened to the face and end plates. The team will then fasten four support brackets, Figure C-10, onto both the face and end plates, which will then allow the team to attach the two framing extrusions to the Forest Sign Maker. Similar to the foundation braces, these framing extrusions, Figure C-11, will be purchased from McMaster-Carr at a stock length and then cut down to size. It is important to note that before the horizontal extrusions may be fastened, the fastening interests must be slid into the groves so that the foundation stiffener, Figure C-12, and aluminum tees, Figure C-25, may be fastened. When completed, the mentioned foundation stiffener may be fastened to the top of the framing extrusion and the aluminum tees may be fastened to the bottom. This will ultimately allow for the horizontal extrusions, Figure C-22, to be attached to the rest of the structure. The final component of this support structure assembly consists of attaching the mounting feet, Figure C-21, to the exterior of the face and endplate. Excluding all shipping times, this set of steps should only take a few hours to complete.

The fifth set of steps focuses on assembling the motor components. For user simplicity, this step is best assembled separately from the rest of the x-axis. To start off, fasten the motor mount, Figure C-20, to the motor, Figure C-24. Since the motor shaft is not concentric to the motor, there is only one arrangement where the motor will fit on the motor mount. Next slide the rigid shaft coupling, Figure C-23, onto motor shaft and then slide the other side onto the lead screw. When aligned, insert the four motor mount spacers, Figure C-19, between the motor mount and the face plate and fasten them together. Once completed insert the set screws into the rigid shaft coupling, and this will conclude the motor setup. Excluding all shipping times, this set of steps should only take a few hours to complete.

The sixth and final set of steps focuses attaching the electrical components to the system. The first major electrical component would be the emergency stop button. This button will be inserted into the emergency stop hole and its wires will be secured along the top 10-32 hole brackets. Next, fasten the limit switches onto the interior of the face and end plates to designate the minimum and maximum coordinates for the machines x-axis. Lastly, fasten the electrical control panel onto the face plate, and then the mechanical assembly will be completed. Excluding all shipping times, this set of steps should only take a few hours to complete.

When looking at the entire mechanical assembly, it is reasonable to assemble the entire mechanical system in just a couple days. However, it should be noted that the true consumption of time was designing and ordering parts.

5.4. Maintenance and Repair

Overall, the maintenance for the Forest Sign Maker is straight forward. With regards to the user interface, the only real maintenance that should be taken place is to periodically update the Fusion360 software on the laptop. This will help to patch any bugs in the system as well as improve the software's efficiency and effectivity. Since the user interface is comprised of computers and software, if something breaks, it will most likely need to be replaced rather than repaired. However, both the laptop and Raspberry Pi B+ are both commercially available parts so replacing one should not be too big of an issue.

For the control system, the only maintenance required would be to periodically clean the control box. Since all the software for the controllers is designed specifically for the Forest Sign Maker by the team, no new updates and patches will be available or required. Similarly, since the control system is using commercially available parts, repair, although highly unlikely, is manageable.

When looking at the mechanical system, there are three major aspects of maintenance to be acknowledged. First, it is important to periodically clean the machine of dust and debris. Too much dust/debris in the threads or bearings of the Forest Sign Maker could potentially become harmful. Second, for smooth operation, it is recommended that all rotating parts be adequately lubricated. Last, it is important that the router bit be checked before use and replaced if worn down. Not only can a broken bit ruin a sign, but it could potentially harm the user. As for repair, the team has supplied the user with spare parts for most of the Forest Sign Maker. However, for anything that is not provided, the team has determined those components are highly unlikely to fail, but can be reproduced if necessary. It is important to note that although the Forest Sign Maker does contain custom made parts, these parts all contain detail drawings to aid in the reproduction.

6. Design Verification

6.1. Testing

6.1.1. Fusion 360

The most obvious area for testing involves the actual use of Fusion 360 to design the appropriate schematics for a sign. A fully documented and detailed process can be found within the user manual included within the report. Within this user manual, each step in the sign creation process is document through textual and image based support. The manual shows the creation of a brand new project and the necessary steps taken to create functional GRBL-based g-code which will then be supplied to the Raspberry Pi B+ through USB connection.

6.1.2. Control System Function

The move to FOSS and commercially available components changed the scope of control system testing. The use of existing components and software eliminated the need for low-level testing: hardware is tested by the manufacturer, and software by the hundreds of users that support and contribute to it. However, this change also introduced the need to fine tune the settings of the controller to suit the needs of this project.

The main body of control system testing was spent configuring the controller's model of the machine to match its actual geometry. The controller tracks many different parameters (maximum axis travel, maximum axis speed, maximum axis acceleration, etc.) for each axis. The '[stepper motor] steps per millimeter [of travel]' took the most time and the most care, as it determines Grbl's ability to accurately position the machine. These settings were configured until commands entered into bCNC were accurately reflected by the machine (i.e., a 10cm diagonal move, a 5cm curve, etc.).

Other tests checked the wiring of the limit switches. Limit switches are used both for limiting movement and for homing the axes. Thus, their operation is critical to the machine's accurate positioning. It was found that occasionally, electrical noise would trigger the limit switches when the machine had not; various settings and the debounce filter network were adjusted to minimize this behavior.

6.1.3. Motor Function

Motor testing investigated the ability of the motors to accurately and reliably move the machine's gantry and cutting head. A stepper motor is fundamentally different from a brushed motor. A brushed motor rotates continuously in a certain direction upon receiving power, whereas a stepper must receive a series of alternating positive and negative pulses to step its rotor through each rotation. This behavior makes steppers excellent for precise positioning applications, while also affecting their performance at higher speeds. The faster a stepper motor steps, the lower its torque.

Thus, the stepper motors must balance speed and torque: speed for cutting durations within tolerable times, and torque for the ability to move the device. While the stepper motors used can produced very large torques, they also generate a lot of heat within themselves and the gshield. Thus, speed and torque must be balanced such that a safe operating temperature is maintained on the controller board. There are several software parameters, mentioned above, that help control how Grbl instructs the motors to move. Additionally, the gshield has adjustable components which can set the number of steps per rotation of and the current delivered to each motor. These settings were adjusted until the machine displayed adequate speed, while still having sufficient surplus torque for cutting.

The speed and number of steps per motor also affect the vibration produced by the stepper motors. By nature of their operation, stepper motors produce more vibration than other types of DC motors; thus, the tolerable vibration must also be adjusted along with the previously mentioned parameters.

6.1.4. Orthogonality and Straightness

To ensure the Forest Sign Maker would produce quality signs within the given specifications, the first set of mechanical test focused on the orthogonality of the machine.

To begin, each side of the Forest Sign Maker was measured and compared to each other to ensure each side's lengths were within 1/16" of each other. This process would then be repeated for each end of the Forest Sign Maker to guarantee the width of each end was within 1/16" of each other. Next, the diagonal distance between the front right corner and the bottom left corner was compared with its diagonal counterpart. Once these values were also within 1/16" of each other, the base was assumed to be orthogonal.

The second stage of the orthogonality testing focused on the orthogonality of the gantry. To ensure the gantry structure is orthogonal with respect to itself, the same set of tests on the base were performed on the gantry. However, in addition to these tests, the both gantry supports were spaced off the end plate of the end plate to confirm the orthogonality between the base and the gantry.

The third stage of the orthogonality testing was centered around the orthogonality of the router plate. This testing phase essentially mimicked the steps found in the second stage.

The final stage of the orthogonality testing focused on total system alignment and straightness. For this test, a probe was inserted in the router hole and barely pressed up along the base foundation wall. As the gantry would slide down the x-axis, the probe would run against the wall. If the probe would ever bend or become separated from the wall, adjustments would be made and the test would be repeated until a straightens within 1/64" was achieved. Once completed, the same test would be performed for the y-axis.

6.1.5. Marker

To verify the Forest Sign Maker was functioning properly without running the risk of harming any of the users or the machine itself, the router was replaced with a marker and signs were drawn on a piece of paper. This test allowed the team to test the full functionality of the Forest Sign Maker without running the router.

6.1.6. Sign Cuttings

The final test is simply cutting signs. This test verified whether the Forest Sign Maker worked properly and fulfilled its sign specifications, and its result may be seen in Table 6-1.

6.2. Specification Fulfillment

Table 6-1. Specification Fulfillment Results

Index	Parameter Description	Requirement or Targets	Tolerance	Result
1	System Weight	200 lb.	Max	PASS
2	Width	30 in.	Max	PASS
3	Length	6 ft.	Max	PASS
4	Height	4 ft.	Max	PASS
5	Cost	$5,00	Max	PASS
6	Sign Production Time	2.0 hrs.	Max	PASS
7	Max Blank Size	2 ft. x 4 ft.	± 0.25"	PASS
8	Positional Accuracy	Target dimension	±0.03125"	PASS
9	Cutting Depth	Target dimension	± 0.03125"	PASS
10	Graphical User Interface	Fusion 360	--	PASS
11	Local Operation	No network connection necessary	--	PASS
12	Multi-platform Capabilities	Function on Chrome, Firefox browsers	--	??
13	Tool Path Errors	Zero out-of-bounds errors for the tool path	Max	PASS
14	CNC Design Input	Interface hardware can function with sawdust present	--	PASS
15	Vacuum Capabilities	50% of total debris vacuumed	Min	PASS
16	Clamp Rigidity	0.012 in	Max	PASS
17	Cutting Tool	Holds stock Bosch Colt Router	--	PASS
18	Mounting Feature	Securely fasten CNC machine to table	--	PASS
19	Shutdown Time	0.5 sec	Max	PASS
20	Electronics Temperature	60 °C	Max	PASS
21	AC-DC Power Supply	300 W	Min	PASS

6.3. Cost Analysis

An abbreviated cost analysis for the Forest Sign Maker's individual assembly may be found in Table 5-2. When looking at the numbers, it is abundantly clear that most the Forest Sign Maker's cost can be attributed to its mechanical structure. Both the X-Axis Assembly and the Y-Axis Assembly each make up roughly a third of the Forest Sign Maker's Cost. Thus, the remaining third may be broken up into the Z-Axis Assembly, Cutter Assembly, Work Surface Assembly, Control Systems Assembly, and User Interface Assembly. To help illustrate the cost distribution amongst the different systems, Figure 5-3 provides a pie chart depicting the cost distribution for each independent assembly. Additionally, a full cost breakdown of all the individual parts may be viewed in Appendix D.

Table 5-2. Assembly Cost Breakdown

Assembly Name	Cost
X-Axis Assembly	$1,198.95
Y-Axis Assembly	$1,025.90
Z-Axis Assembly	$548.21
Cutter Assembly	$258.77
Work Surface Assembly	$271.98
Control Systems Assembly	$130.75
User Interface	$31.94
Total	**$3,466.50**

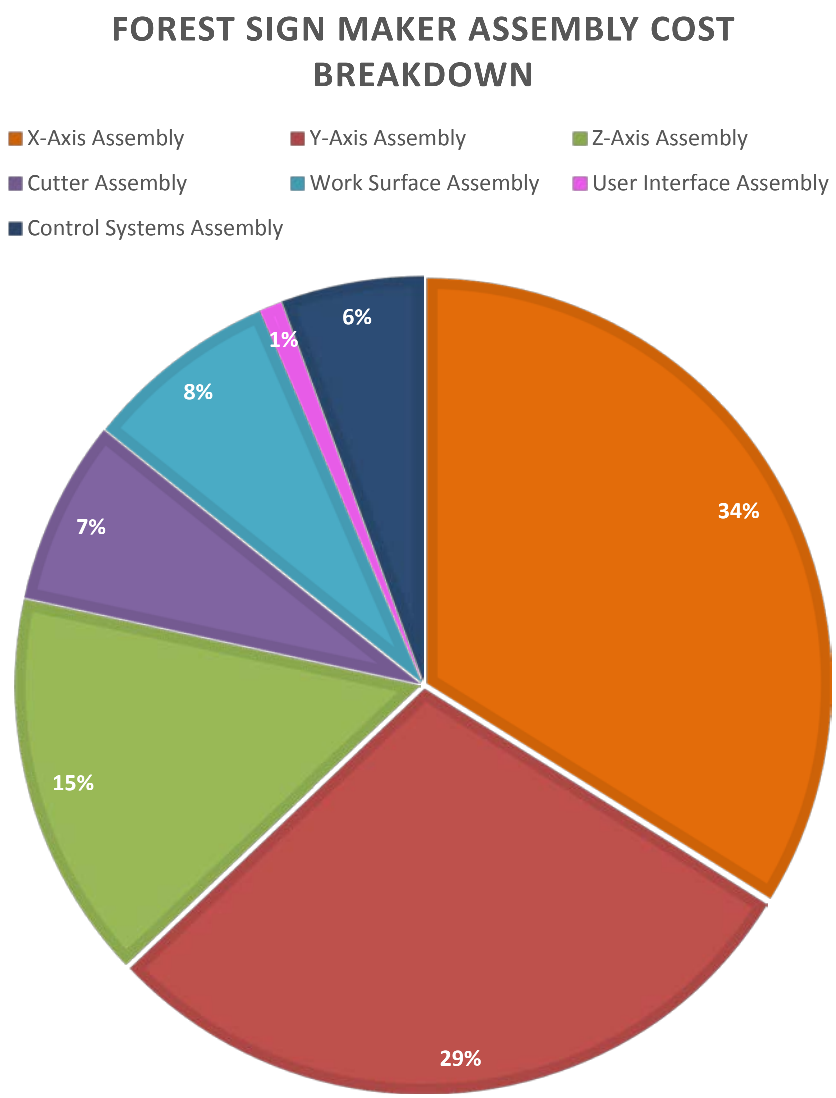


Figure 5-3. Pie chart depicting cost distribution amongst the Forest Sign Maker's different assemblies

6.4. Project Justification

Paul McFarland and the volunteers of the Friends of the Inyo spend countless hours carving and repairing the numerous trail signs that mark the hiking paths of Inyo National Forest. The recreation of each sign is done by and and can take up to 3 business days to complete. With the introduction of the Forest Sign Maker, Paul McFarland and the Friends of the Inyo will have a new tool to increase the rate at which signs are produced and reproduced. Rather than spending several days hand carving a sign, Paul McFarland will be able to create a simple CAD drawing in under thirty minutes and design the corresponding sign in under 2.0 hours. With the introduction of the Forest Sign Maker, a 24-hour process will now take 2-hours.

The design of the Forest Sign Maker utilizes three motors to manipulate a wood-carving drill bit on a three-axis plane. The wood cutting machine is designed to be easily portable, weighing roughly 150 pounds fully assembled or roughly 100 pounds when the wooden foundation is removed, such that two individuals can easy move it. In addition, the machine has a minimum width of 15.25 inches (when tilted) such that it can fit through any common doorway. As with any large machinery, the safety of the user must be of the highest importance. The Forest Sign Maker comes with a variety of safety mechanisms including, limit switches, emergency-stops, and a means of grounding the entire electrical system in under ⅛ of a second. Despite these safety measures, any individual operating the Forest Sign Maker should take caution and wear the appropriate safety materials dawned in any environment where heavy machinery is being operated. Such equipment includes, but is not limited to: Safety Goggles, Ear Plugs, and a Face Mask. These three pieces of equipment will minimize the amount of sawdust and noise pollution that affects the user or any individual within the workshop that the Forest Sign Maker will be housed.

In addition to the mechanical prowess of the Forest Sign Maker, Cal Poly Tree's Company has designed a user interface that is both intuitive and cost-friendly. The user interface makes use of the hobbyist version of Fusion 360 and the flexible micro-computer, the Raspberry Pi B+. With the combined work of Fusion 360 and the Raspberry Pi B+, the Forest Sign maker will be able to carve redwood planks of varying sizes and varying designs. Fusion 360 is a CAD/CAM software designed to be highly intuitive to any non-CAD expert. Thus, designing a sign and delivering the related G-Code will be a simple and non-time-consuming task.

By designing and building the CNC from scratch, Cal Poly Tree's Company is able to produce a low-budget device of approximately $3,500, which is $1,500 below the designed budget, capable of doing work equivalent to that of a CNC's which cost an upwards of 15K commercially.

7. Management Plan

7.1. Team Member Responsibilities

Each individual member of Cal Poly Tree's Company brings their own unique, specialized set of knowledge and skills. Despite these distinctions, each member has agreed to participate and assist in all aspects of the project's development. While the senior project is intended to provide a functional, high-quality product to the sponsor, it also serves as an experience to promote the growth of knowledge and skills of each individual team member.

7.1.1. Brandon Mainini

Brandon is the communication officer. He will be the main point of contact between Cal Poly Tree’s Company and the project’s sponsor, Lee McFarland. His duties include coordinating and facilitating meetings between the current senior project group, the past senior project group, and the sponsor.

Brandon will also focus on the mechanical engineering tasks related to the project. Such tasks include, but are not limited to, the following:

1. Hands-on mechanical design
2. Development and interpretation of mechanical schematics
3. Construction of mechanical components

7.1.2. Lauren Kirk

Lauren is the recorder. She is charged with maintaining the information repository for Cal Poly Tree’s Company. The team has agreed the main source of information will be collected within a shared Google Drive.

Lauren will also concentrate on the aspects regarding User Experience. She will take lead of tasks including, but not limited to, the following:

1. Design and development of software directly related to the interactions between user with the machine
2. Meaningful and intuitive applications of user actions
3. Conversion between user-input and motor-signal output

7.1.3. Alec Boyer

Alec is both the treasurer and the timekeeper. He is responsible for maintaining both the team's travel budget as well as the material budget. Alec must also monitor the team's progress and address any encroaching milestone deadlines.

Alec will focus on the low-level aspects of the team’s software and hardware interactions. This duty includes, but are not limited, to the following tasks:

1. Backend programming
2. Mathematical algorithms regarding the systems executing of user-inputted commands
3. Three-dimensional translations of the machine on the board

7.2. Gantt Chart

The Gantt Chart, as seen in Figure 5-1, is a roadmap to producing the Forest Sign Maker. The different milestones (red) and components (white) may be found in Table 5-1.

Table 6-1. Gantt Chart Key

Number	Description	Number	Description
2	Enhance Design Requirements	26	Detailed Cost Analysis
3	Design Conception	27	Safety Hazard Identification Checklist
4	Design Selection	28	Review and Edit
5	Revise And Edit	29	CDR Report
6	Concept Model & Pugh Matrices	30	Schedule CDR Presentation w/Sponsor
7	PDR Presentation	31	CDR With Sponsor
8	PDR Report	32	Operation
9	Schedule PDR with Sponsor	33	Maintenance and Repair
10	PDR With Sponsor	34	Review And Edit
11	Test Development With Equipment	35	Operator's Manual
12	Specification Verification Checklist	36	Work On Ethics Memo
13	FMEA, DVP, & Analysis Plan	37	Ethics Memo
14	Determine Time Spent	38	Photos
15	Determine Time Planned	39	Update Gantt
16	Determine Percent Completed	40	Work Progress
17	Gantt Chart	41	Budget Analysis
18	Functional Description	42	Percentage Complete
19	Subassembly Isometric and 3D Drawings	43	Prognosis of Completion
20	Supporting Analysis	44	Project Update Report
21	Detailed Safety Discussion	45	Prep
22	Explanation of Material Selection	46	Project Hardware/Safety Demo
23	Fabrication and Assembly Instructions	47	FDR Project Expo
24	Maintenance Considerations	48	FDR hardware Handoff
25	Assembly Drawings with BOM	49	FDR Report Due

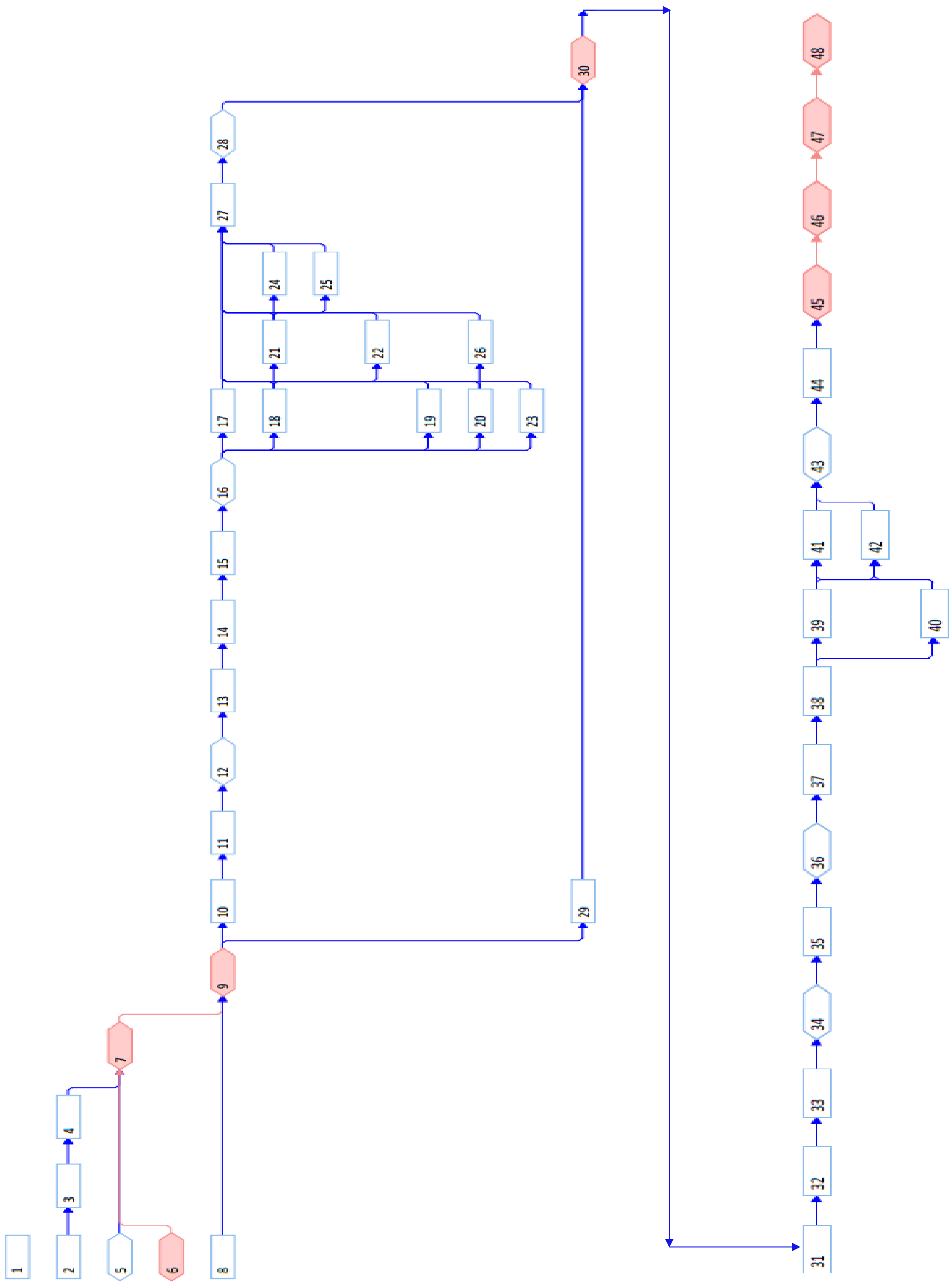


Figure 6-1. Gantt Chart

- Revision 1/31/17 -

Below is an updated version of the Gantt Chart. This revision only shows what is left to be completed.

Table 6-2. Revised Gantt Chart Key

Number	Description	Number	Description
2	CDR Presentation	20	Motor Controller
3	Operator's Manual	21	Software Testing
4	Ethics Memo	22	Hardware Testing
5	Project Update Report	23	Assembly
6	User Interface Complete	24	Motor Controller Complete
7	Network Setup	25	Mechanical Systems
8	G-Code Analysis Code	26	Part Sourcing
9	Testing	27	Guide Rods
10	User Interface Complete	28	End Plate Construction
11	Motor Controller	29	Lead Screw Assembly
12	PCB Sourcing	30	Support Structure Assembly
13	Component Sourcing	31	Motor Assembly
14	PCB Design	32	Electrical Routing
15	PCB Assembly	33	Assembly
16	RTOS installed	34	Mechanical Systems Complete
17	Communications Module	35	Project Hardware/Safety Demo
18	G-Code Interpreter	36	FDR Project Expo
19	Instruction State Machine	37	FDR hardware Handoff

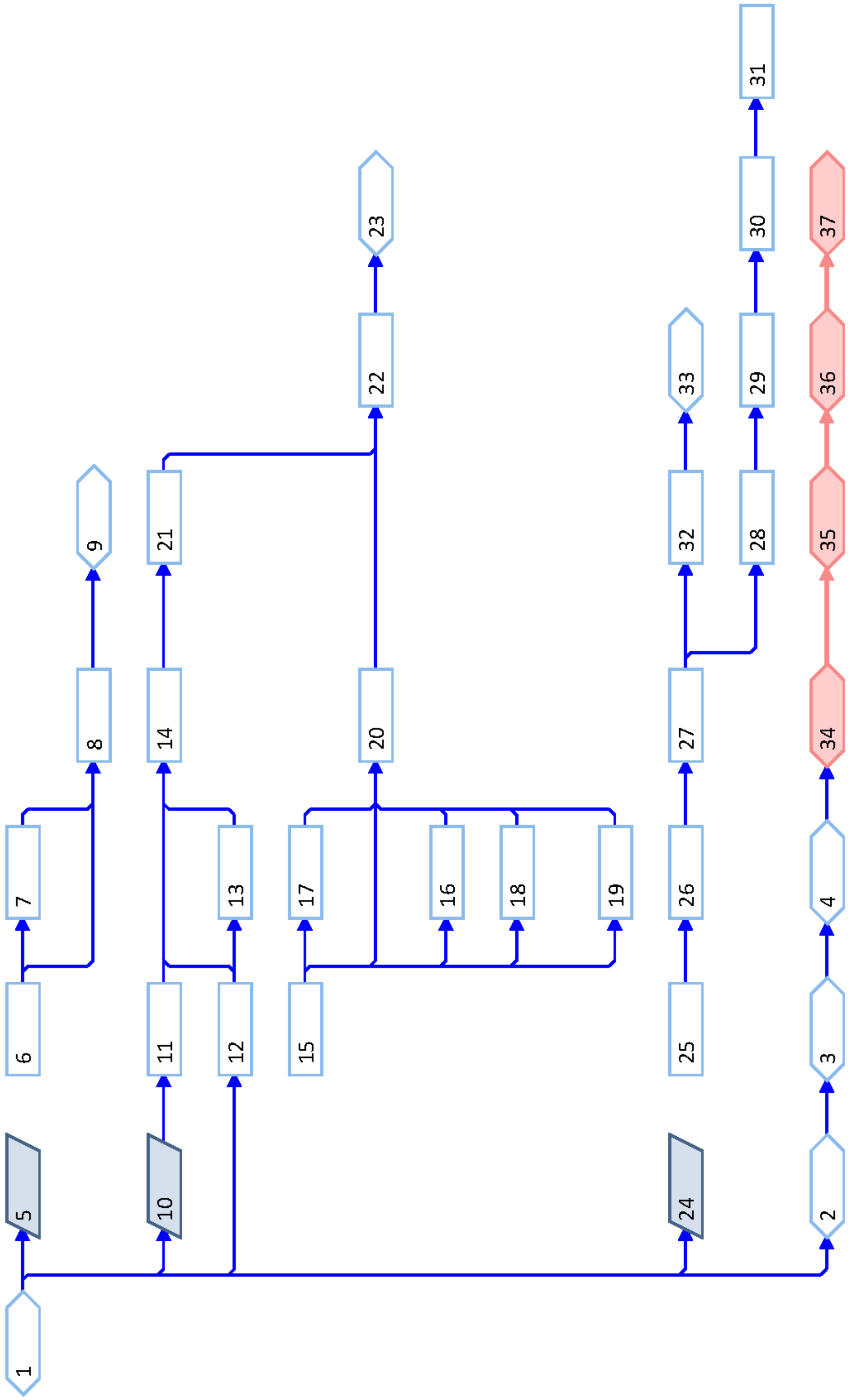


Figure 6-2. Revised Gantt Chart

7.3. Milestone Timetable

The milestone timetable, as seen below in Table 5-2, provides all the times of all major project components relevant to the sponsor. It should be noted that although the majority of these milestones are deadlines for deliverables for the sponsor, a few of them are actually scheduled meetings between both the team and the sponsor.

Table 6-3. Milestone Timetable

Date	Milestone
10/25	Project Proposal
11/3	Concept Model & Pugh Matrices
11/11	Schedule PDR With Sponsor
11/17	PDR Report
12/2	PDR With Sponsor
12/6	FMEA, DVP, & Analysis Plan
12/8	Gantt Chart
1/31	Schedule CDR With Sponsor
2/7	CDR Report
2/16	CDR with Sponsor
3/9	Operators’ Manual
3/9	Ethics Memo
3/16	Project Update Report
5/2	Project Hardware/Safety Demo
6/2	FDR Project Expo
6/2	FDR Hardware Handoff
6/2	FDR Report Due

8. Conclusion

8.1. Process and Results

The original objective of the senior project group was to refine and complete the design of an existing CNC machine such that it followed the sponsor's original project constraints: a reasonably priced CNC machine capable of cutting redwood for reproducing and replacing worn signs along the trails of Inyo National Forest. Following the appropriate design process laid out in the ME 428/429/430 coursework and a surplus of research into the design process of existing CNC Machines, a series of goals were designed and adhered to during the process.

Throughout the design processes, the team performed ample research and having identified a feasible set of goals, began developing the appropriate concepts to create the Forest Sign Maker. A management plan was formed to detail the responsibilities of each team member, and a Gantt chart coupled with a milestone timetable was made to guarantee the timely production and completion of the project at the end of the Spring 2017 quarter.

8.2. Recommendations

8.2.1. Running bCNC

The Raspberry Pi B+ is a small, low-powered computer while the bCNC software (used to translated g-code built for GRBL into machine signals for the connected CNC machine) is fairly complex. Unfortunately, the bCNC program was designed for a more robust computer, rather than the minimalist computation power supplied by the Raspberry Pi B+. Running the bCNC software requires significantly more computational power than the Raspberry Pi B+ has readily available. This results in slow, seemingly unresponsive performance. Despite the slow performance, bCNC still works as it should (minus slow running speeds). Were this project to be re-attempted, it is advised that the designers take significant time stripping out unnecessary components of the bCNC software to minimize the computational needs of the program itself.

8.2.2. USB Based Communication

In the initial design, it was determined that a small LAN (local area network) based hub would be set up between the Raspberry Pi B+, the motor controller, and the personal computer. After developing the networked system, it was determined that such a setup was an over-complication of what could have been a simple connection of wires. The minimal wired-setup of the LAN based hub appears more elegant but would be more time-consuming to repair and re-setup if ii were to fail. As such, wired connections were established between the Raspberry Pi B+ and the motor controller and removable USB based connections were established between the Raspberry Pi B+ and the personal computer. If any communication issues were to occur within the present setup, the main repair work to be done would simply be a replacement of wires or a new USB.

9. Appendices

9.1. Appendix A: Glossary and Terms

AC – Alternating Current. This form of electrical power is found in all main power lines and home circuits. The Forest Sign Maker will be powered by AC electricity.

ASA – American Standards Association. The name of this organization has changed a few times since its creation in 1918, from the original American Engineering Standards Committee (AESC) to the present American National Standards Institute (ANSI). Despite the name changes, the standards that have been documented have not changed.

BOM – Bill of Materials. The BOM is a list of the subassemblies and parts that comprise a final design. Usually, BOMs will provide information such as part quantities, part numbers, vendor information, initial cost breakdown, and any additional information or descriptions.

CNC – Computer Numerical Control. CNC computers automate machine tools via digital commands, rather than mechanical linkages controlling the motion. These computers, usually microcontroller processors, receive digital position data from the machine sensors and output motor commands that actuate the system appropriately.

DC – Direct Current. This form of electricity will be used to power all devices of the Forest Sign Maker except for the router and vacuum system. An AC-DC converter must be used to obtain this form of electrical power.

DRO – Digital Read Out. An electronic display that provides positional information.

Encoder – Incremental shaft encoders are optical sensors that are specialized for sensing shaft rotation. Although the exact output can be varied depending on the model selected, the output data is generally digital shaft position information, which can then be utilized by the microcontroller for closed-loop feedback loops.

FHWA – Federal Highway Administration. This administration oversees all United States road and highway sign formatting guidelines, along with other public service duties.

FMEA – Failure Modes and Effects Analysis.

FS – The U.S. National Forest Services. Focuses on sustaining the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations

Gearmotor – Gearmotors are the product of combining an electric DC motor with a step-down gearbox into one unit. The gearbox reduces the output shaft velocity but increases the output shaft torque. Irreversibilities in the gearbox reduce the total mechanical power of the gearmotor by approximately 5-10%, generally.

GUI – Graphical User Interface. This digital display program runs on the user's personal computer and allows the user to input the necessary information into a digital format that can program the Forest Sign Maker accordingly.

HTML5 – HyperText Markup Language 5.

Knots – Distortions and defects in wood grain produce high-density grain structures that are stronger and more resilient than the normal grain. This deformity may overload the router.

Laser Cutter – Cutting device that uses a directed high-energy light to burn, etch, or cut the substrate instead of using a physical sharp cutting blade.

Lead Screw – A screw with evenly spaced threads that translates rotational motion into linear actuating motion along the ends of the lead screw.

Microcontroller – A small programmable computing device that performs logic on sets of inputs and produces outputs. It is small and it interacts with devices that are connected to the microcontroller.

Motor Driver – An electrical component that amplifies a weak signal to higher voltages as inputs to a motor.

PCB – Printed Circuit Board. Printed boards have connecting leads, but lacks the electrical components. Electrical components can be soldered onto the board.

PCBA – Printed Circuit Board Assembly. This is a PCB with electrical components soldered onto it, producing a finished circuit board assembly.

PWM – Pulse Width Modulation is a technique to mimic analog signals using digital signals. The analog strength is proportional to the duty cycle of how fast the square digital wave is kept on high.

Redwood – A type of hardwood that is the substrate material for sign making.

Router – The cutting tool used to etch letters onto the wooden board. The router spins a router bit at a very high velocity, which when plunged into a substrate, will cut it away.

Sawdust – A waste product of woodworking. They are small particles of wood matter that get displaced during a woodcut that are small and light enough to be blown away.

USDA – United States Department of Agriculture

Wood Chips – Wood chips are larger pieces of waste wood particle matter that are not easily blown away. Their comparatively large size prevents them from flying away and instead rests on the surface due to gravity.

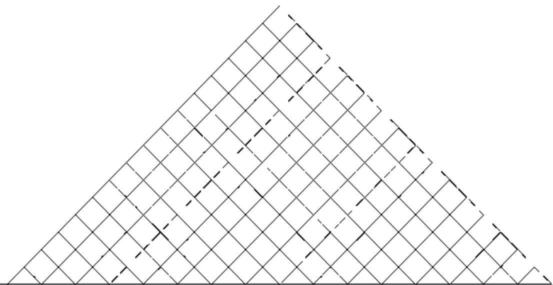
9.2. Appendix B: House of Quality

QFD: House of Quality
Project:
Revision:
Date:

Correlations	
Positive	+
Negative	–
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

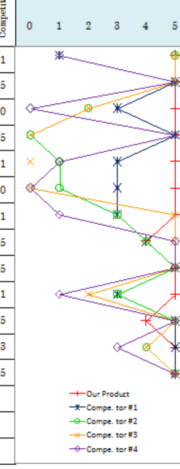


Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Direction of Improvement	▲	▼	▼	◇	▼	▼	▼	◇	▼	▼	▼	◇	▼	◇	◇	▼
HOW: Engineering Specifications	Max Sign Dimensions	Shut Down Time	Minimal Pinch Points	File Input	Uncluttered Graphical Userface (Intuitive To Use)	Low Cost	Low Weight	Desired Dimensions	Quiet and Smooth	Desired Speed	Minimum Speed	Cuts Desired Woods	Minimal Training	Can Handle Peak Currents and Voltages	Can be Easily Purchased or Sourced	Path Deviation Tolerance

WHO: Customers

Row #	Weight Chart	Relative Weight	Friends of the Inyo	Paul McFarland	Lee McFarland	Cal Poly Tree's Company	Forest Visitors	Maximum Relationship	WHAT: Customer Requirements (explicit & implicit)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Our Current Product	Competitor #1: *Rockler CNC Shark HD4*	Competitor #2: *ShopBot Buddy*	Competitor #3: *Baileigh Industrial CNC*	Competitor #4: *KL-6090 Desktop CNC*	Row #
1		15%	8	8	2	5	10	10	Produce Signs of Multiple Sizes	●							○									5	1	5	5	1	1
2		7%	9	10	6	8	0	10	Operate Safely		●	●											●			5	5	5	5	5	2
3		7%	9	10	0	7	0	10	Utilize a Simple User Interface				●	●								●				5	3	2	2	0	3
4		6%	8	6	11	6	1	10	Be Affordable						●											5	5	0	0	5	4
5		7%	9	9	8	8	0	10	Maintain a Portable Weight							●										5	3	1	0	1	5
6		6%	9	9	8	5	0	10	Maintain a Portable Size								●									5	3	1	0	0	6
7		5%	7	8	0	5	0	10	Produce Limited Sound and Vibration									●								5	3	3	5	1	7
8		13%	8	9	5	6	8	10	Produce Signs Quickly										○	●						4	4	4	5	5	8
9		6%	10	8	0	6	0	10	Cut Dense Woods												●					5	5	5	5	5	9
10		5%	7	8	0	4	0	10	Embody a Quick Learning Curve				○									●				5	3	3	2	1	10
11		4%	2	2	4	9	0	10	Utilize a Quality Motor Controller						○								●			4	5	5	5	5	11
12		6%	7	9	8	8	0	10	Utilize Easily Replaceable Parts															●		5	5	4	4	3	12
13		15%	10	9	7	10	8	10	Produce High Quality Signs																●	5	5	5	5	5	13
14		0%																													14
15		0%																													15
16		0%																													16

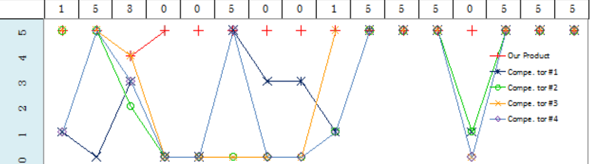
NOW: Current Product Assesment - Customer Requirements



Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
HOW MUCH: Target	Up to 2' x 4'	0.5 Seconds	0 (No Pinch Points)	Adobe Illustrator (.ai)	< 10 Interactive Components	< $5,000	< 150 pounds	30" x 5' x 4'	Produces Less Than 80 dbas (Without Router)	1.5 Hours	8 Hours	Cuts Redwood Density Woods	Requires Less Than 15 Minutes Of Training	30A and 24V	Parts Available for Purchase (Yes/No)	< 0.03125 in.
Max Relationship	9	9	9	9	9	9	9	9	9	3	9	9	9	9	9	9
Technical Importance Rating	130.88	61.778	61.778	73.452	59.192	64.827	59.636	95.505	45.365	39.648	118.95	54.505	101.97	93.709	55.267	133.66
Relative Weight	10%	5%	5%	6%	5%	5%	5%	8%	4%	3%	10%	4%	8%	7%	4%	11%
Weight Chart																

Current Product Assessment - Engineering Specifications

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Our Product	5	5	4	5	5	5	5	5	5	5	5	5	5	5	5	5
Competitor #1: Rockler CNC Shark HD4	1	0	3	0	0	5	3	3	1	5	5	5	1	5	5	5
Competitor #2: ShopBot Buddy	5	5	2	0	0	0	0	0	1	5	5	5	1	5	5	5
Competitor #3: Baileigh Industrial CNC	5	5	4	0	0	0	0	0	5	5	5	5	0	5	5	5
Competitor #4: KL-6090 Desktop CNC	1	5	3	0	0	5	0	0	1	5	5	5	0	5	5	5



Template Revision: 09 Date: 4/25/2010
Christopher Battles

Figure B-1. House of Quality Matrix

9.3. **Appendix C: Drawings**

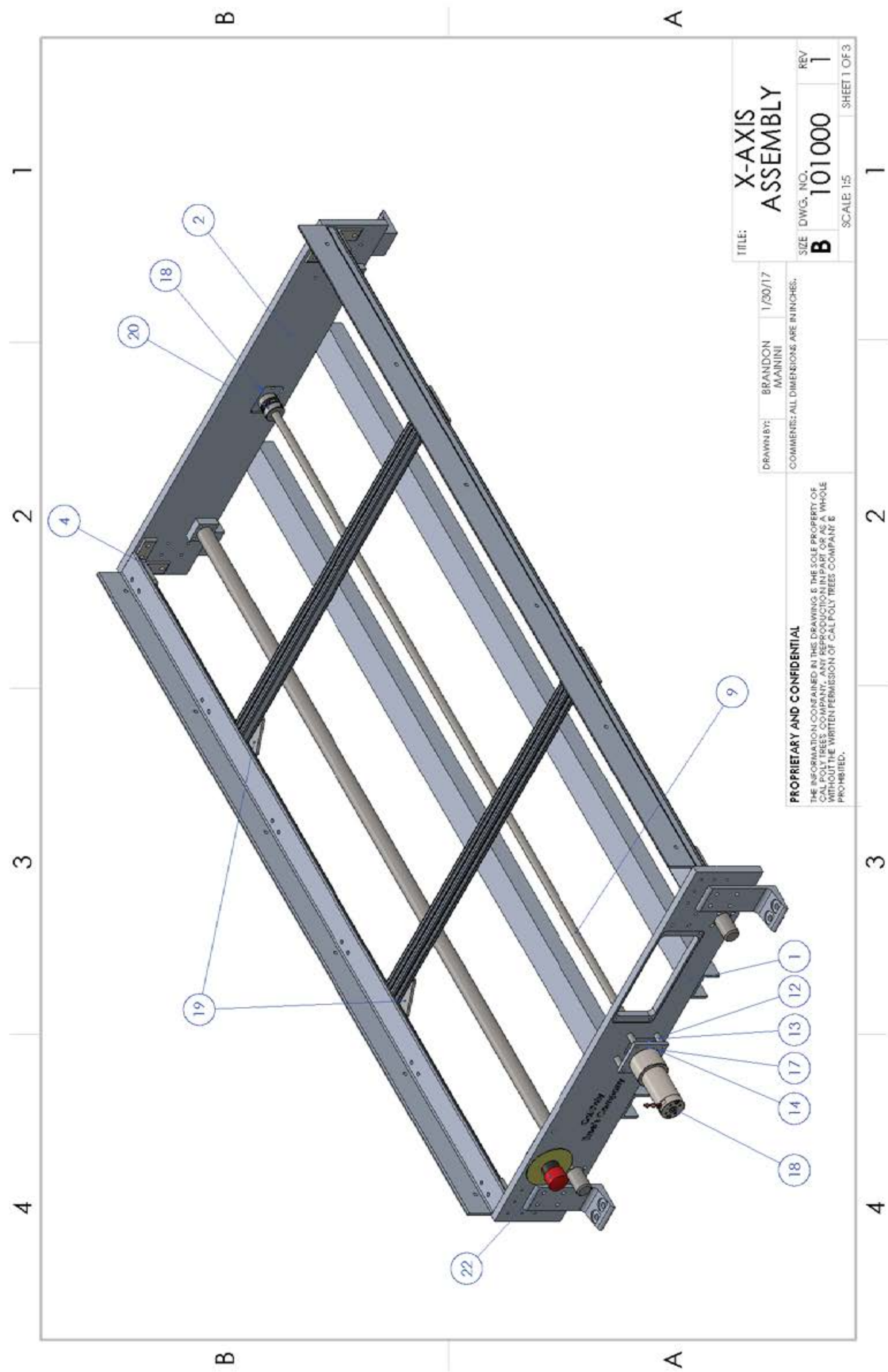


Figure C-1. X-Axis Assembly Drawing Sheet 1 of 3

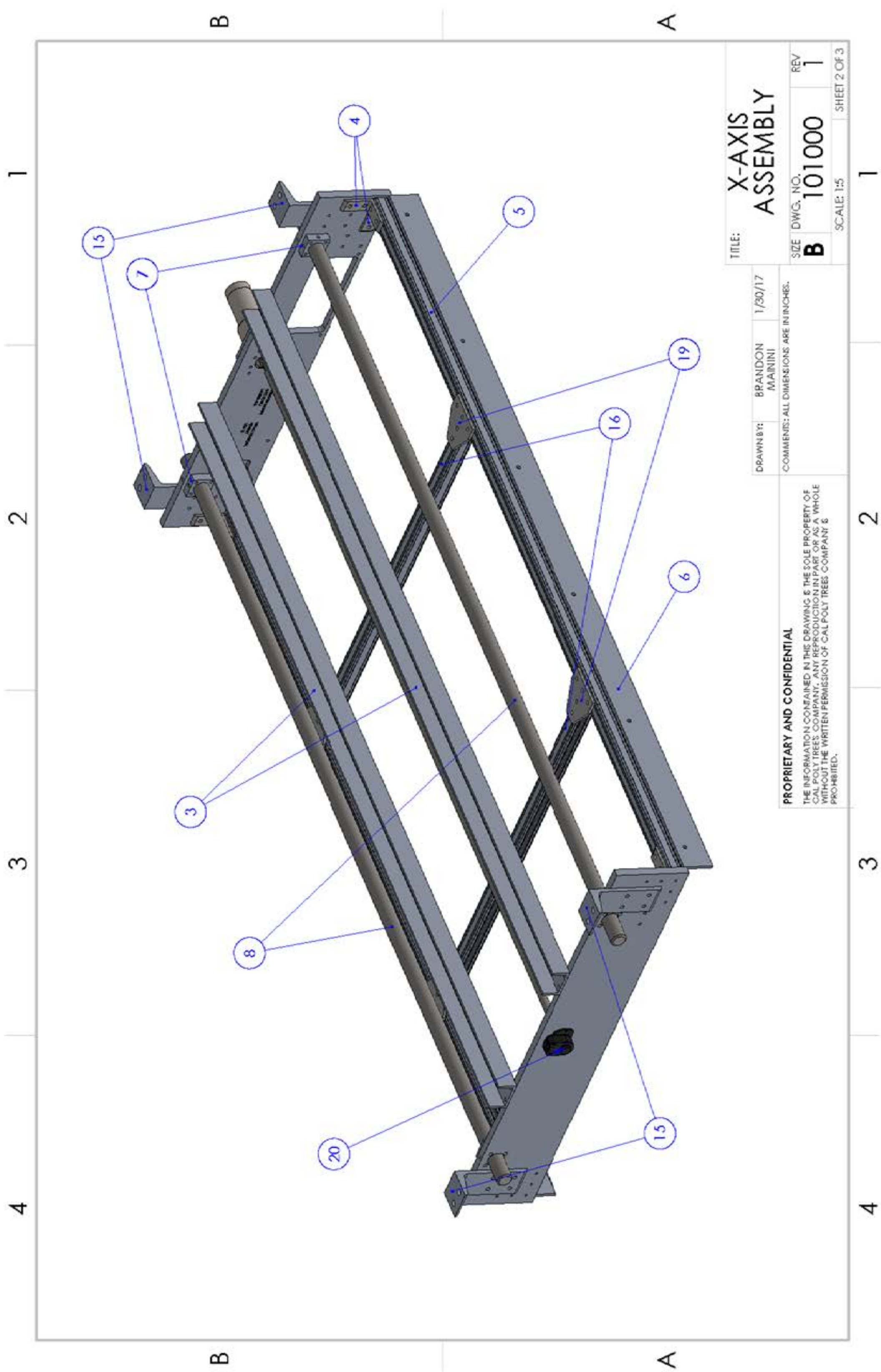


Figure C-2. X-Axis Assembly Drawing Sheet 2 of 3

ITEM NUMBER	PART NUMBER	VENDOR NUMBER	VENDOR	DESCRIPTION	QUANTITY
1	102001	--	OnlineMetals	Face Plate (Machined Panel, 6061, Flat Bar, 0.5"x5"x3')	1
2	102002	--	OnlineMetals	End Plate (Machined Panel, 6061, Flat Bar, 0.5"x5"x4')	1
3	102003	1630T47	McMaster-Carr	Foundation Brace (U-Channel, 2' Base x 1-1/4" Legs)	2
4	102004	47065T311	McMaster-Carr	Support Bracket (T-Slot Single Extrusion, 90° Bracket)	8
5	102005	47065T101	McMaster-Carr	Framing Extrusion (Single Profile, 1" Size, Solid)	2
6	102006	8982K18	McMaster-Carr	Foundation Stiffener (90 Degree Angle, 3/16" Thick, 2" x 2" Legs)	2
7	102007	--	McMaster-Carr	Guide Rod Supports	4
8	102008	6061K85	McMaster-Carr	X-Axis Guide Rod (Guide Rod, 1" OD, 60in CUT TO LENGTH)	2
9	102009	61422	Roton	X-Axis Lead Screw (ACME 1/2" - 8 TPI Lead Screw, 5' Long)	2
10	102010	2342K184	McMaster-Carr	End Plate Ball Bearing (Double Sealed, for 1/4" Shaft Diameter, 3/4" OD)	1
11	102011	2780T57	McMaster-Carr	Face Plate Ball Bearing (Double Sealed, for 3/8" Shaft Diameter, 1-1/8" OD)	3
12	102012	--	McMaster-Carr	Bearing Retainer	2
13	102013	92510A293	McMaster-Carr	Motor Mount Spacer (3/8" OD, 13/16" Length, for Number 10 Screw Size)	4
14	102014	460-008	OnlineMetals	Motor Mount (6061 AL, Flat Bar, 0.25" x 2.5", Random Length)	1
15	102015	47065T842	McMaster-Carr	Mounting Feet (T-Slot 4-hole Floor Mounting Bracket, 1" T-Slot)	4
16	102016	47065T101	McMaster-Carr	Horizontal Extrusion (Single Profile, 1" Size, Solid) (102005 SCRAPS)	2
17	102017	2424K11	McMaster-Carr	Rigid Shaft Coupling (Aluminum Set Screw Rigid Shaft Coupling)	1
18	102018	GM9236S014-R1-SP	McMaster-Carr	Pittman & Metek Motor (DC Gearmotor)	1
19	102019	47065T315	McMaster-Carr	Aluminum Tee (Black Tee, 3" Long for 1" High Single Profile Aluminum T-Slotted Framing Extrusion)	4
20	102020	9861T826	McMaster-Carr	Flexible Shaft Coupling (Set Screw, 1/2" x 1/4" Diameter Shaft, 1-1/4" Length)	1
21	102021	CC1758-ND	USDigital	X-Axis Encoder (Incremental Shaft Encoder, 32 CPR)	1
22	102022	6741K410	McMaster	Emergency Shutoff Switch (Pull to Reset, 1-1/4" Button Diameter, 1 Normally Closed Contact)	1

DRAWN BY: BRANDON MAININI 1/30/17

COMMENTS: ALL DIMENSIONS ARE IN INCHES.

TITLE: X-AXIS ASSEMBLY

SIZE B | DWG. NO. 101000 | REV 1

SCALE: 1:5 | SHEET 3 OF 3

Figure C-3. X-Axis Assembly Drawing Sheet 3 of 3

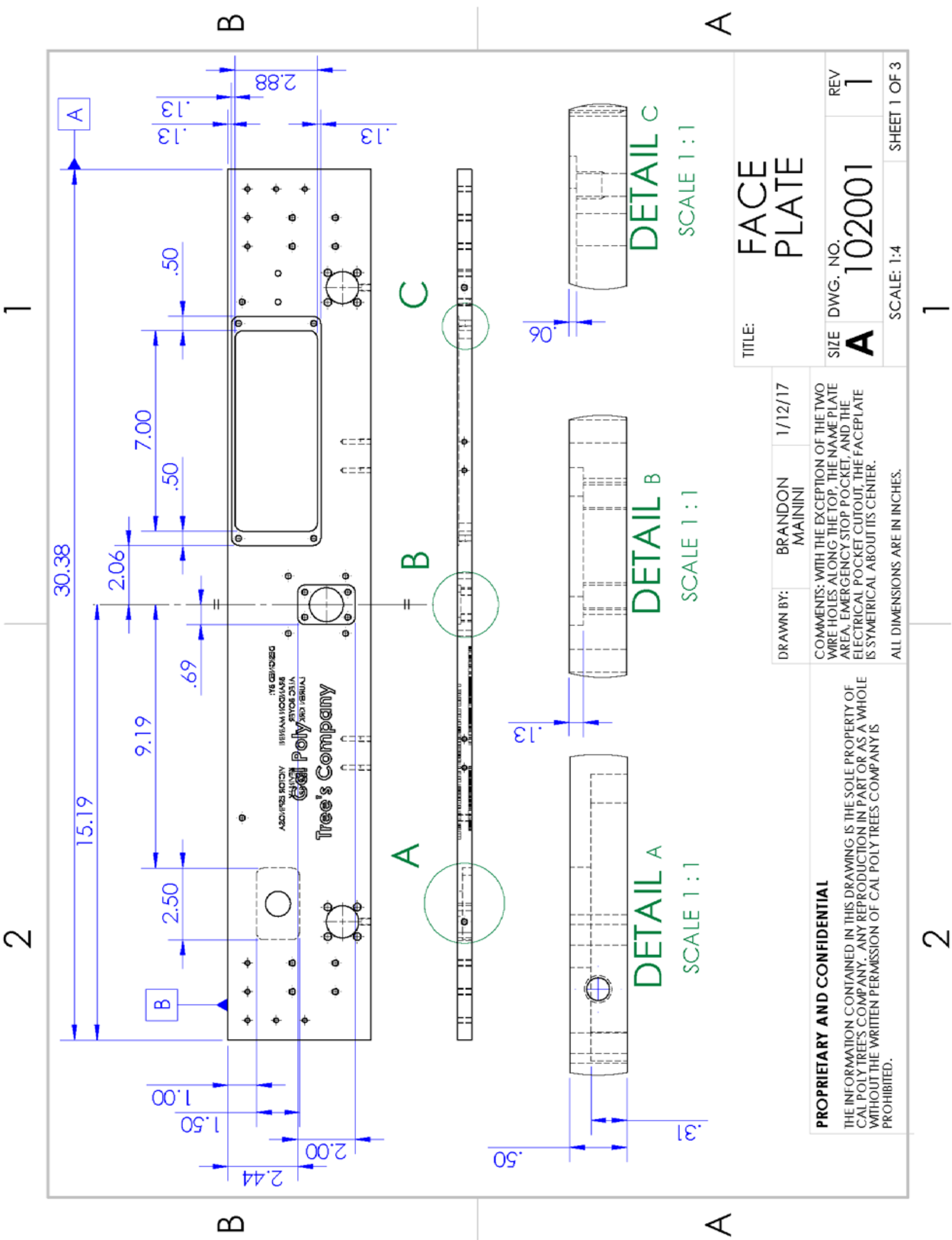


Figure C-4. Face Plate Detail Drawing Sheet 1 of 3

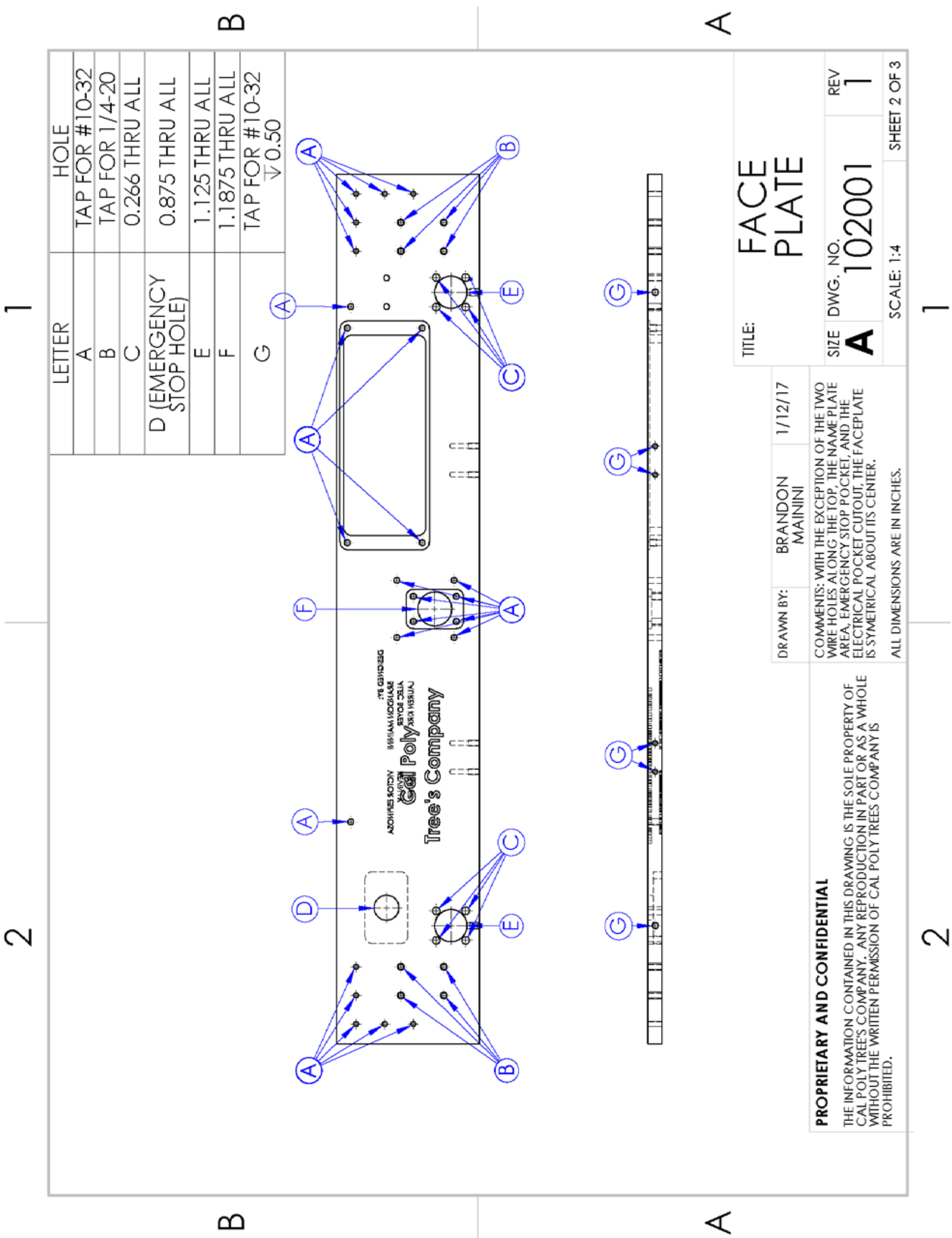


Figure C-5. Face Plate Detail Drawing Sheet 2 of 3

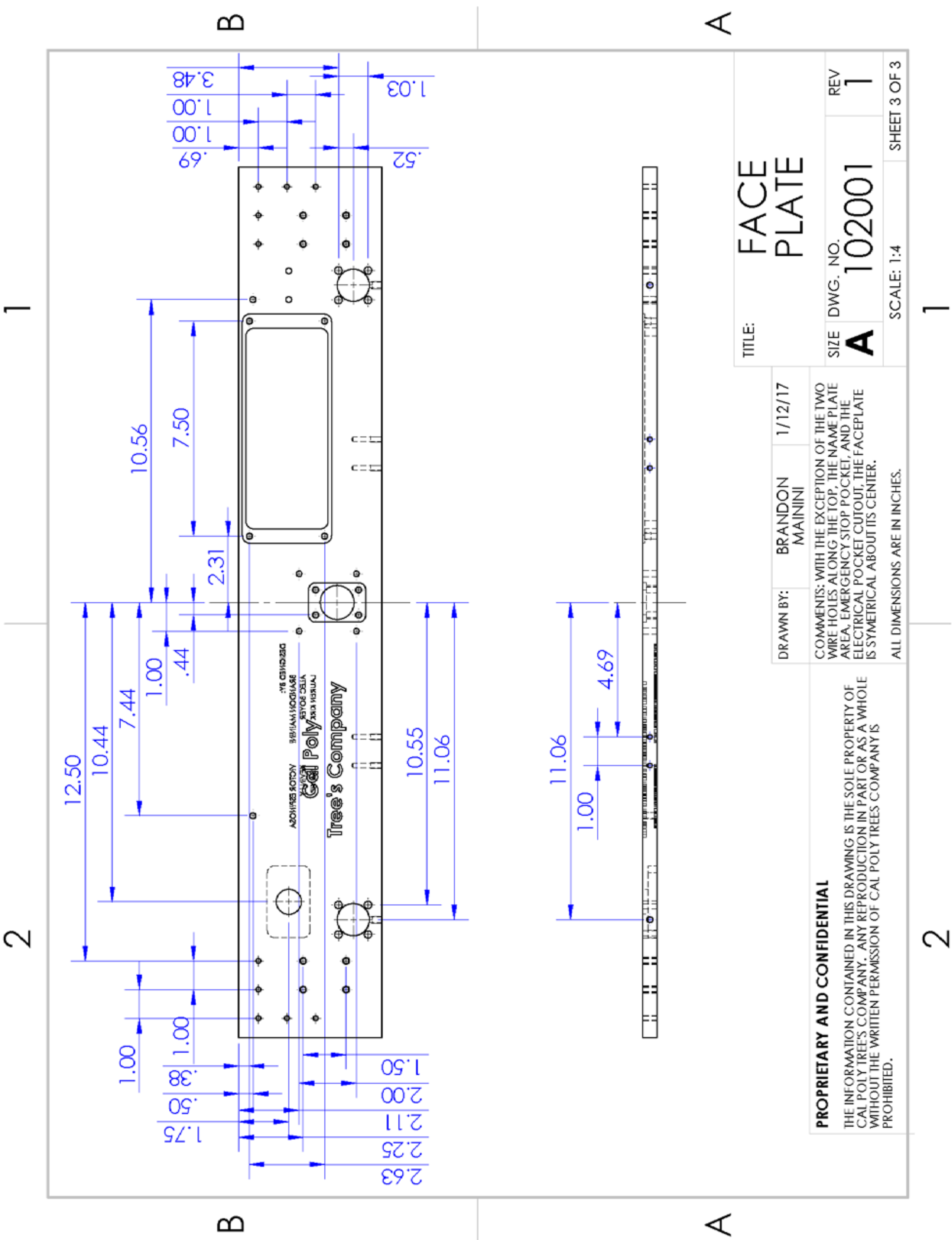


Figure C-6. Face Plate Detail Drawing Sheet 3 of 3

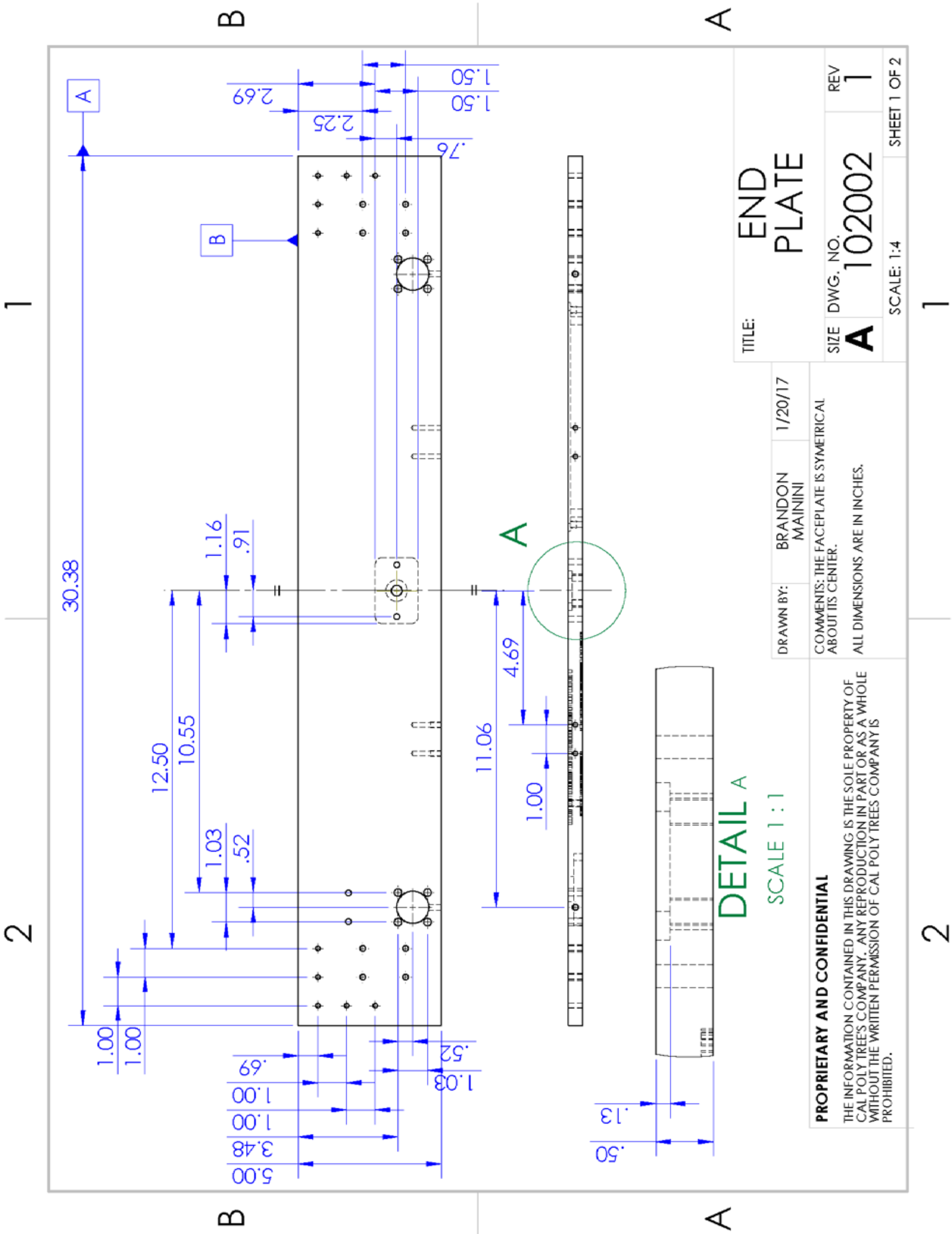


Figure C-7. End Plate Detail Drawing Sheet 1 of 2

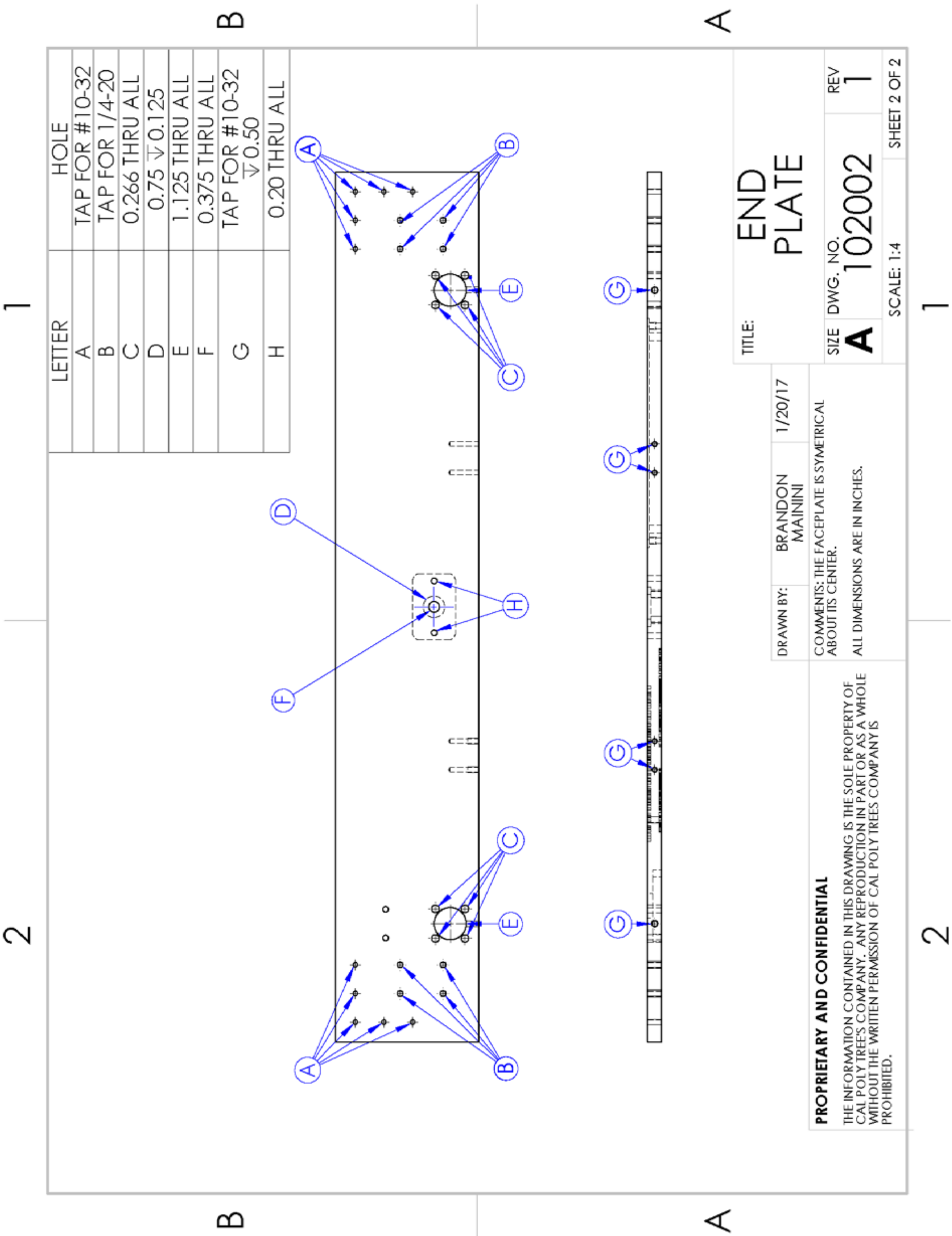


Figure C-8. End Plate Detail Drawing Sheet 2 of 2

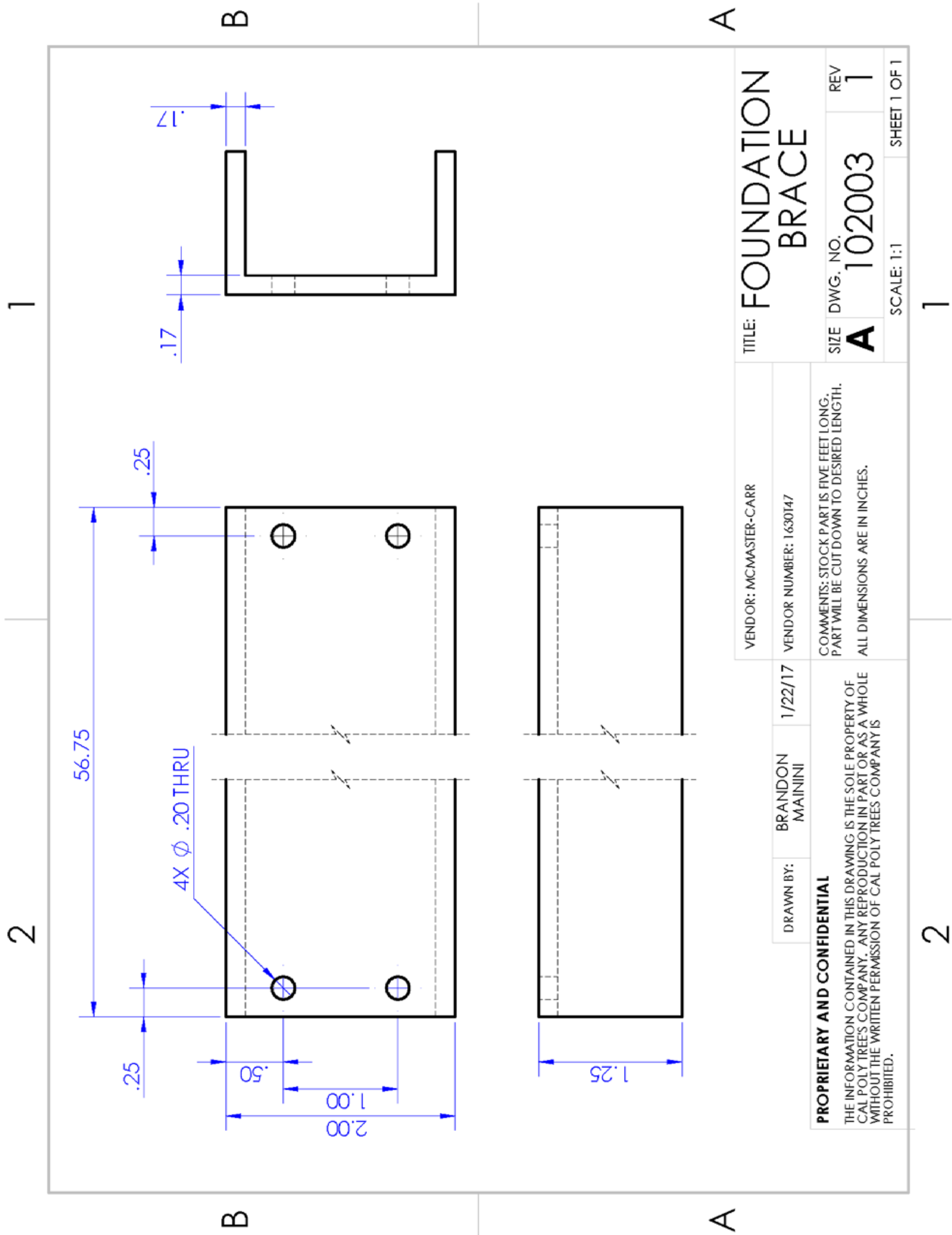


Figure C-9. Foundation Brace Detail Drawing

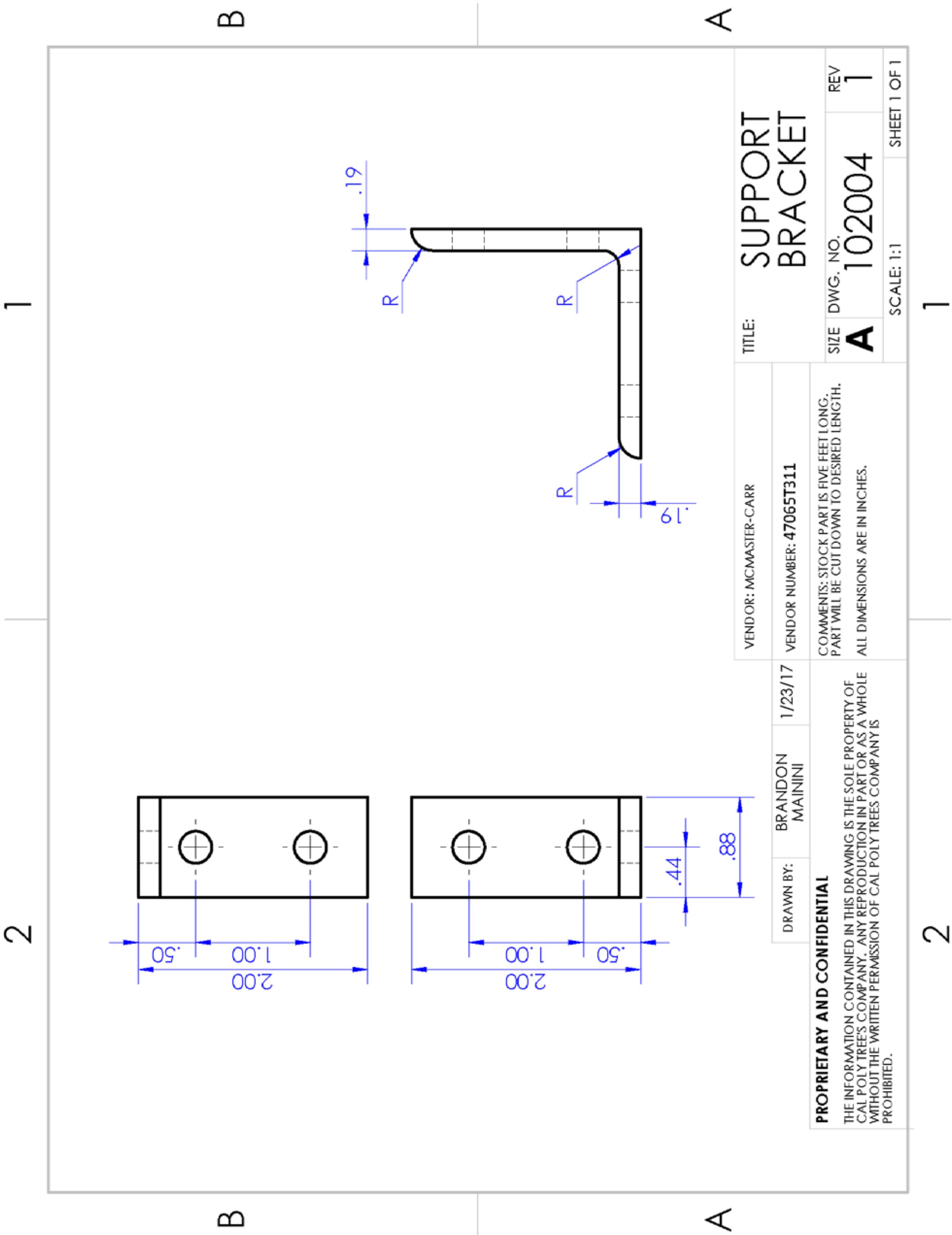


Figure C-10. Support Bracket Detail Drawing

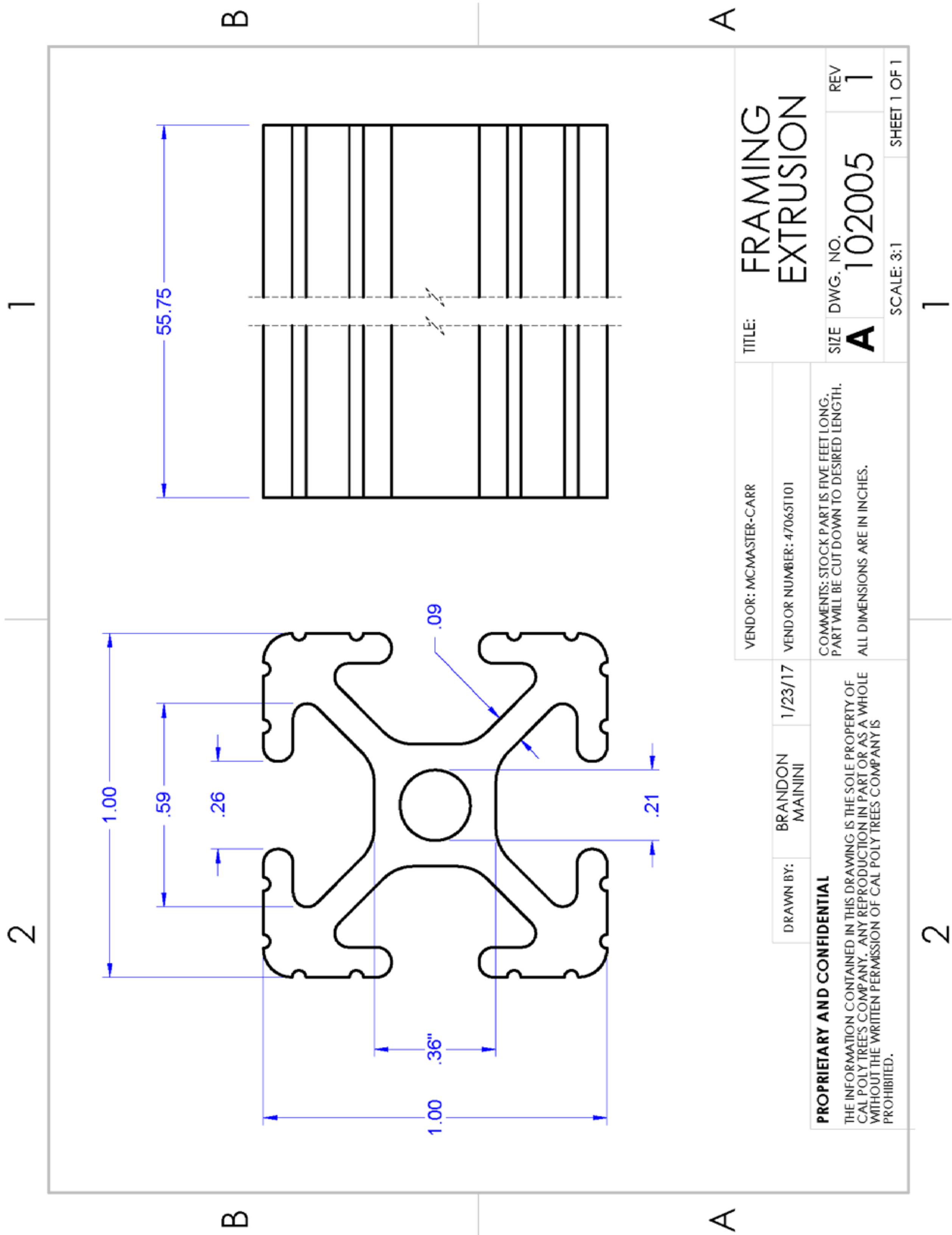


Figure C-11. Framing Extrusion Detail Drawing

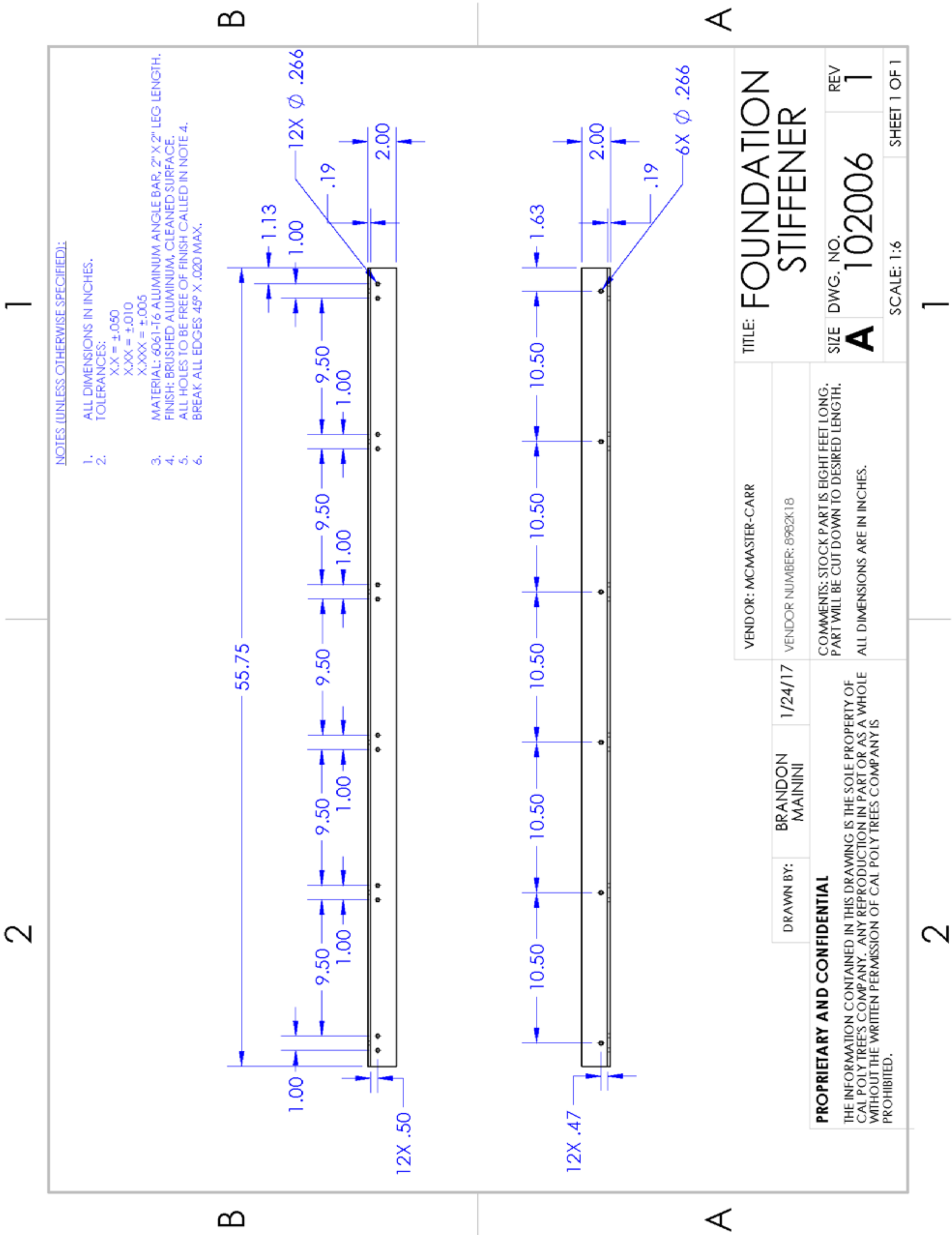


Figure C-12. Foundation Stiffener Detail Drawing

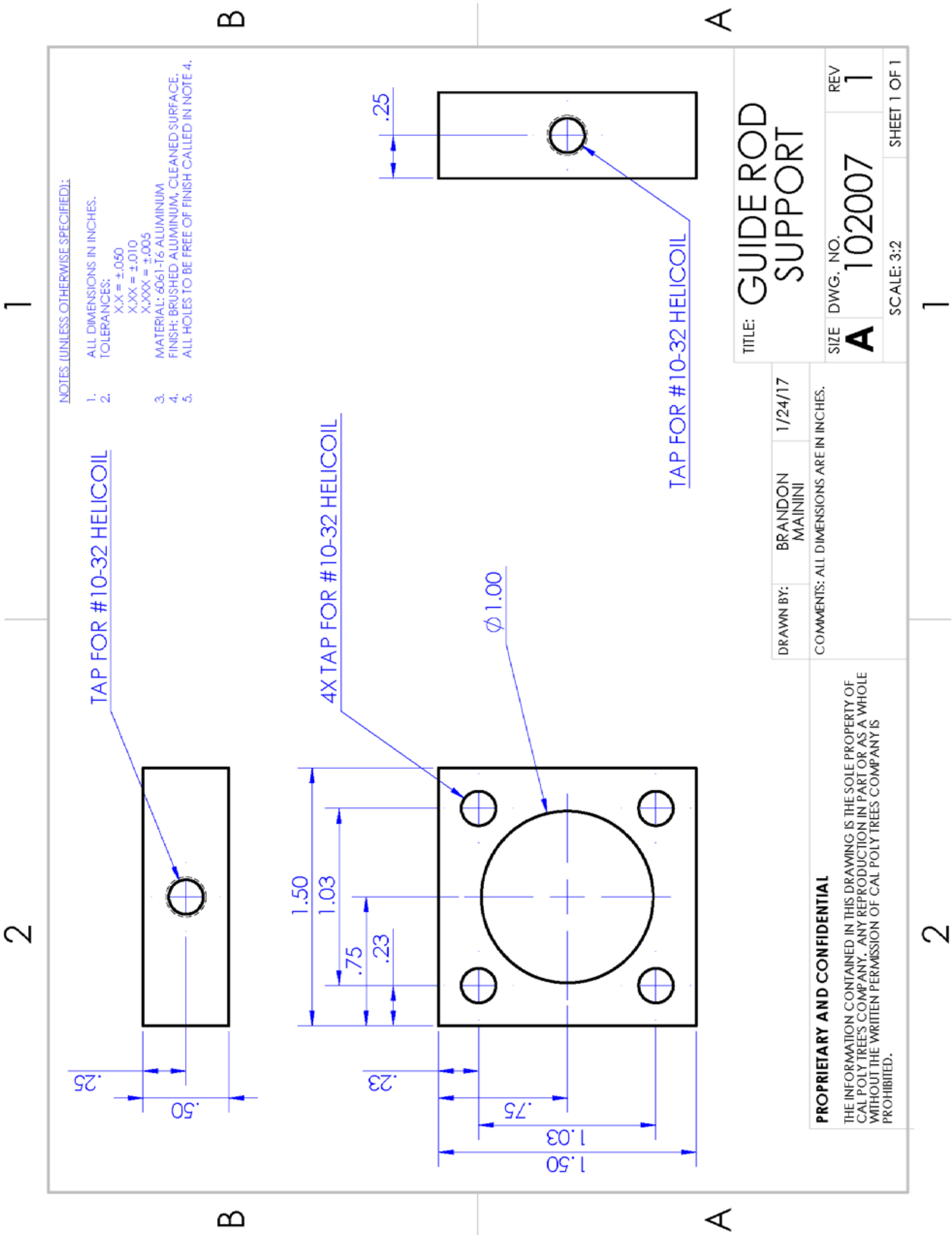


Figure C-13. Guide Rod Support Detail Drawing

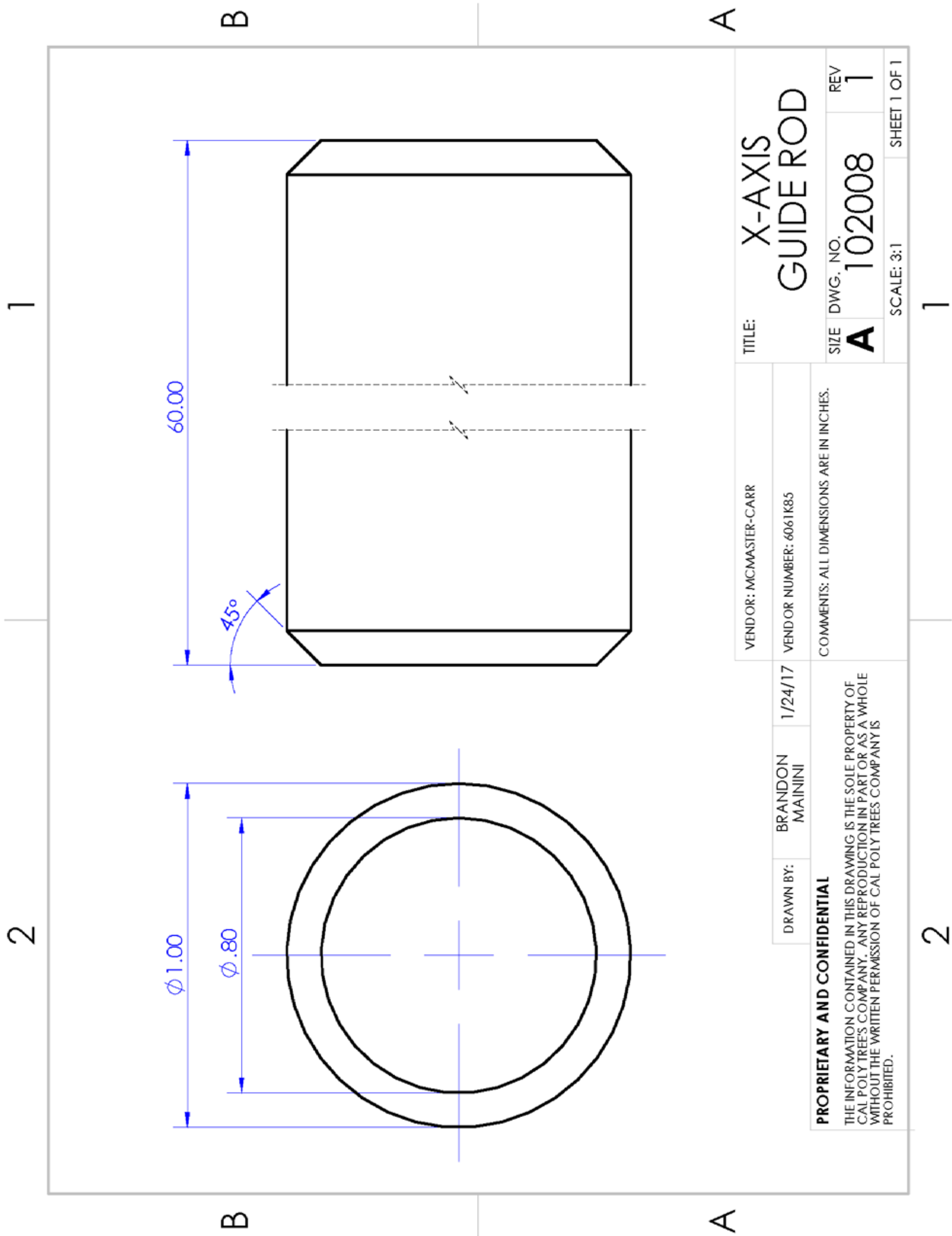


Figure C-14. X-Axis Guide Rod Detail Drawing

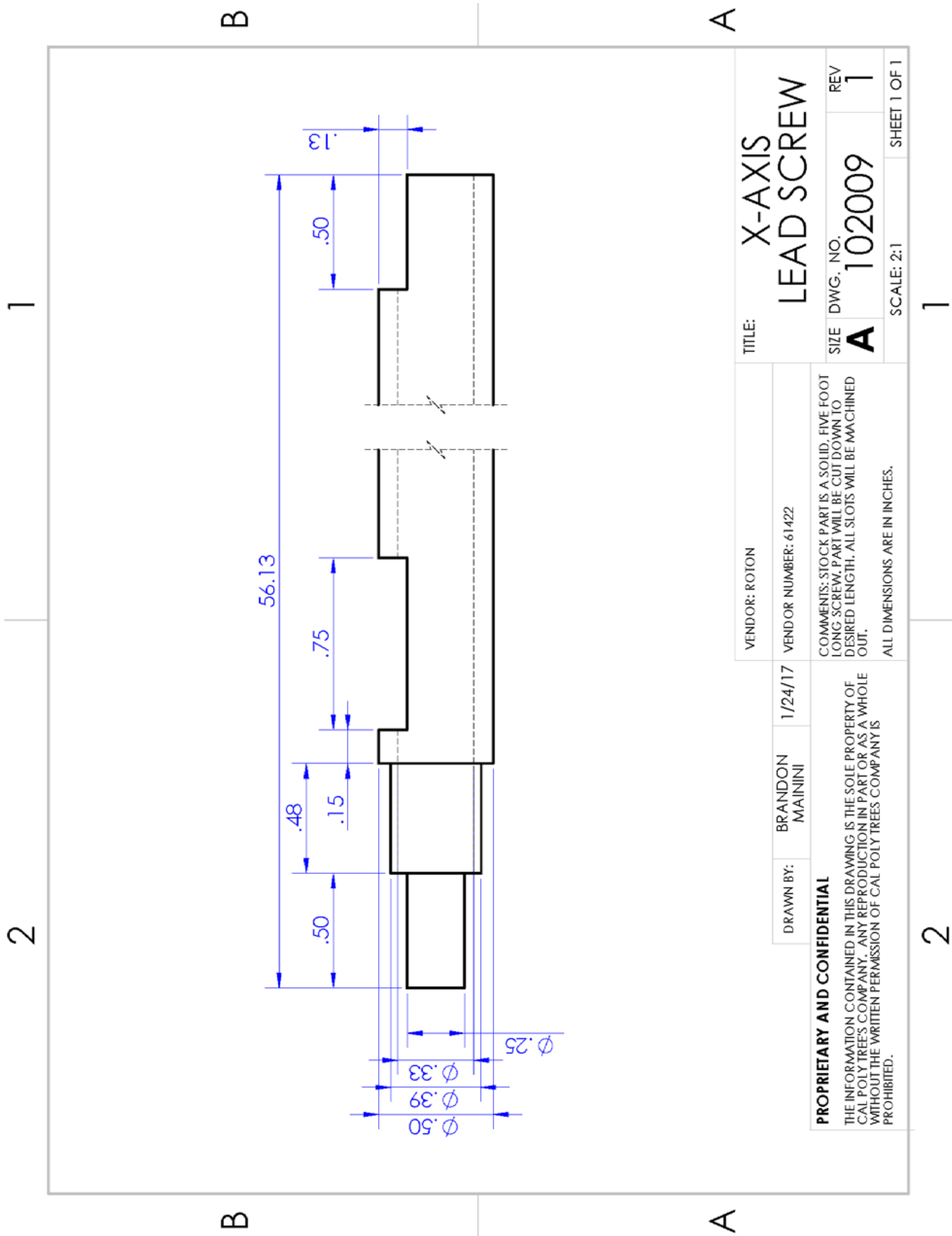


Figure C-15. X-Axis Lead Screw Detail Drawing

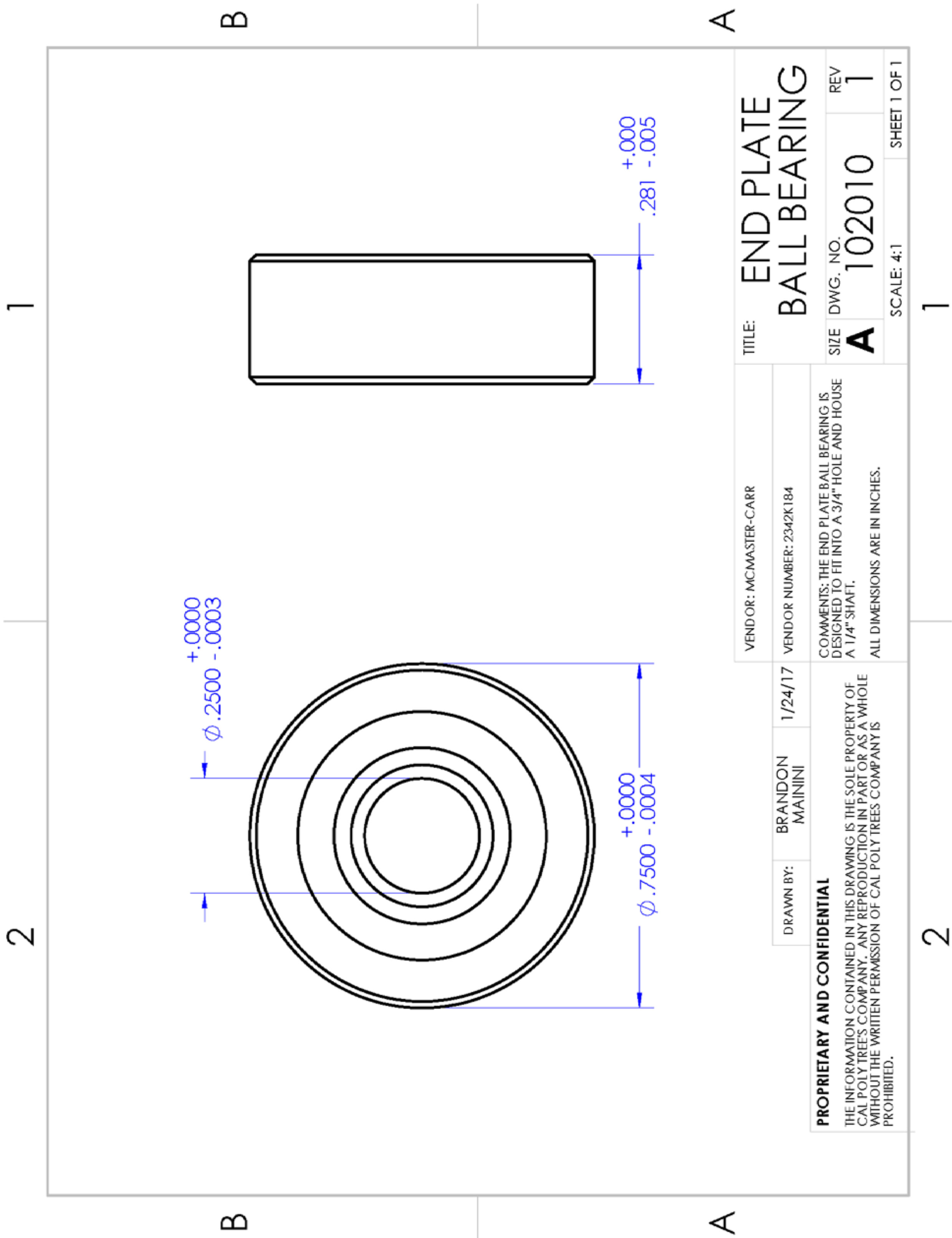


Figure C-16. End Plate Ball Bearing Detail Drawing

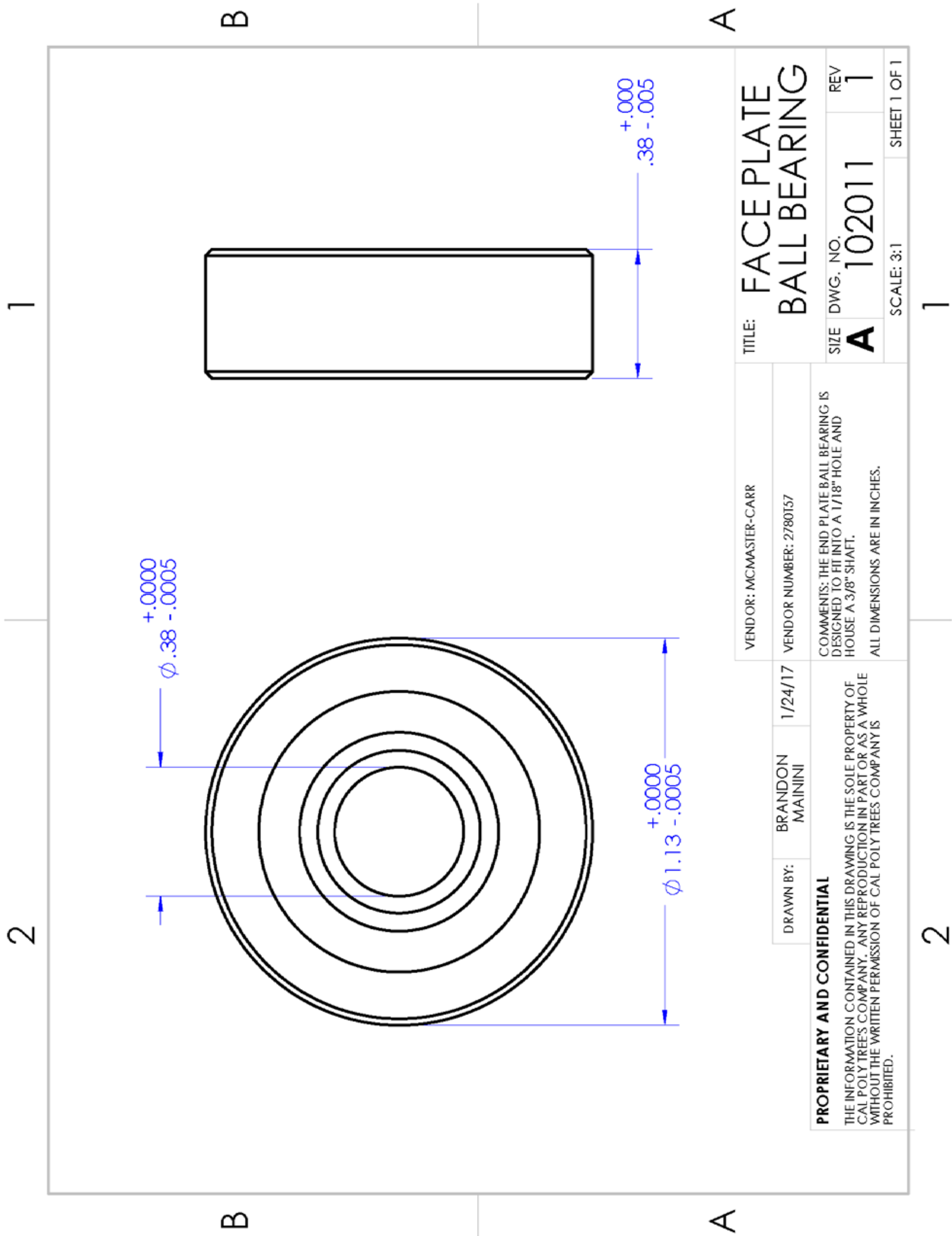


Figure C-17. Face Plate Ball Bearing Detail Drawing

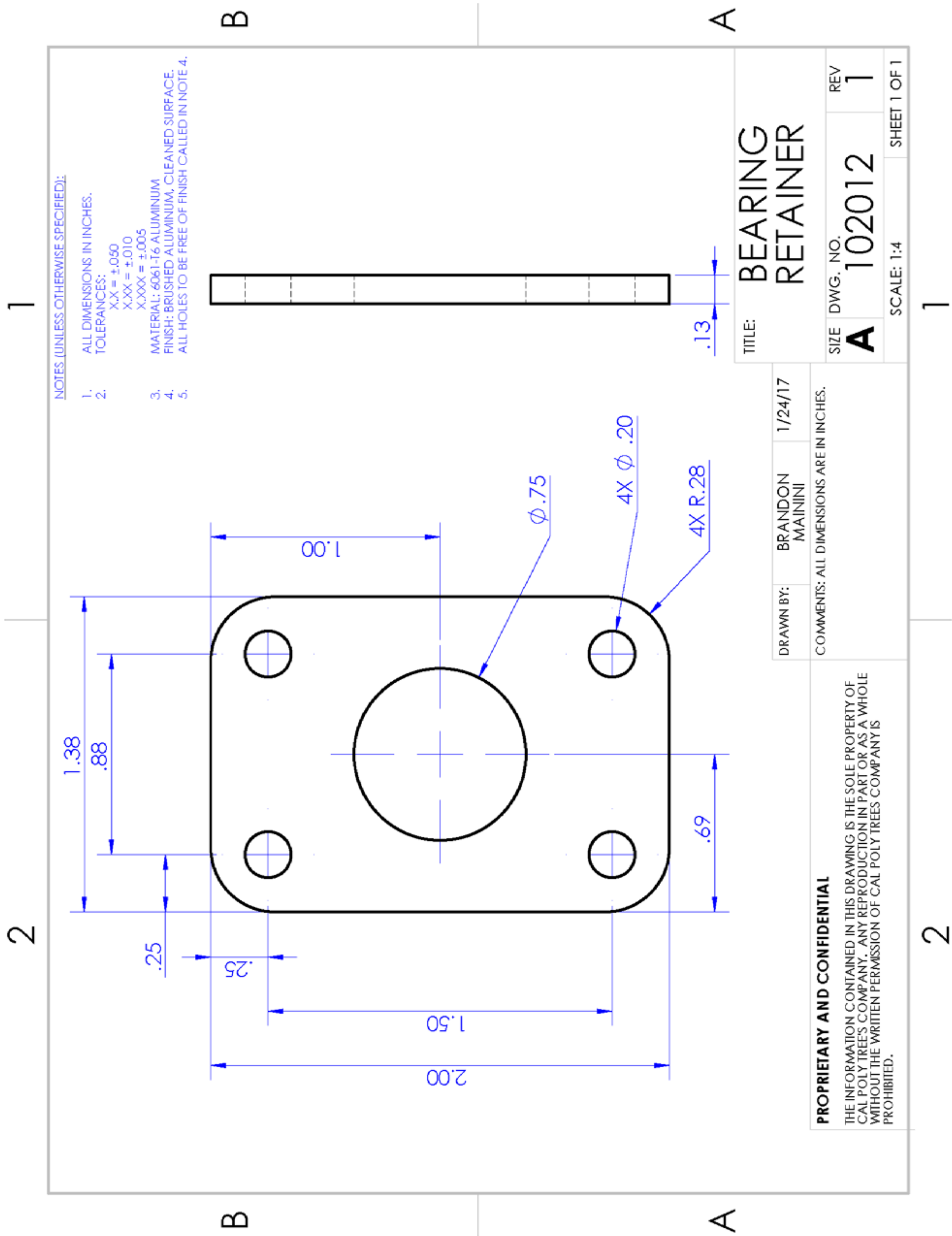


Figure C-18. Bearing Retainer Detail Drawing

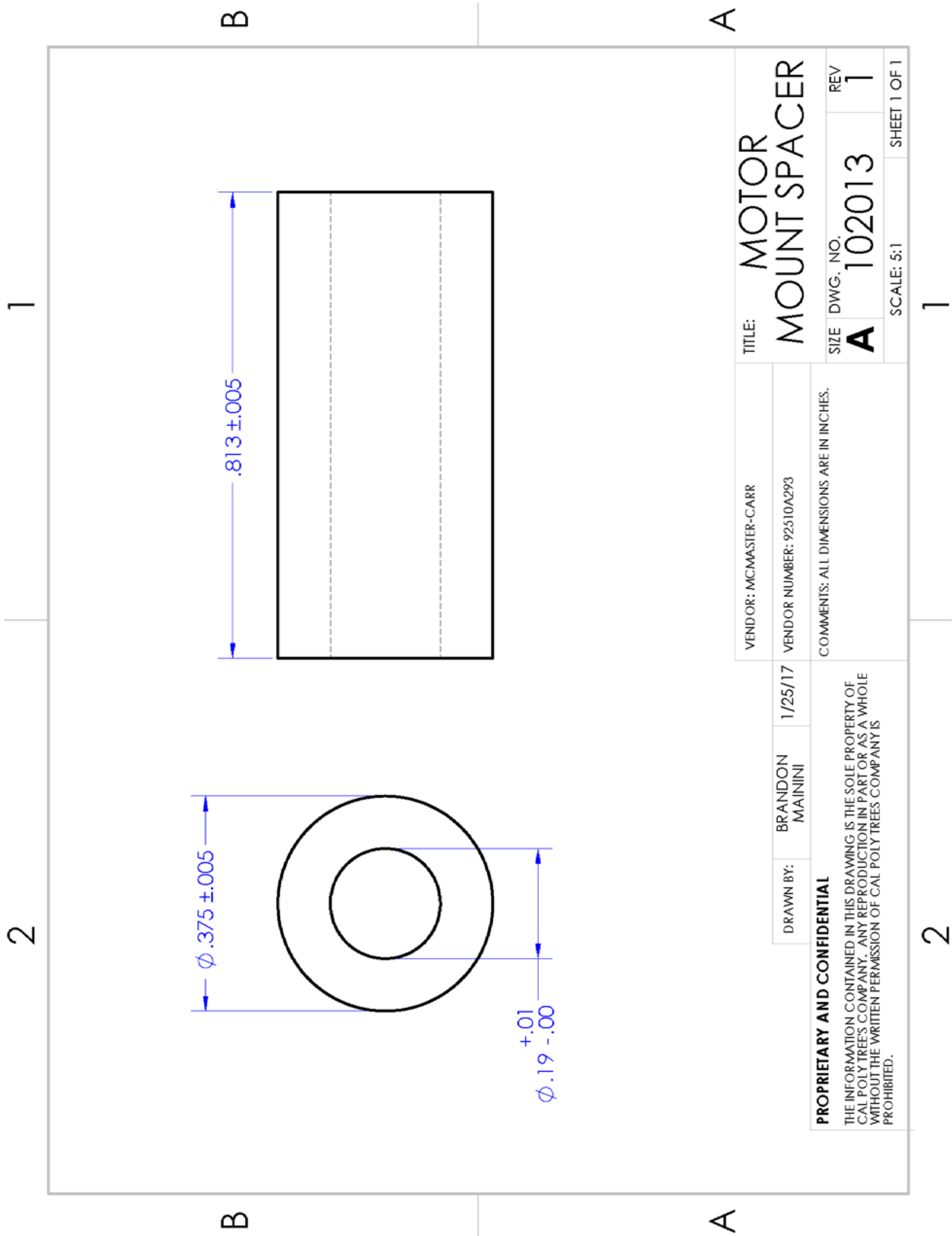


Figure C-19. Motor Mount Spacer Detail Drawing

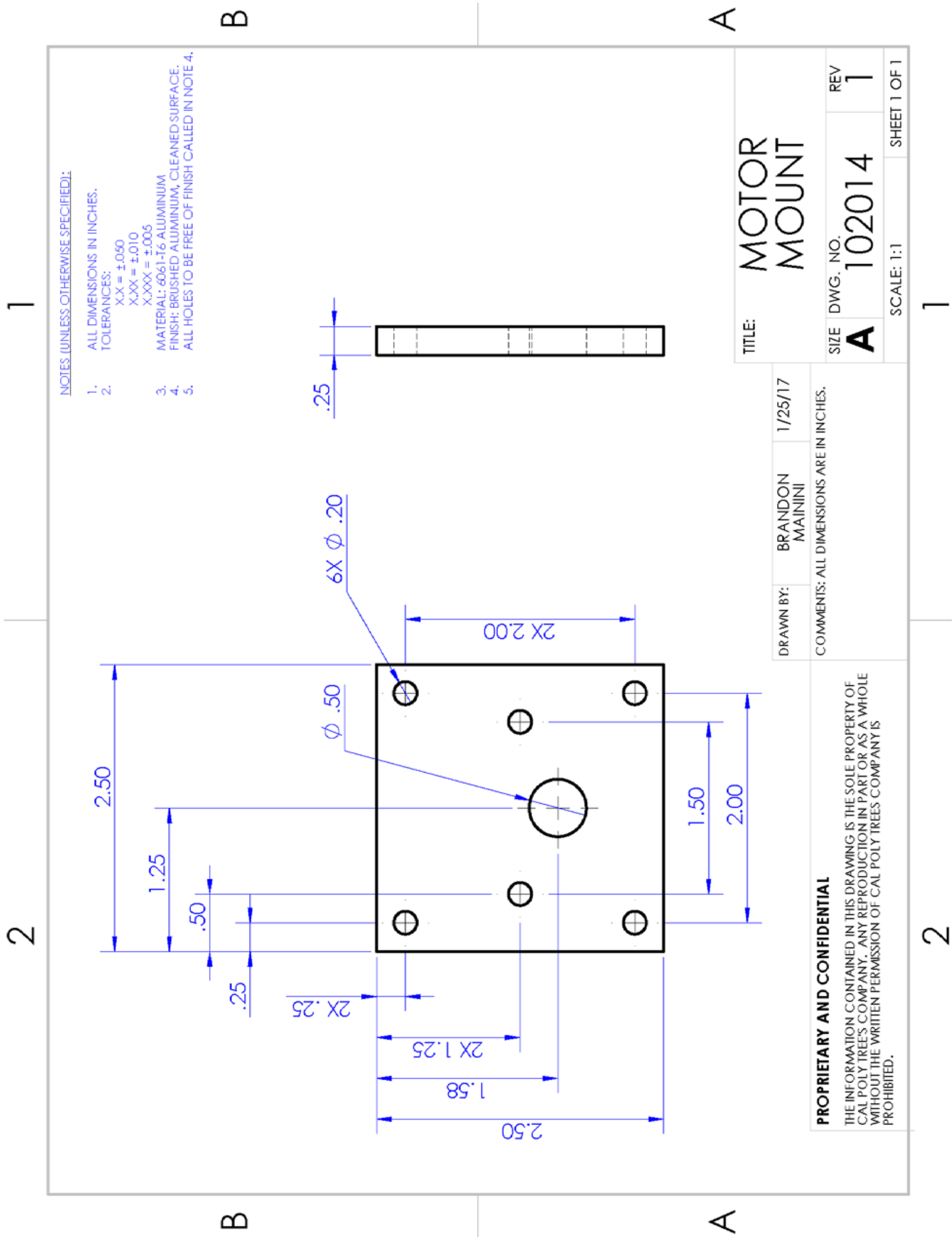


Figure C-20. Motor Mount Detail Drawing

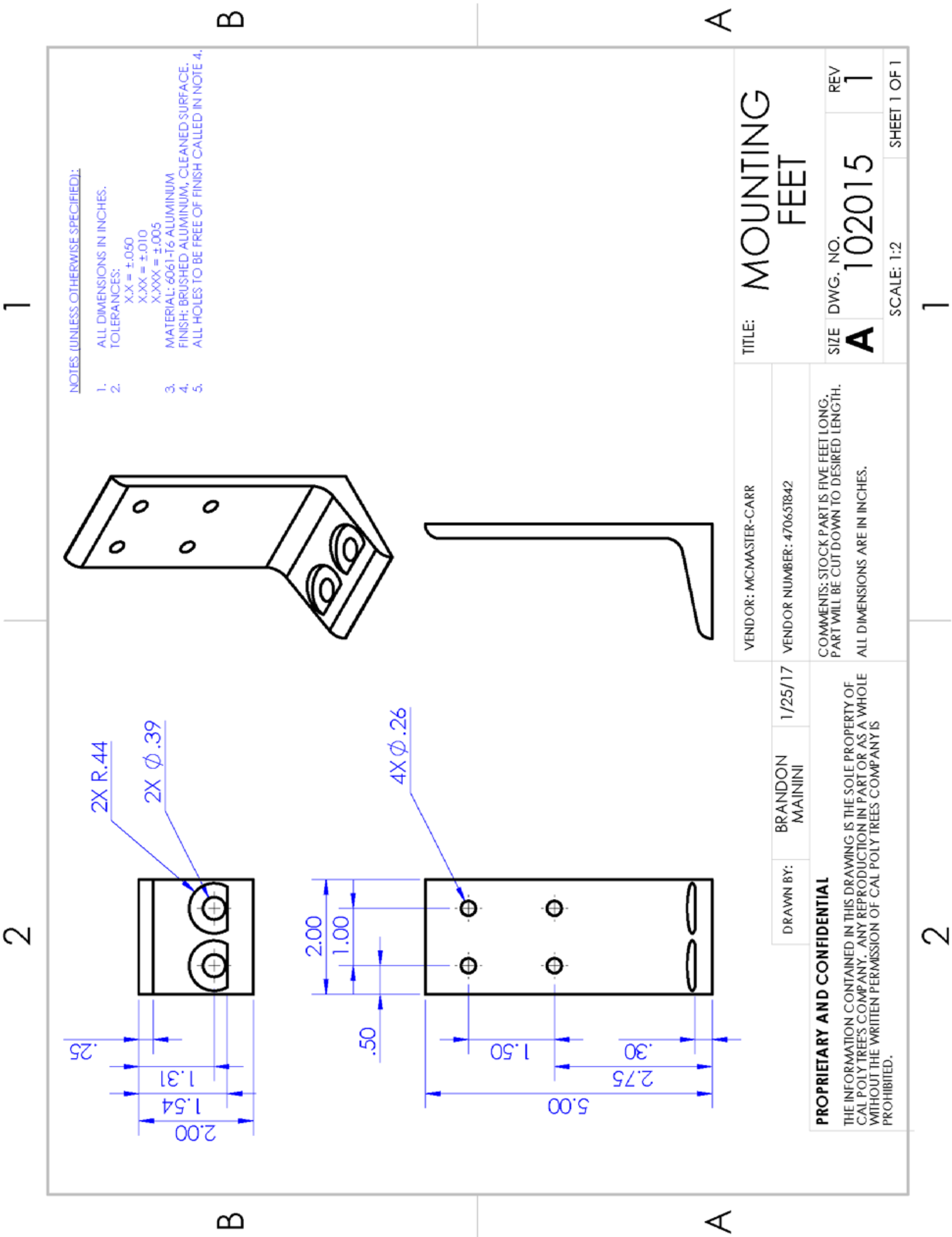


Figure C-21. Mounting Feet Detail Drawing

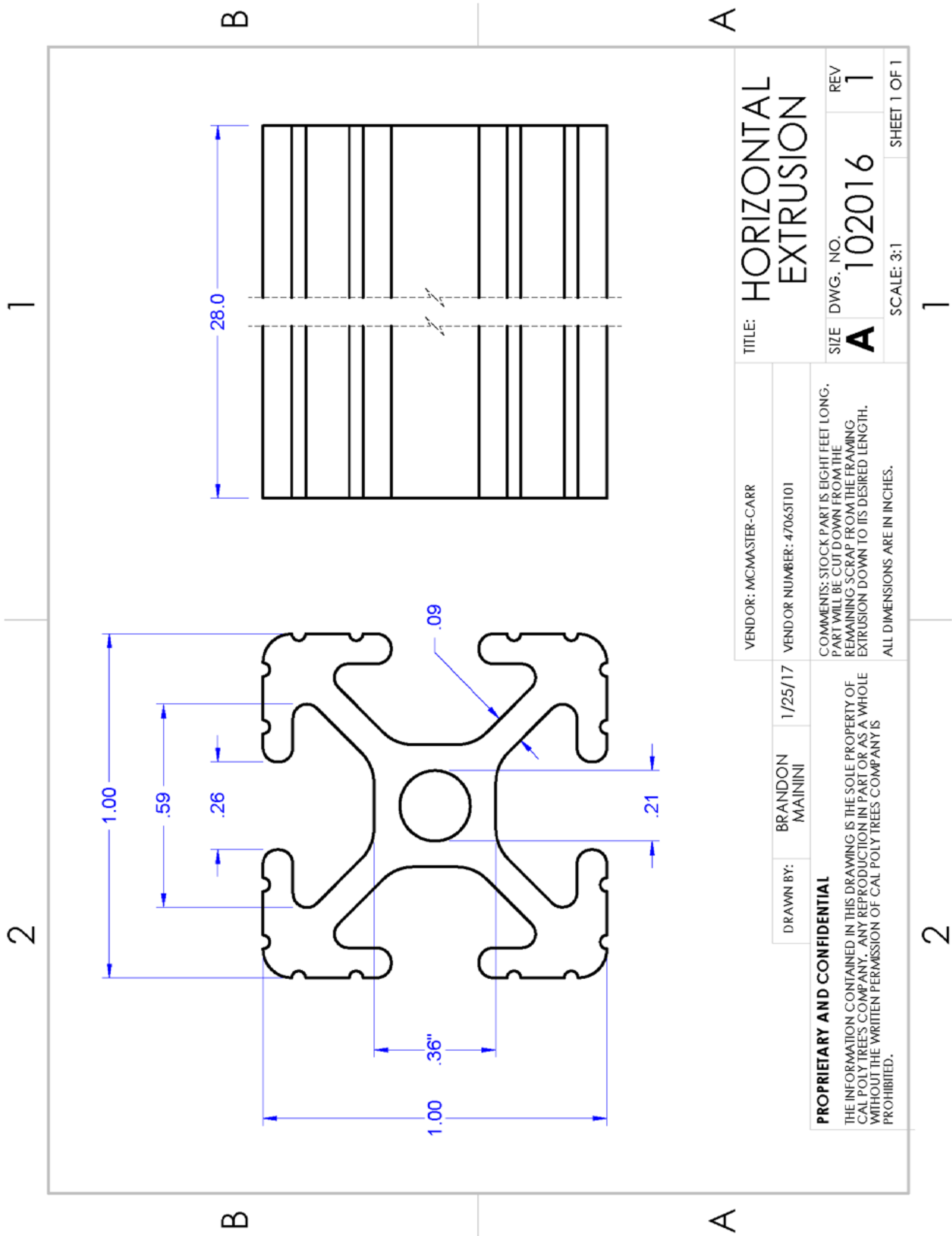


Figure C-22. Horizontal Extrusion Detail Drawing

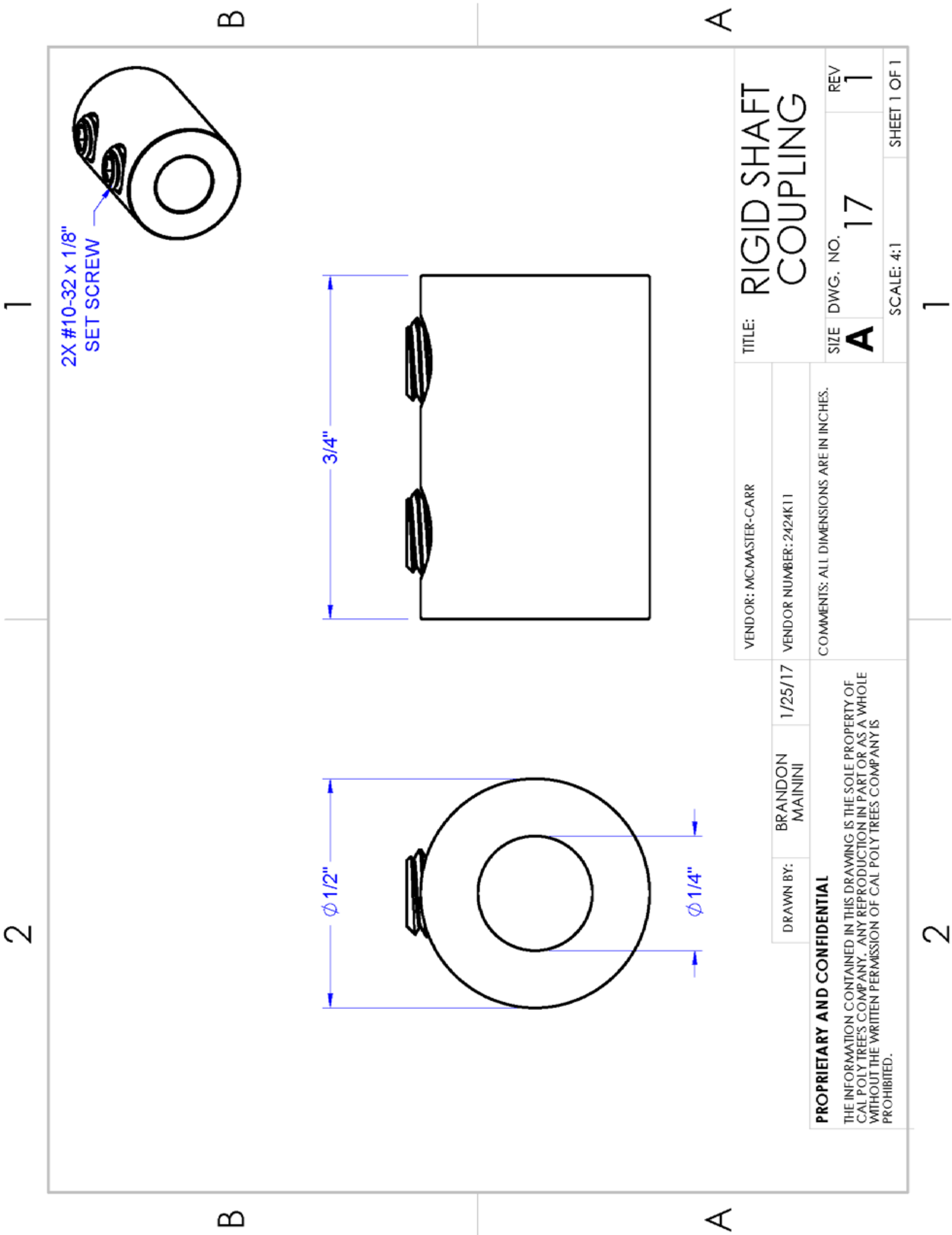


Figure C-23. Rigid Shaft Coupling Detail Drawing

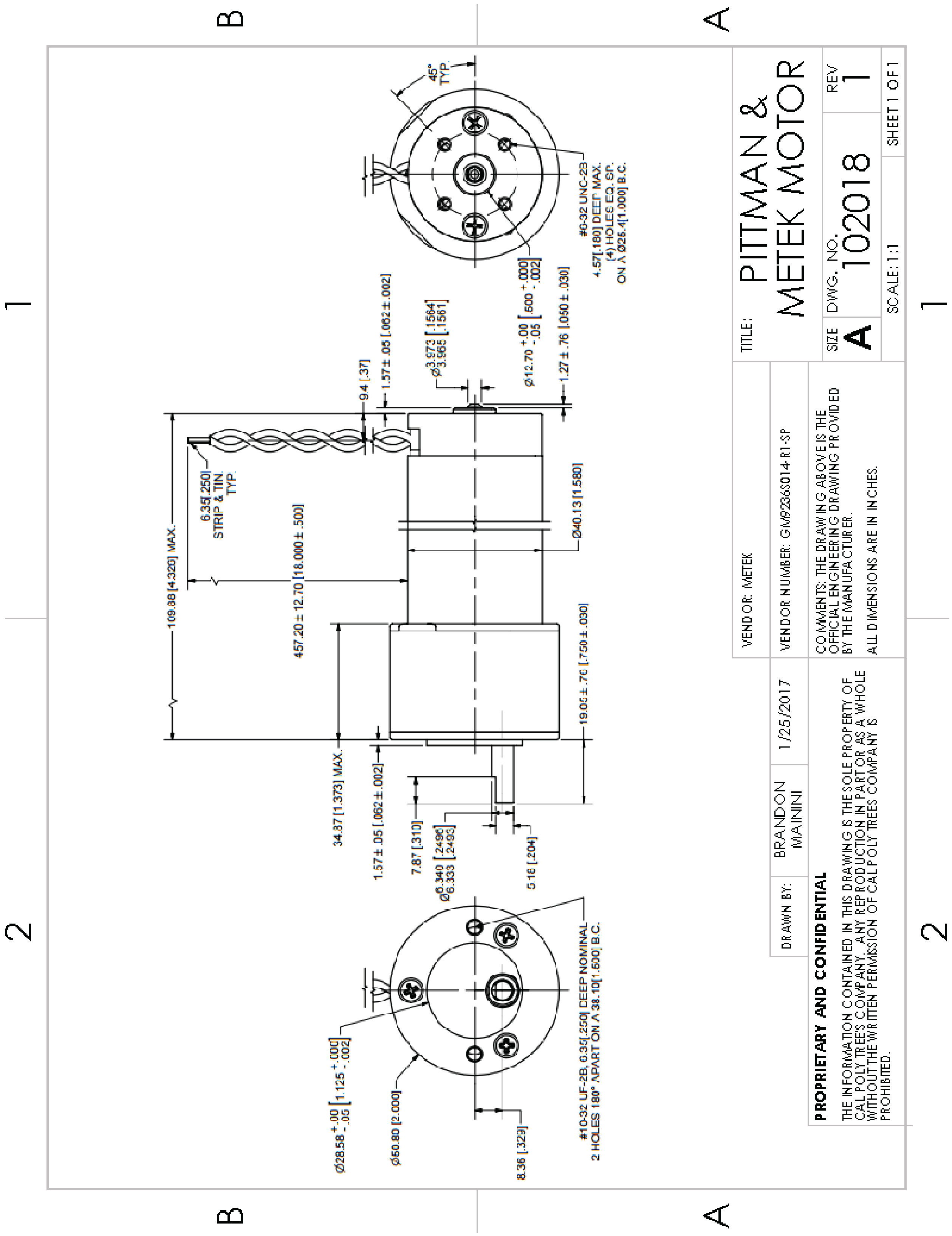


Figure C-24. Pittman & Metek Motor Detail Drawing

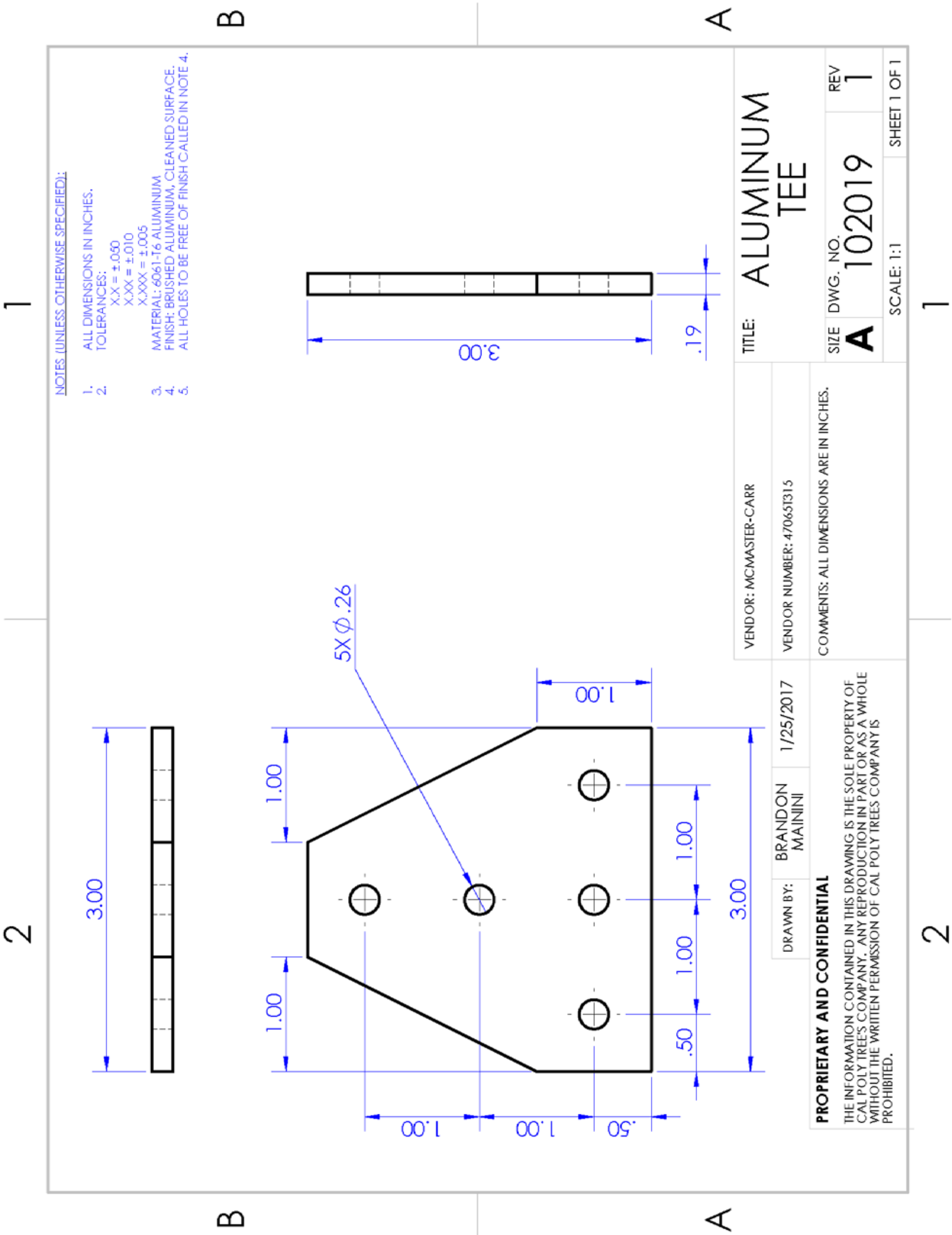


Figure C-25. Aluminum Tee Detail Drawing

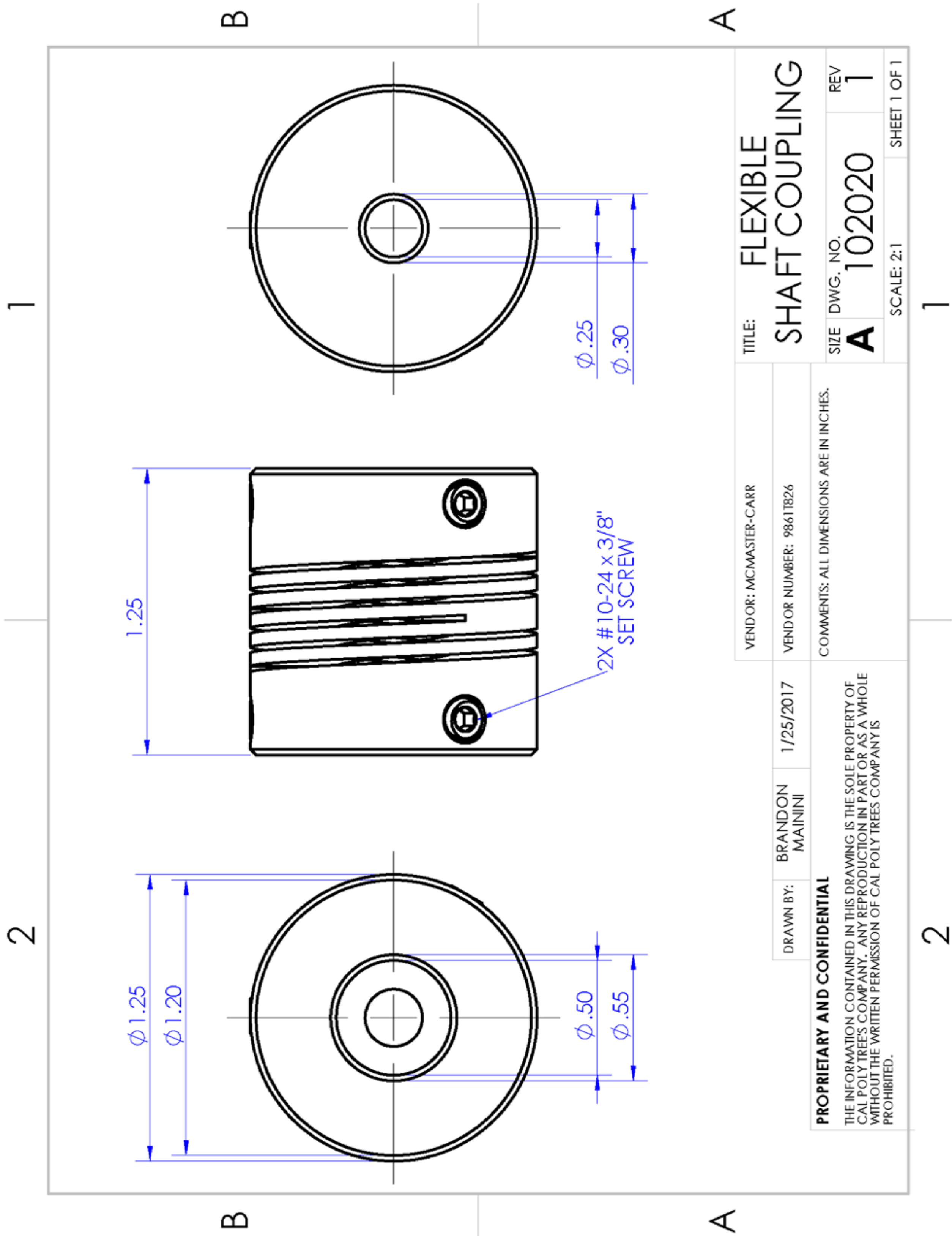


Figure C-26. Flexible Shaft Coupling Detail Drawing

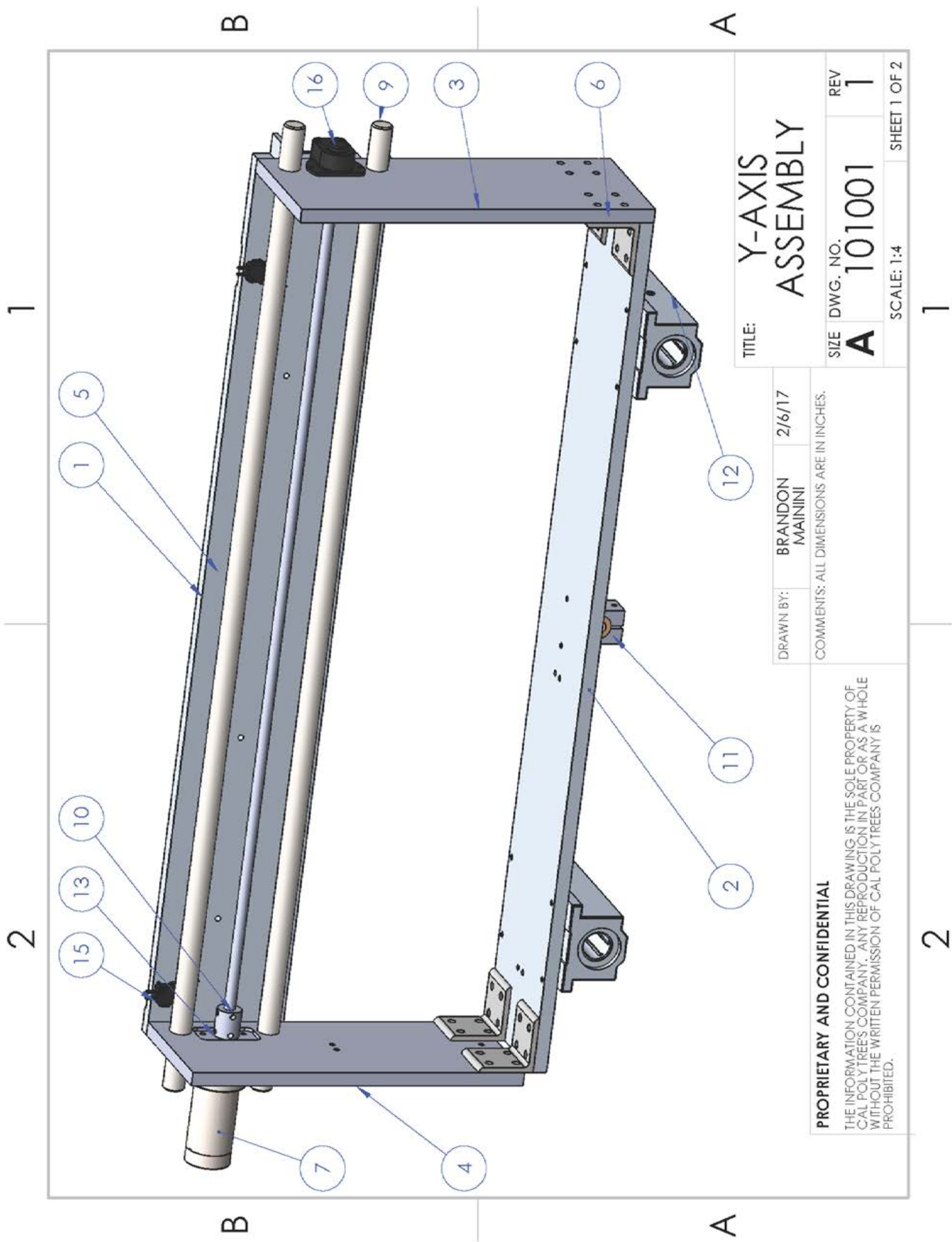


Figure C-27. Y-Axis Assembly Detail Drawing (Page 1 of 2)

ITEM NO.	PART NUMBER	VENDOR NUMBER	VENDOR	DESCRIPTION	QTY.
1	102033	--	--	GANTRY, BRIDGE MEMBER, TOP	1
2	102034	--	--	GANTRY, BRIDGE MEMBER, BOTTOM	1
3	102035	--	--	GANTRY, VERTICAL MEMBER, ENCODER SIDE	1
4	102036	--	--	GANTRY, VERTICAL MEMBER, MOTOR SIDE	1
5	102037	--	--	GANTRY, BRIDGE MEMBER, TOP, STIFFENER	1
6	102052	47065T176	McMaster-Carr	VERTICAL MEMBER ANGLE BRACKET	4
7	102046	GM9236S014-R1-SP	PITTMAN	PITTMAN DC GEARMOTOR, 2" FRAME SIZE	1
8	102043	2938T2	McMaster-Carr	BRONZE FLANGE BUSHING, SAE 863, 1/4" ID, 3/8" L	2
9	102047	6061K64	McMaster-Carr	GUIDE ROD (Y-AXIS), .75 OD, 36" L	2
10	102042	60896	ROTON	ROTON LEAD SCREW, 3/8" - .125 ACME, 30.875 L	1
11	102038	--	--	SLEEVE NUT HOUSING, 1/2"	1
12	102051	9338T11	McMaster-Carr	DOUBLE LINEAR BALL BEARING, SEAL, PILLOW BLOCK, 1" ID	2
13	--	P-307	--	GANTRY, SHAFT COUPLING, RIGID	1
14	102048	9861T615	McMaster-Carr	HELICAL FLEXIBLE SHAFT COUPLING	1
15	--	7779K63	McMaster-Carr	MINI LIMIT SWITCH	2
16	102050	H5-32-NE-S	US DIGITAL	US DIGITAL INCREMENTAL SHAFT ENCODER	1

DRAWN BY:	BRANDON MAININI	2/6/17

COMMENTS: ALL DIMENSIONS ARE IN INCHES.

TITLE: Y-AXIS ASSEMBLY

SIZE	DWG. NO.	REV
A	101001	1
	SCALE: 1:4	SHEET 2 OF 2

Figure C-28. Y-Axis Assembly Detail Drawing (Page 2 of 2)

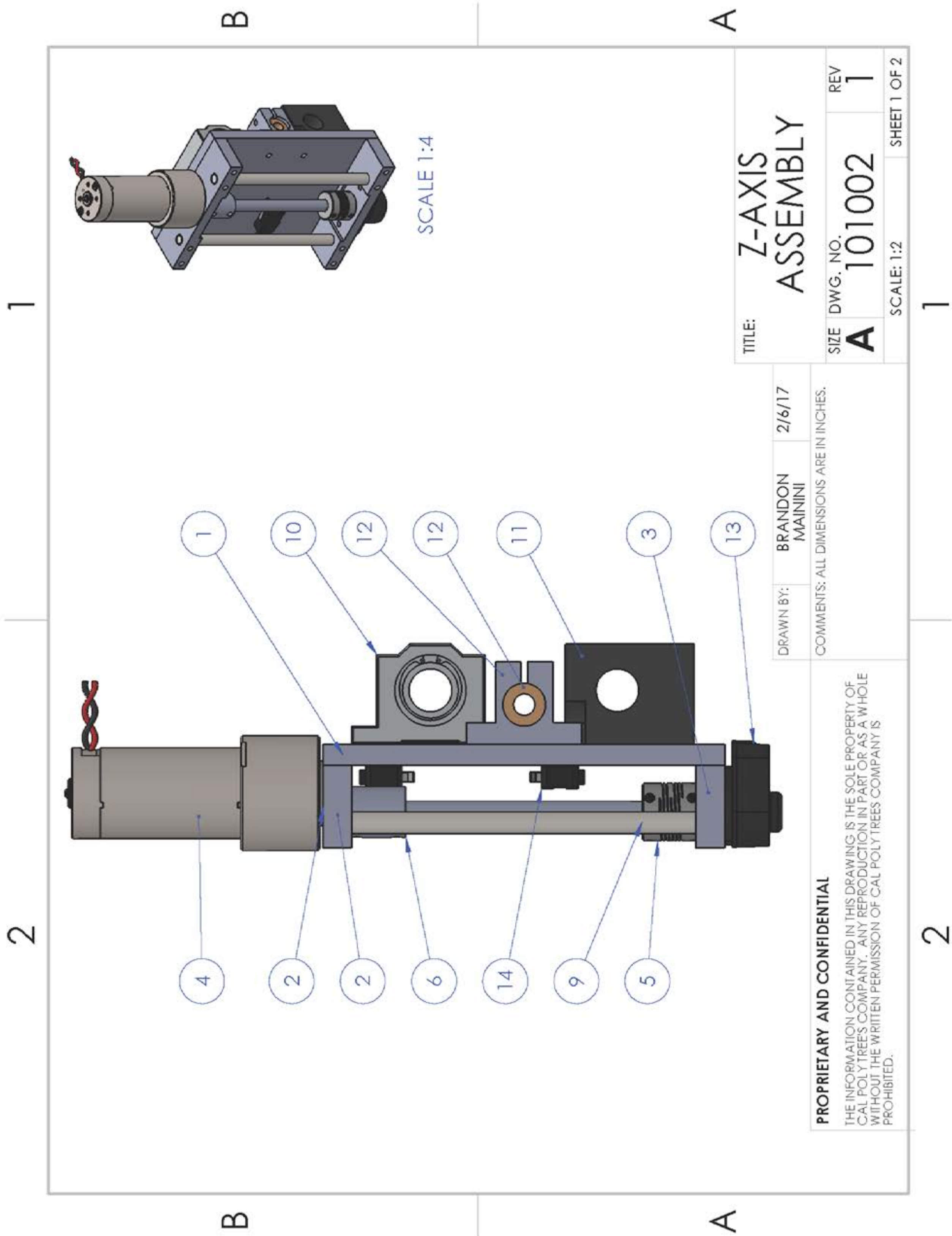


Figure C-29. Z-Axis Assembly Detail Drawing (Page 1 of 2)

ITEM NO.	PART NUMBER	VENDOR NUMBER	VENDOR	DESCRIPTION	QTY.
1	102053	--	--	Y-MODULE, BACKPLATE	1
2	102054	--	--	Y-MODULE, ENDPLATE, TOP	1
3	102055	--	--	Y-MODULE, ENDPLATE, BOTTOM	1
4	102063	GM9236S014-R1-SP	PITTMAN	PITTMAN DC GEARMOTOR, 2" FRAME SIZE	1
5	102065	9861T615	McMaster-Carr	HELICAL FLEXIBLE SHAFT COUPLING	1
6	--	--	--	GANTRY, SHAFT COUPLING, RIGID	1
7	102062	2938T2	McMaster-Carr	BRONZE FLANGE BUSHING, SAE 863, 1/4" ID, 3/8" L	2
8	102064	6061K103	McMaster-Carr	GUIDE ROD (Z-AXIS), 3/8" OD, 8 L	2
9	102061	60896	ROTON	ROTON LEAD SCREW, 3/8" - .125, 6 L	1
10	102067	9338T3	McMaster-Carr	LINEAR BALL BEARING, SEALED, PILLOW BLOCK, 3/4" ID	1
11	102057	P-405	McMaster-Carr	Y-MODULE, GUIDE ROD, BUSHING, DELRIN	1
12	102060	460-018	McMaster-Carr	SLEEVE NUT W/ HOUSING, 3/8"	1
13	102066	H5-32-NE-S	US DIGITAL	US DIGITAL INCREMENTAL SHAFT ENCODER	1
14	--	7779K63	--	MINI LIMIT SWITCH	2

DRAWN BY: BRANDON MAININI 2/6/17

COMMENTS: ALL DIMENSIONS ARE IN INCHES.

TITLE: Z-AXIS ASSEMBLY

SIZE A DWG. NO. 101002 REV 1

SCALE: 1:2 SHEET 2 OF 2

Figure C-30. Z-Axis Assembly Detail Drawing (Page 2 of 2)

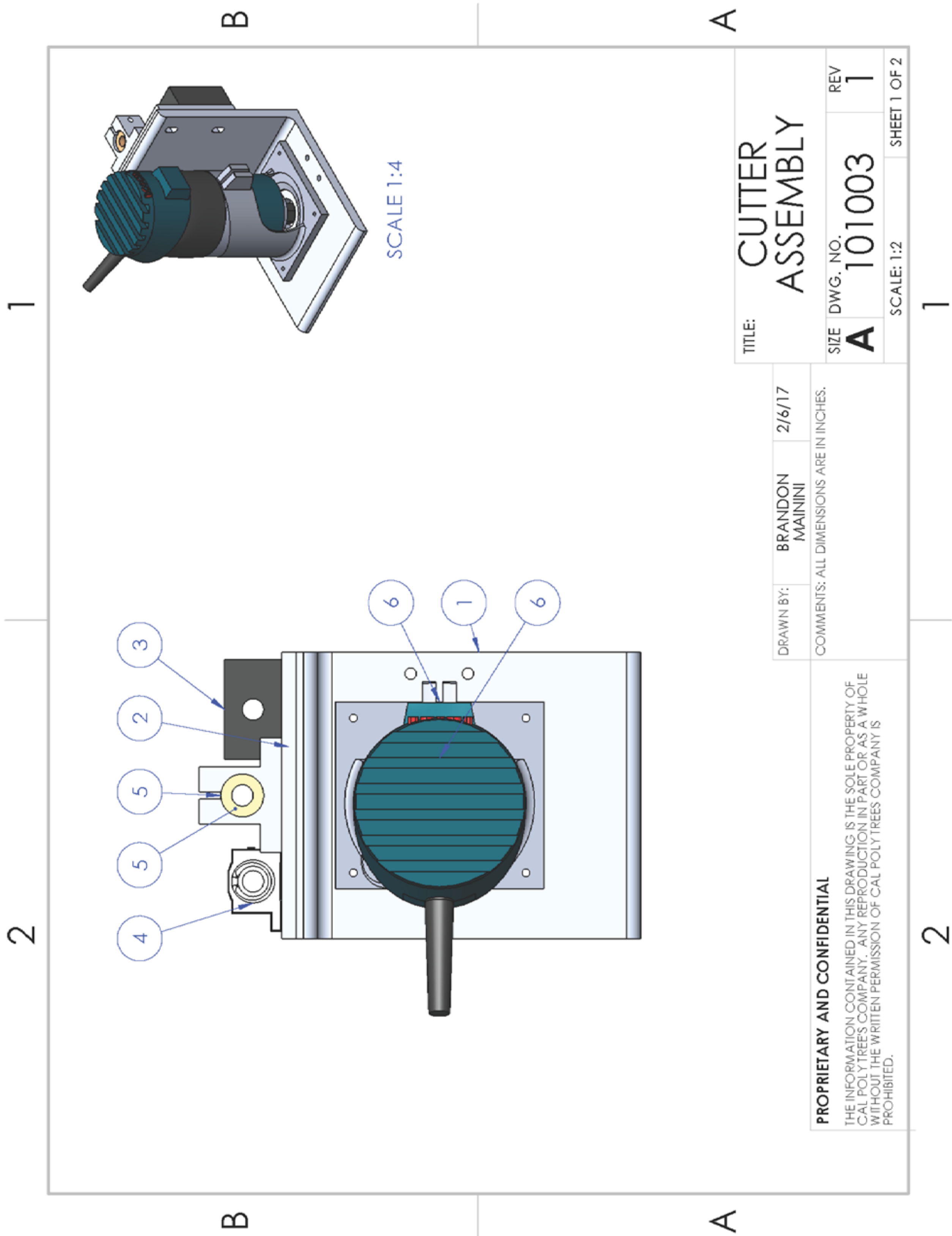


Figure C-31. Cutter Assembly Detail Drawing (Page 1 of 2)

ITEM NO.	PART NUMBER	PART NUMBER	VENDOR	DESCRIPTION	QTY.
1	102069	460-030	ONLINE METALS	Z-MODULE, ROUTER MOUNT, BRACKET	1
2	102070	461-033	ONLINE METALS	Z-MODULE, ROUTER MOUNT, ADAPTER	1
3	102072	--	--	Z-MODULE, GUIDE ROD, BUSHING, DELRIN	1
4	102077	6255K32	McMaster-Carr	LINEAR BALL BEARING, SEALED, PILLOW BLOCK, 3/8" ID	1
5	102075	460-018	McMaster-Carr	SLEEVE NUT W/ HOUSING, 3/8"	1
6	102076	PR20EVSK	HOME DEPOT	BOSCH COLT PALM ROUTER	1
7	--	90891	McMaster-Carr	ROUTER BIT, 1/4" SHANK, BALL TIP	1

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF CAL POLY TREE'S COMPANY. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF CAL POLY TREES COMPANY IS PROHIBITED.

DRAWN BY: BRANDON MAININI 2/6/17

COMMENTS: ALL DIMENSIONS ARE IN INCHES.

TITLE: CUTTER ASSEMBLY

SIZE A | DWG. NO. 101003 | REV 1

SCALE: 1:2 | SHEET 2 OF 2

Figure C-32. Cutter Assembly Detail Drawing (Page 2 of 2)

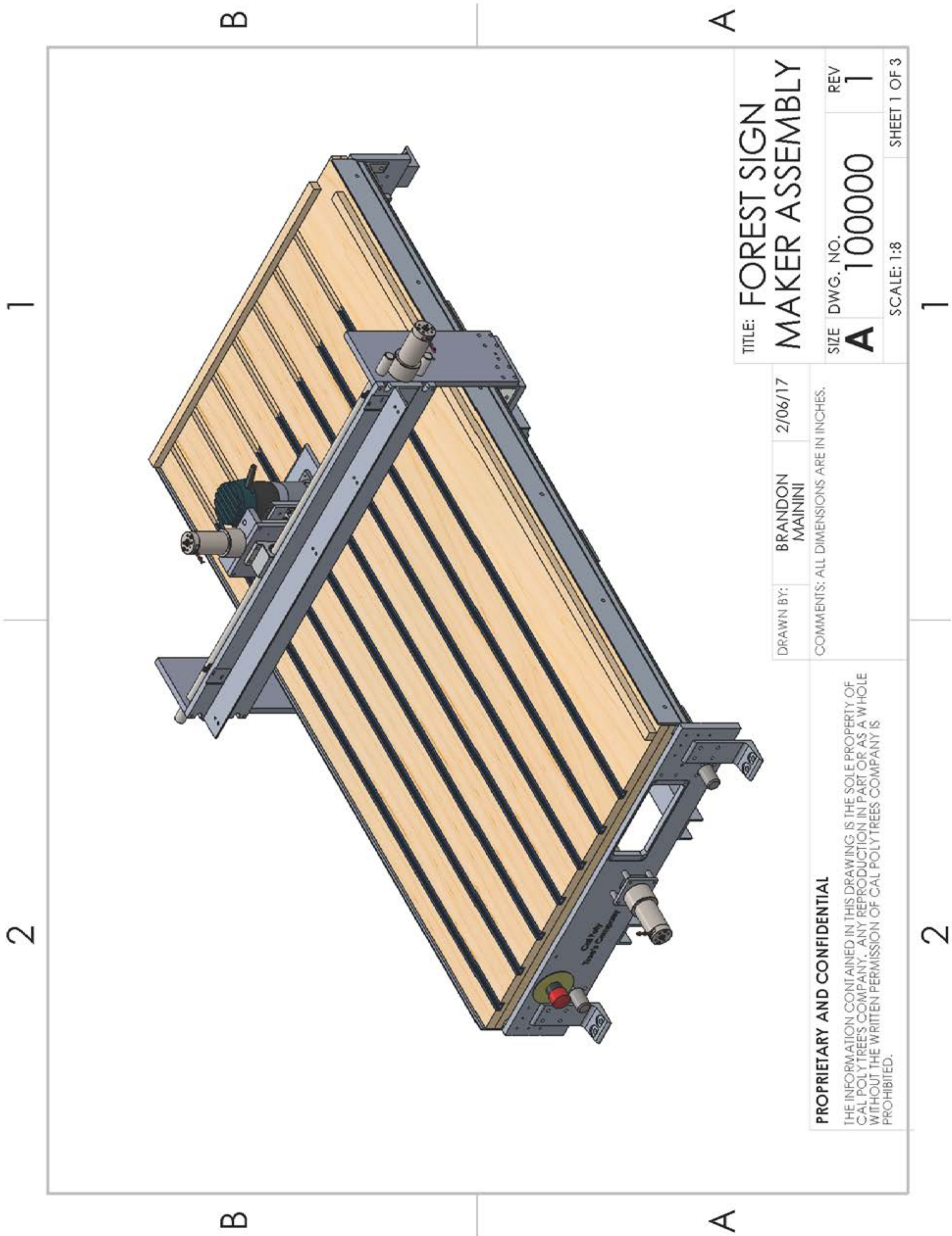


Figure C-33. Forest Sign Maker Assembly Detail Drawing (Page 1 of 3)

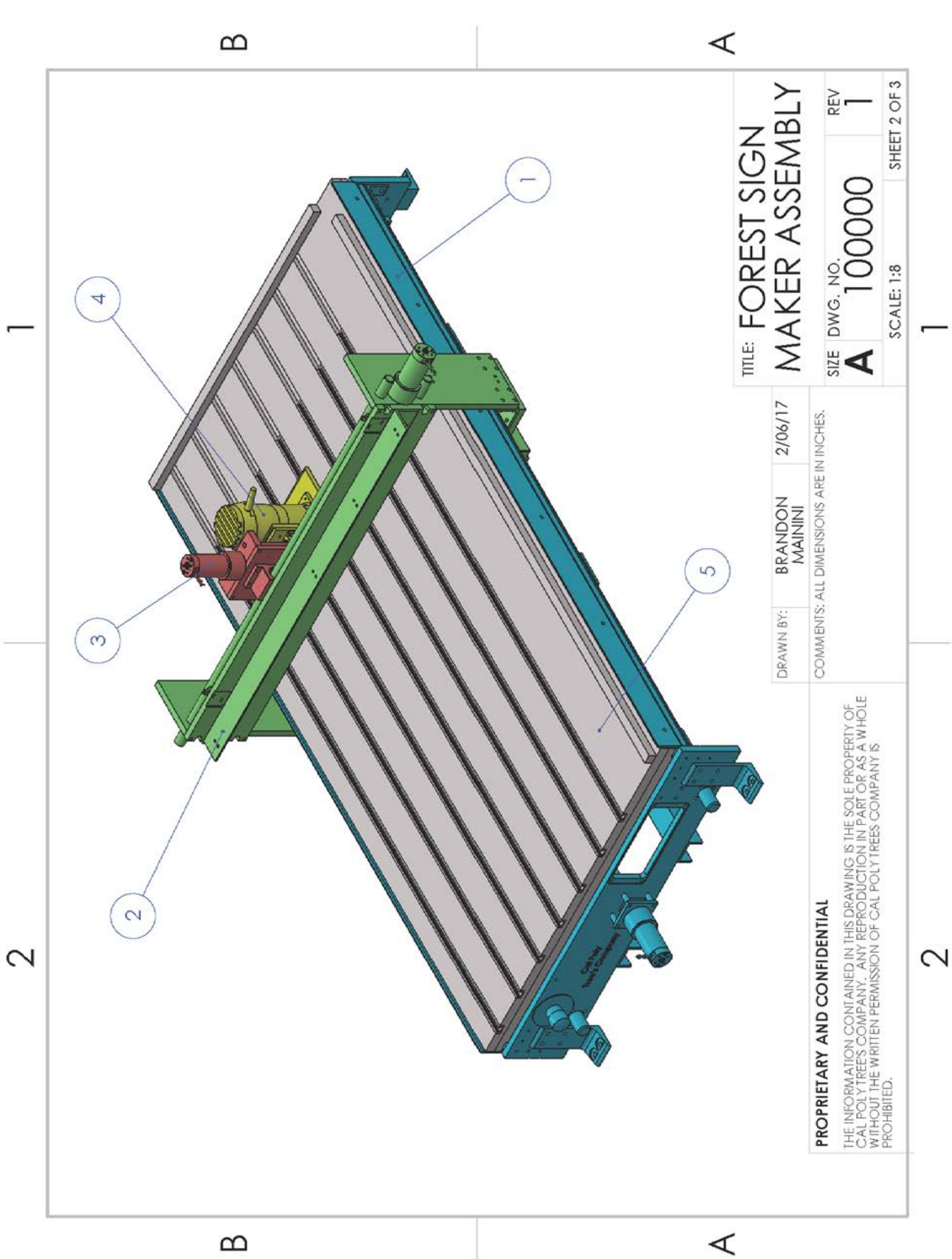


Figure C-34. Forest Sign Maker Assembly Detail Drawing (Page 2 of 3)

ITEM NUMBER	PART NUMBER	DESCRIPTION	QUANTITY
1	101000	X-AXIS ASSEMBLY	1
2	101001	Y-AXIS ASSEMBLY	1
3	101002	Z-AXIS ASSEMBLY	1
4	101003	CUTTER ASSEMBLY	1
5	101004	WORK SURFACE ASSEMBLY	1

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF CAL POLY TREE'S COMPANY. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF CAL POLY TREES COMPANY IS PROHIBITED.

DRAWN BY: BRANDON MAININI 2/06/17

COMMENTS: ALL DIMENSIONS ARE IN INCHES.

TITLE: FOREST SIGN MAKER ASSEMBLY

SIZE A DWG. NO. 100000 REV 1

SCALE: 1:8 SHEET 3 OF 3

Figure C-35. Forest Sign Maker Assembly Detail Drawing (Page 3 of 3)

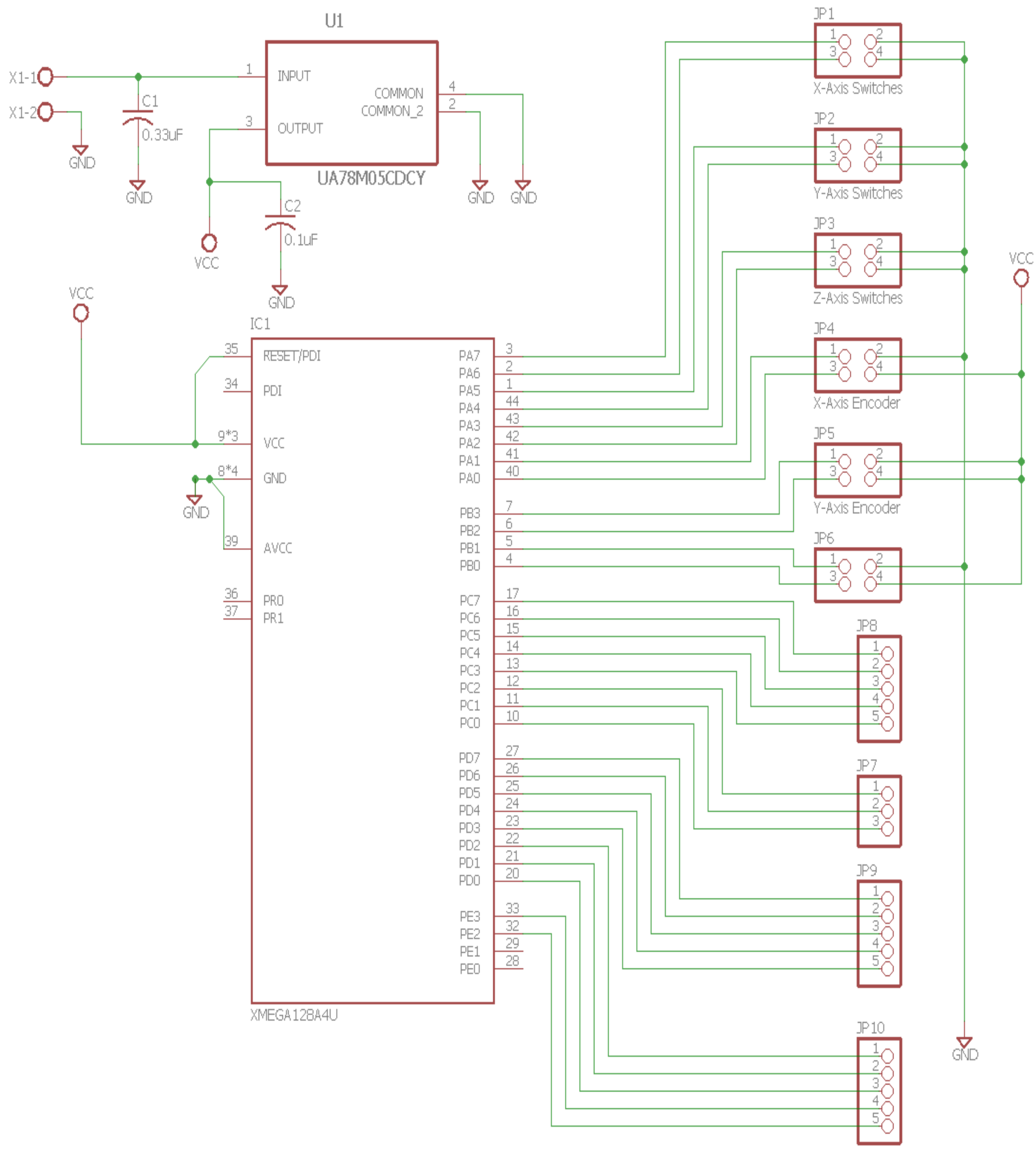


Figure C-36. System Controller Detail Drawing

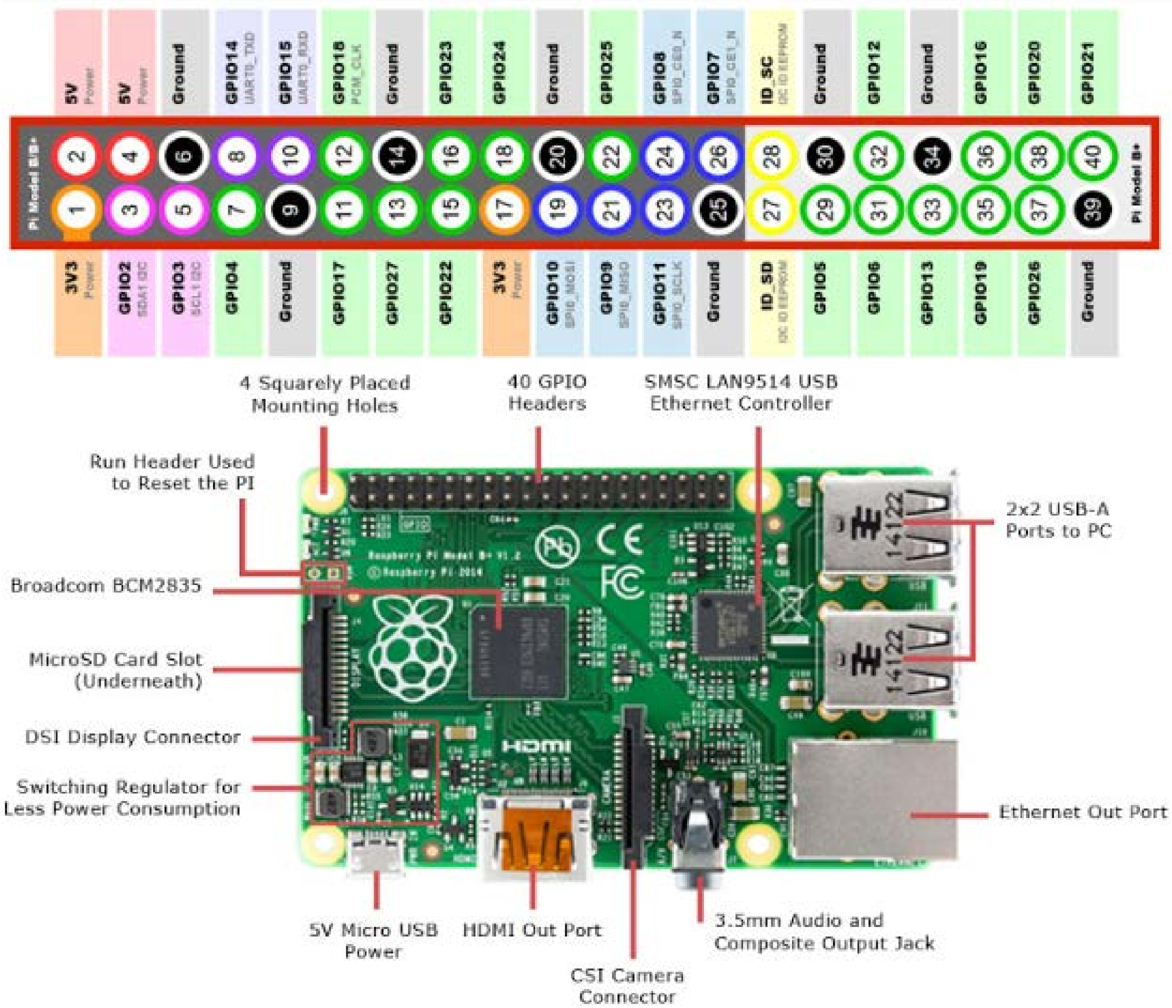


Figure C-37. GPIO Pinout diagram

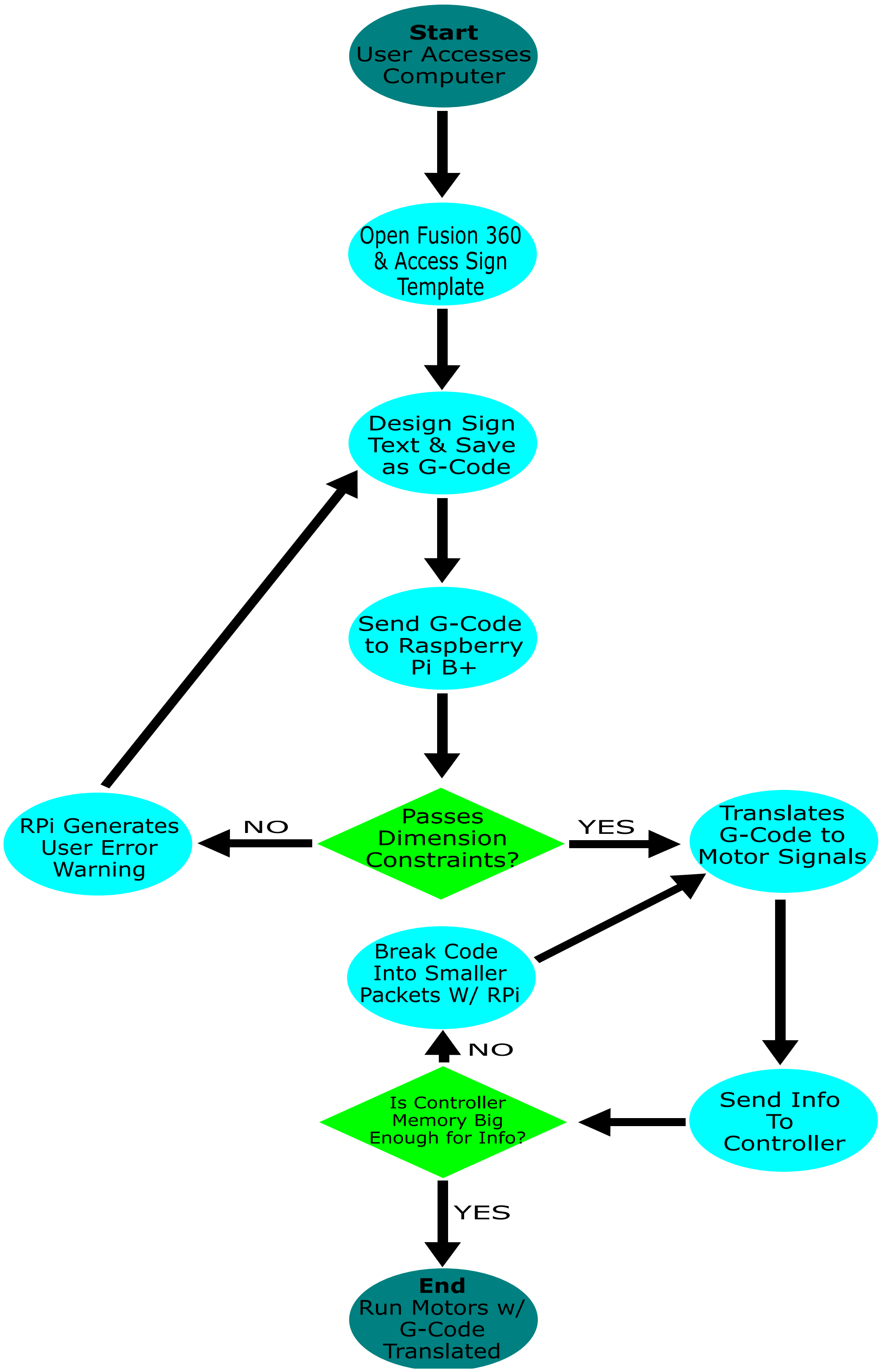


Figure C-38. Software Flow Diagram

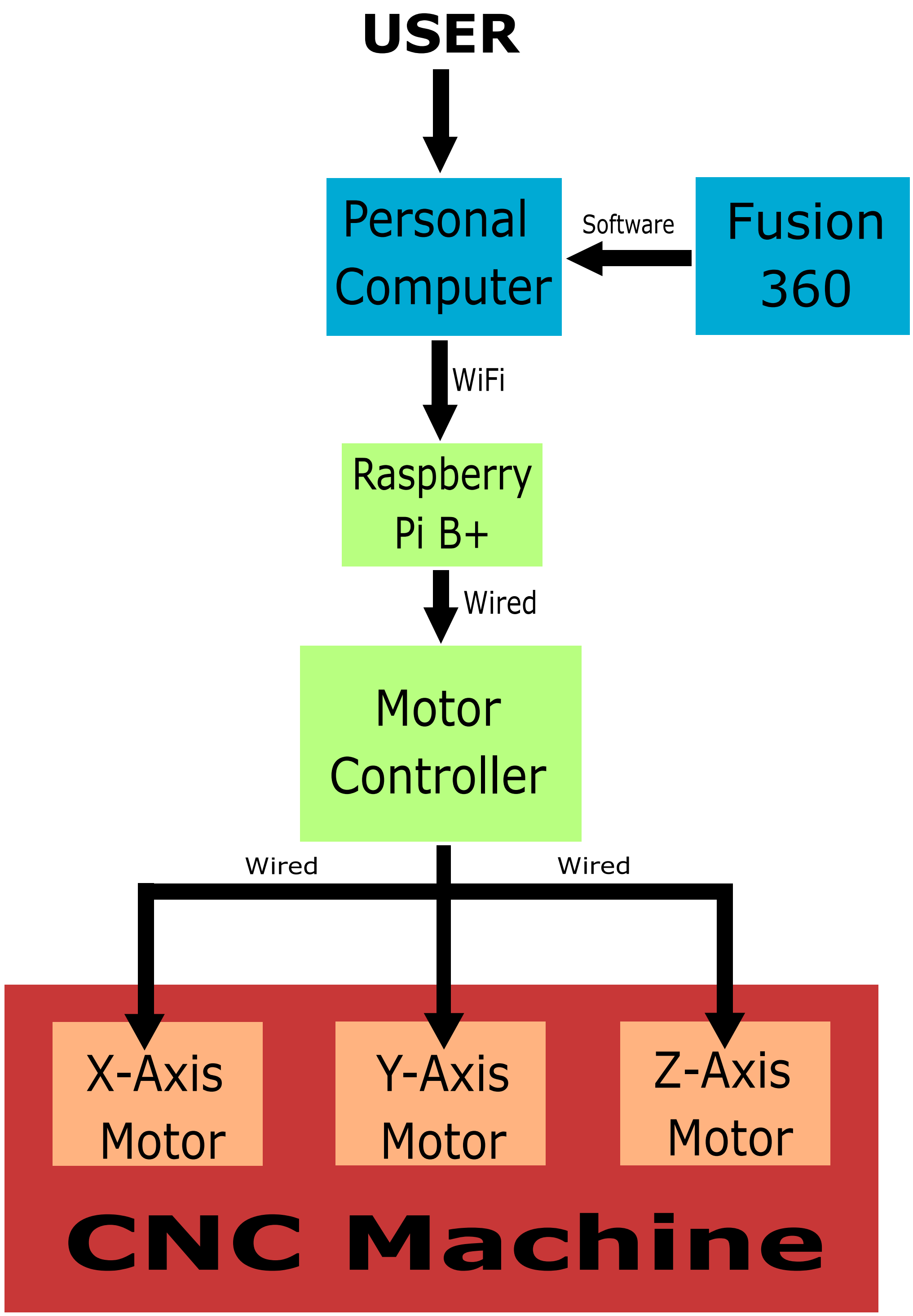


Figure C-39. User Interface Diagram

9.4. Appendix D: BOM and Cost Breakdown

Table D-1: Bill of Materials

No.	Assy Lvl	Part No.	Vendor PN	Assembly Level (0 1 2)	Vendor	Qty	Unit Cost	Total Cost
0	0	100 000		Forest Sign Maker Assembly				
1	1	101 000		X-Module ASSY				
2	2	102 001	--	Face Plate (Machined Panel, 6061, Flat Bar, 0.5"x5"x3')	OnlineMetals	1	$ 42.94	$ 42.94
3	2	102 002	--	End Plate (Machined Panel, 6061, Flat Bar, 0.5"x5"x4')	OnlineMetals	1	$ 50.90	$ 50.90
4	2	102 003	1630T47	Foundation Brace (U-Channel, 2" Base x 1-1/4" Legs)	McMaster-Carr	2	$ 32.47	$ 64.94
5	2	102 004	47065T311	Support Bracket (T-Slot Single Extrusion, 90° Bracket)	McMaster-Carr	8	$ 4.56	$ 36.48
6	2	102 005	47065T101	Framing Extrusion (Single Profile, 1" Size, Solid)	McMaster-Carr	2	$ 17.75	$ 35.50
7	2	102 006	8982K18	Foundation Stiffener (90 Degree Angle, 3/16" Thick, 2" x 2" Legs)	McMaster-Carr	2	$ 66.17	$ 132.34
8	2	102 007	--	Guide Rod Supports	McMaster-Carr	4	$ -	$ -
9	2	102 008	6061K85	X-Axis Guide Rod (Guide Rod, 1" OD, 60in CUT TO LENGTH)	McMaster-Carr	2	$ 73.67	$ 147.34
10	2	102 009	61422	X-Axis Lead Screw (ACME 1/2" - 8 TPI Lead Screw, 5' Long)	Roton	2	$ 44.60	$ 89.20
11	2	102 010	2342K184	End Plate Ball Bearing (Double Sealed, for 1/4" Shaft Diameter, 3/4" OD)	McMaster-Carr	1	$ 12.27	$ 12.27
12	2	102 011	2780T57	Face Plate Ball Bearing (Double Sealed, for 3/8" Shaft Diameter, 1-1/8" OD)	McMaster-Carr	3	$ 14.25	$ 42.75
13	2	102 012	--	Bearing Retainer	McMaster-Carr	2	$ -	$ -
14	2	102 013	92510A293	Motor Mount Spacer (3/8" OD, 13/16" Length, for Number 10 Screw Size)	McMaster-Carr	4	$ 1.27	$ 5.08
15	2	102 014	460-008	Motor Mount (6061 AL, Flat Bar, 0.25" x 2.5", Random Length)	OnlineMetals	1	$ 3.57	$ 3.57
16	2	102 015	47065T842	Mounting Feet (T-Slot 4-hole Floor Mounting Bracket, 1" T-Slot)	McMaster-Carr	4	$ 12.93	$ 51.72
17	2	102 016	47065T101	Horizontal Extrusion (Single Profile, 1" Size, Solid) (102005 SCRAPS)	McMaster-Carr	2	$ -	$ -
18	2	102 017	2424K11	Rigid Shaft Coupling (Aluminum Set Screw Rigid Shaft Coupling)	McMaster-Carr	1	$ 8.17	$ 8.17
19	2	102 018	GM9236S014-R1-SP	Pittman & Metek Motor (DC Gearmotor)	McMaster-Carr	1	$ 175.19	$ 175.19
20	2	102 019	47065T315	Aluminum Tee (Black Tee, 3" Long for 1" High Single Profile Aluminum T-Slotted Framing Extrusion)	McMaster-Carr	4	$ 12.74	$ 50.96
21	2	102 020	9861T826	Flexible Shaft Coupling (Set Screw, 1/2" x 1/4" Diameter Shaft, 1-1/4" Length)	McMaster-Carr	1	$ 49.62	$ 49.62
22	2	102 021	CC1758-ND	X-Axis Encoder (Incremental Shaft Encoder, 32 CPR)	USDigital	1	$ 92.95	$ 92.95
23	2	102 022	6741K410	Emergency Shutoff Switch (Pull to Reset, 1-1/4" Button Diameter, 1 Normally Closed Contact)	McMaster	1	$ 37.76	$ 37.76
24	2	102 023	6741K55	Emergency Shutoff Switch Panel	McMaster	1	$ 7.96	$ 7.96
25	2	102 024	91732A726	#10-32, Heli-Coil Thread Insert, .475L, Pack of 10	McMaster	1	$ 4.98	$ 4.98

26	2	102 025	92141A011			#10-32, Flat Washer, 18-8, Pack of 100	McMaster	1	$	2.33	$	2.33
27	2	102 026	91831A411			#10-32, Nylon-Insert Locknut, 18-8, Pack of 100	McMaster	1	$	6.28	$	6.28
28	2	102 027	90251A256			#10-32, Set Screw, Thread Locking Nylon Patch, 18-8, .375L, Pack of 25	McMaster	1	$	15.81	$	15.81
29	2	102 028	93705A266			#10-32, SHCP, Thread Locking Nylon Patch, 18-8, .75L, Pack of 25	McMaster	1	$	6.04	$	6.04
30	2	102 029	92141A029			1/4-20, Flat Washer, 18-8, Pack of 100	McMaster	1	$	3.37	$	3.37
31	2	102 030	91831A029			1/4-20, Nylon-Insert Locknut, 18-8, Pack of 50	McMaster	1	$	4.69	$	4.69
32	2	102 031	90251A535			1/4-20, Set Screw, Thread Locking Nylon Patch, 18-8, .375L, Pack of 10	McMaster	1	$	7.34	$	7.34
33	2	102 032	92196A542			1/4-20, Socket Head Cap Screw (SHCP), 18-8, 1"L, Pack of 50	McMaster	1	$	10.47	$	10.47
34	1	101 001			Y-Module ASSY							
35	2	102 033	--			Upper Bridge Member	--	1	$	-	$	-
36	2	102 034	--			Lower Bridge Member	--	1	$	-	$	-
37	2	102 035	--			Front Vertical Member	--	1	$	-	$	-
38	2	102 036	--			Back Vertical Member	--	1	$	-	$	-
39	2	102 037	--			Gantry Stiffener	--	1	$	-	$	-
40	2	102 038	--			Sleeve Nut Housing, 1/2"	--	1	$	-	$	-
41	2	102 039	91732A726			#10-32, Heli-Coil Thread Insert, .475L, Pack of 10	McMaster	2	$	4.98	$	9.96
42	2	102 040	93705A268			#10-32, SHCP, Thread Locking Nylon Patch, 18-8, 1.0L, Pack of 25	McMaster	2	$	6.46	$	12.92
43	2	102 041	92036			ACME 1/2" - 8 TPI Bronze Sleeve Nut	Roton	2	$	24.77	$	49.54
44	2	102 042	60896			ACME 3/8" - 8 TPI (STUB) ACME Lead Screw	Roton	3	$	8.58	$	25.74
45	2	102 043	2938T2			Bronze Flange Bearing, .25 ID, SAE 863 Super Oilite	McMaster	2	$	0.73	$	1.46
46	2	102 044	460-016			Cable Routing Shelf, 6061, Angle Bar, 2"x2"x0.1875", Length 3'	OnlineMetals	1	$	13.15	$	13.15
47	2	102 045	8975K52			Custom Bearing/Nut Housings, Aluminum Stock 1"x1.5"x2'	McMaster	1	$	27.95	$	27.95
48	2	102 046	9236S014-R1-SP			DC Gearmotor	Pittman	1	$	175.19	$	175.19
49	2	102 047	6061K64			Guide Rod, .75in OD, 36"L	McMaster	2	$	31.13	$	62.26
50	2	102 048	9861T615			Helical Flexible Shaft Coupling, 3/8" to 1/4"	McMaster	2	$	38.63	$	77.26
51	2	102 049				Horizontal Members, 6061, Flat Bar, 0.5"x5"x3'	OnlineMetals	2	$	42.94	$	85.88
52	2	102 050	H5-32-NE-S			Incremental Shaft Encoder, 32 CPR	USDigital	1	$	92.95	$	92.95
53	2	102 051	9338T110			Linear Bearings w/ Housing, 1" ID	McMaster	2	$	183.90	$	367.80
54	2	102 052	47065T176			Vertical Member Angle Bracket	McMaster	4	$	5.96	$	23.84
55	1	101 002			Z-Module ASSY							
56	2	102 053	--			Backplate	--	1	$	-	$	-
57	2	102 054	--			Top Support Plate	--	1	$	-	$	-

58	2	102 055	--			Bottom Support Plate	--	1	$ -	$ -
59	2	102 056	--			Sleeve Nut Housing, 3/8"	--	1	$ -	$ -
60	2	102 057	--			Delrin Sleeve Bushing, 3/4"	--	1	$ -	$ -
61	2	102 058	91732A725			#10-32, Heli-Coil Thread Insert, .380L, Pack of 10	McMaster	2	$ 4.32	$ 8.64
62	2	102 059	93705A266			#10-32, SHCP, Thread Locking Nylon Patch, 18-8, .75L, Pack of 25	McMaster	1	$ 6.04	$ 6.04
63	2	102 060	91248			ACME 3/8"x8 (STUB) Bronze Sleeve Nut	Roton	1	$ 24.98	$ 24.98
64	2	102 061	60896			ACME 3/8"x8 (STUB) Lead Screw, 12" Long	Roton	1	$ 8.58	$ 8.58
65	2	102 062	2938T2			Bronze Flange Bearing, .25 ID, SAE 863 Super Oilite	McMaster	2	$ 0.73	$ 1.46
66	2	102 063	9236S014-R1-SP			DC Gearmotor	Pittman	1	$ 175.19	$ 175.19
67	2	102 064	6061K102			Guide Rod, .375 OD, 8"L	McMaster	2	$ 4.60	$ 9.20
68	2	102 065	9861T615			Helical Flexible Shaft Coupling, 3/8" to 1/4"	McMaster	2	$ 38.63	$ 77.26
69	2	102 066	H5-32-NE-S			Incremental Shaft Encoder, 32 CPR	USDigital	1	$ 92.95	$ 92.95
70	2	102 067	9338T3			Linear Bearings w/ Housing, .75" ID	McMaster	2	$ 66.60	$ 133.20
71	2	102 068	460-017			Vertical Mounting Plate, 6061, Flat Bar, 0.375"x5", Random Length (10-12")	OnlineMetals	1	$ 10.71	$ 10.71
72	1	101 003			Cutter ASSY			1		
73	2	102 069	--			Router Mount Angle Bar	--	1	$ -	$ -
74	2	102 070	--			Router Mount Adapter Plate	--	1	$ -	$ -
75	2	102 071	--			Vacuum Angle Bracket	--	1	$ -	$ -
76	2	102 072	--			Delrin Sleeve Bushing, 3/8"	--	1	$ -	$ -
77	2	102 073	--			Vacuum Tubing	--	1	$ -	$ -
78	2	102 074	93705A266			#10-32, SHCP, Thread Locking Nylon Patch, 18-8, .75L, Pack of 25	McMaster	1	$ 6.04	$ 6.04
79	2	102 075	91248			ACME 3/8"x8 (STUB) Bronze Sleeve Nut	Roton	1	$ 24.98	$ 24.98
80	2	102 076	--			Bosch Colt Router	Home Depot	1	$ 102.48	$ 102.48
81	2	102 077	6255K32			Linear Bearings w/ Housing, .375" ID	McMaster	2	$ 42.02	$ 84.04
82	2	102 078	--			PVC, Pipe Size 2in, 2 ft.	Home Depot	1	$ 4.32	$ 4.32
83	2	102 079	--			PVC, Pipe Size 2in, 90° Elbow	Home Depot	1	$ 0.95	$ 0.95
84	2	102 080	--			PVC, Pipe Size 2in, 45° Elbow	McMaster	1	$ 2.14	$ 2.14
85	2	102 081	460-030			Router Mount, 6061, Angle Bar, 6"x6"x.375", Random Length (10-12")	OnlineMetals	1	$ 26.68	$ 26.68
86	2	102 082	461-033			Adapter Plate, 6061 AL, Flat Bar, 0.25" x 5", Random Length (10-12")	OnlineMetals	1	$ 7.14	$ 7.14
87	1	101 004			Work Surface ASSY					
88	2	102 083	*460-001*			Maple Board, 1 x 8 x 6'	Home Depot	4	$ 5.47	$ 21.88
89	2	102 084	*460-007*			Poplar Board, 1 x 8 x 6'	Home Depot	4	$ 8.87	$ 35.48

90	2	102 085	*460-005, 460-006*			Hard Stop Strips, 5/8" x 3/4" x R/L	Home Depot	10	$ 0.97	$ 9.70
91	2	102 086	24063			17-piece Universal T-Track Kit	Rockler	1	$ 31.99	$ 31.99
92	2	102 087	20054			Rockler 4 ft. Universal T-Track	Rockler	6	$ 25.99	$ 155.94
93	2	102 088	53685			Rockler Small Featherboard	Rockler	1	$ 16.99	$ 16.99
94	2	102 089	--			Scrap maple and high-density rubber, for clamps		2	$ -	$ -
95	1	101 005			User Interface ASSY					
96	2	102 090	--			Fusion 360	AutoDesk	1	$ -	$ -
97	2	102 091	PSKVUU-00S01U			Satellite L15W Laptop	Toshiba	1	$ -	$ -
98	2	102 092	MSIP-CMM-P2R-RPI32			Raspberry Pi B+	Raspberry Pi Foundation	1	$ 31.94	$ 31.94
99	1	101 006			Control Systems ASSY					
100	2	102 093				9 square inch PCB (2 layer, 3 boards, 1 oz copper, 1.6mm thickness)	Osh Park	1	$ 45.00	$ 45.00
101	2	102 094	595-UA78M33CDCYR			Linear Voltage Regulators 3.3V 500mA Fixd Pos	Texas Instruments	1	$ 0.55	$ 0.55
102	2	102 095	81-GRM188R71A334KA1D			Multilayer Ceramic Capacitors MLCC - SMD/SMT 0.33uF 10Volts X7R 10%	Murata	1	$ 0.18	$ 0.18
103	2	102 096	81-GRM188R70J104KA1D			Multilayer Ceramic Capacitors MLCC - SMD/SMT 0.1uF 6.3Volts X7R 10%	Murata	1	$ 0.10	$ 0.10
104	2	102 097	556-ATXMEGA128A4U-AU			8-bit Microcontrollers - MCU 44TQFP, IND TEMP GREEN, 1.6-3.6V	Microchip	1	$ 4.82	$ 4.82
105	2	102 098	485-392			Headers & Wire Housings 36-pin Male Header Breakaway 10 pieces	Adafruit	1	$ 4.95	$ 4.95
106	2	102 099	571-1-2834019-2			Fixed Terminal Blocks 2POS 3.5MM THTS CONN	TE Connectivity	1	$ 0.30	$ 0.30
107	2	102 100	1451			VNH5019 Motor Driver Carrier	Pololu	3	$ 24.95	$ 74.85
108	2	102 101								

9.5. Appendix E: CDR Revision Locations

The following list provides all the sections that have received revisions from the PDR:

1.1.1 Objective

2.3.1. Components

2.7.2 Vibration Isolation

3.1.3 Programming

3.2 Specifications

3.3.7 How Much

4.2.2 User Interface

4.2.9 Safety

4.3.3 Micro-Controller

4.3.5 Actuation

4.3.6 Tensioners

4.4.1 User Interface

4.4.2 Motor Controller

4.6 Design Safety Hazard Identification Checklist

6.2 Gantt Chart

(Additions to 8.2 Unique References)

9.6. Appendix F: Sample Calculations

The following sample calculations, provided by Victor Espinosa, a previous member of the team, were used to determine the size of the system's guide rods to ensure structural rigidity.

Guide Rod Sizing	**ENGR-460**	**Victor Espinosa**

Problem

The Forest Sign Maker design has progressed sufficiently in SolidWorks in order to yield accurate estimations of the guide rod lengths for all three axes of motion. These lengths are $L_x = 56\ in$, $L_y = 32\ in$, $L_z = 7\ in$, rounded up to the nearest integer for simplicity and to maintain a conservative design. The corresponding subassemblies are attached to the hardened steel guide rods via pillow block mounted linear ball bearings. The guide rods must also be stiff enough to resist sag and maintain router accuracy, hence a maximum rod deflection of $\delta = 0.125\ in$.

Schematic

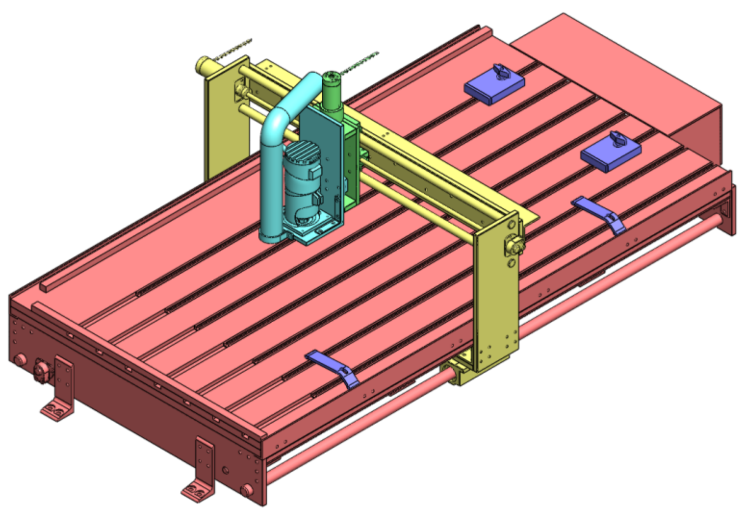


Figure 1. Subassembly layout of the Forest Sign Maker. The foundation is red, the gantry is yellow, the module is green, and the cutter is blue. The foundation controls the x-axis motion, the gantry controls the y-axis motion, and the module controls the z-axis motion.

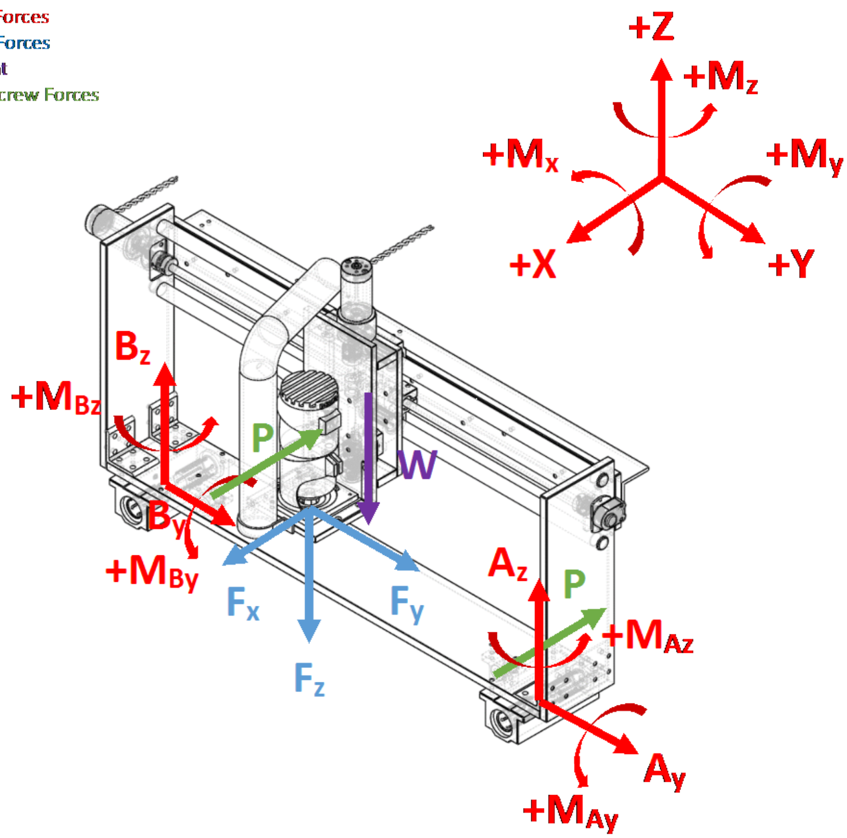
Assumptions (All Axes of Motion)

1. Weight and tension of vacuum hose is negligible and does not load the guide rod or bearings.
2. The cutting resistive force, F, exerted on the router bit can be modeled as a static load.
3. F_{max} through regular grain is $15\ lb_f$.
4. F is directly proportional to grain density
5. Knots in softwood are comparable in density with hardwood, which is approximately $5x$ denser than softwood.
6. F_{max} through knots is $75\ lb_f$.
7. F_{max} can be exerted on all axes at once as worst case scenario.
8. The lead screw nuts completely resist axial forces on their respective subassembly.
9. Guide rod supports are fixed-fixed since they are fastened in the AL plate via set screws.

Figure F-1. Calculation Assumptions

Free Body Diagram – X-Axis Motion

Red = Bearing Forces
Blue = Cutting Forces
Purple = Weight
Green = Lead Screw Forces



Analysis

See the attached Engineering Equation Solver (EES) file for the analysis required to determine the appropriate design X-Axis guide rod diameter, D_x.

Results

After running the EES simulation, the design guide rod diameter for the x-axis came out to be $D_x = 0.83$ *in*. However, it is unreasonable to design the system for a shaft diameter of that size because that is not a standard hardened steel shaft size. To maintain a conservative factor of safety, an x-axis guide rod diameter of $D_x = 1.0$ *in* will be used.

Figure F-2. X-Axis Calculation (Page 1 of 4)

Cal Poly Forest Friends
Victor Espinosa
Appendix F

X-Axis Guide Rod Diameter Sizing

Static analysis parameters extracted from SolidWorks.
The cutting forces were approximated using studies posted in the peer-reviewed journal BioResources.

The objective is to use statics and deflection limits to size the diameter of the rod.

Forces

$F_x = 75$ [lbf]

$F_y = 75$ [lbf]

$F_z = 75$ [lbf]

Weights

$W_{gantry} = 50$ [lbf]

$W_x = 12$ [lbf]

Lengths (Mirrored, so $L_{AF} = L_{BF}$)

$L_x = 56$ [in]

$L_{AB,y} = 27.125$ [in]

$L_{AF,x} = 3.5$ [in]

$L_{AF,y} = \frac{L_{AB,y}}{2}$ *[in]*

$L_{AF,z} = 7$ [in]

$L_{AW,y} = L_{AF,y}$ *[in]*

Newton's Second Law of Motion - Solve for reaction forces acting on guide rod.

Forces in the X-Axis

$F_{x,net} = 0$

$F_{x,net} = F_x + P + P$

Moment about the X-Axis at Point A

$M_{A,x,net} = 0$

$M_{A,x,net} = L_{AF,y} \cdot F_z + L_{AW,y} \cdot W_{gantry} - L_{AB,y} \cdot B_z - L_{AF,z} \cdot F_y$

Moment about the X-Axis at Point B

Figure F-3. X-Axis Calculation (Page 2 of 4)

$M_{B,x,net} = 0$

$M_{B,x,net} = L_{AB,y} \cdot A_z - L_{AF,y} \cdot F_z - L_{AW,y} \cdot W_{gantry} - L_{AF,z} \cdot F_y$

Forces in the Y-Axis

$F_{y,net} = 0$

$F_{y,net} = F_y + A_y + B_y$

$A_y = B_y$

Moment about the Y-Axis at Point A

$M_{A,y,net} = 0$

$M_{A,y,net} = M_{A,y} + M_{B,y} + L_{AF,z} \cdot F_x + L_{AF,x} \cdot F_z$

$M_{A,y} = M_{B,y}$

Moment about the Z-Axis at Point A

$M_{A,z,net} = 0$

$M_{A,z,net} = M_{A,z} + M_{B,z} + L_{AF,x} \cdot F_y + L_{AF,y} \cdot F_x$

$M_{A,z} = M_{B,z}$

Maximum Radial Force on X-Axis Guide Rod

$R_A = \sqrt{A_y^2 + A_z^2}$

$R_B = \sqrt{B_y^2 + B_z^2}$

$R_{max} = \text{Max}\left(R_A, R_B\right)$

Maximum Moment Normal to X-Axis Guide Rod

$M_{max} = \text{Max}\left(\left|M_{A,y}\right|, \left|M_{A,z}\right|\right)$

Stiffness Calculations (Max Deflection cannot exceed 0.125in)

Maximum Deflection due to radial load and weight

$E_{steel} = 3 \times 10^7$ [lbf/in²]

$\delta = 0.125$ [in]

$$\delta = \left[\frac{R_{max}}{192} + \frac{W_x}{384}\right] \cdot \frac{\frac{L_x^3}{E_{steel}}}{\pi \cdot \frac{D_x^4}{64}}$$

Figure F-4. X-Axis Calculation (Page 3 of 4)

File:GuideRodSizing_X.EES 2/15/2015 3:22:06 PM Page 3

EES Ver. 9.699: #552: For use by Mech. Engin. Students and Faculty at Cal Poly

SOLUTION

Unit Settings: Eng F psia mass deg

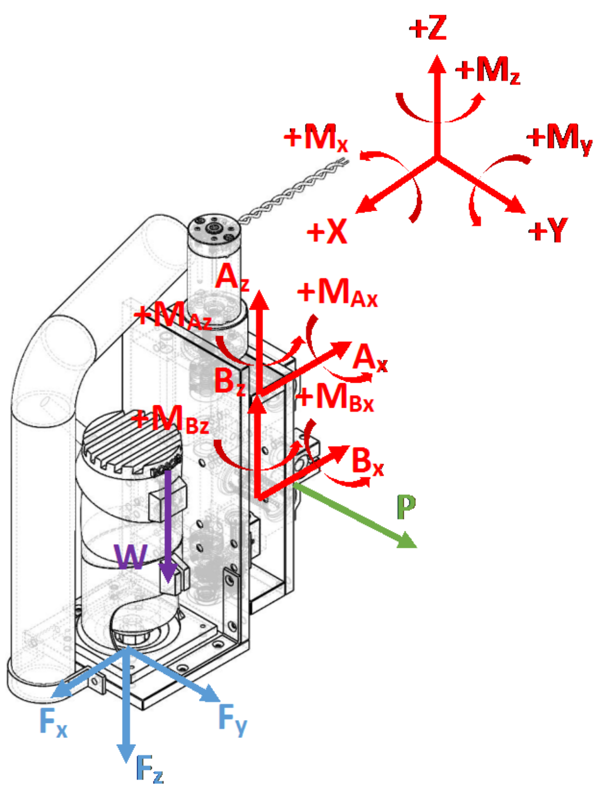
A_y = -37.5 [lbf]	A_z = 81.85 [lbf]
B_y = -37.5 [lbf]	B_z = 43.15 [lbf]
δ = 0.125 [in]	D_x = 0.8311 [in]
E_{steel} = 3.000E+07 [lbf/in^2]	F_x = 75 [lbf]
$F_{x,net}$ = 0 [lbf]	F_y = 75 [lbf]
$F_{y,net}$ = 0 [lbf]	F_z = 75 [lbf]
$L_{AB,y}$ = 27.13 [in]	$L_{AF,x}$ = 3.5 [in]
$L_{AF,y}$ = 13.56 [in]	$L_{AF,z}$ = 7 [in]
$L_{AW,y}$ = 13.56 [in]	L_x = 56 [in]
$M_{A,x,net}$ = 0 [in-lbf]	$M_{A,y}$ = -393.7 [in-lbf]
$M_{A,y,net}$ = 0 [in-lbf]	$M_{A,z}$ = -639.8 [in-lbf]
$M_{A,z,net}$ = 0 [in-lbf]	$M_{B,x,net}$ = 0 [in-lbf]
$M_{B,y}$ = -393.7 [in-lbf]	$M_{B,z}$ = -639.8 [in-lbf]
M_{max} = 639.8 [in-lbf]	P = -37.5 [lbf]
R_A = 90.04 [lbf]	R_B = 57.16 [lbf]
R_{max} = 90.04 [lbf]	W_{gantry} = 50 [lbf]
W_x = 12 [lbf]	

No unit problems were detected.

Figure F-5. X-Axis Calculation (Page 4 of 4)

Free Body Diagram – Y-Axis Motion

Red = Bearing Forces
Blue = Cutting Forces
Purple = Weight
Green = Lead Screw Forces



Analysis

Refer to the following EES file for the analysis required to determine the appropriate design Y-Axis guide rod diameter, D_y.

Results

After running the EES simulation, the design guide rod diameter for the x-axis came out to be $D_y = 0.49$ *in*, which is very close to the standard size of ½". However, to maintain a conservative factor of safety, a y-axis guide rod diameter of $Dy = 0.75$ *in* will be used.

Figure F-6. Y-Axis Calculation (Page 1 of 3)

Cal Poly Forest Friends
Victor Espinosa
Appendix F

Y-Axis Guide Rod Diameter Sizing

Static analysis parameters extracted from SolidWorks.
The cutting forces were approximated using studies posted in the peer-reviewed journal BioResources.

The objective is to use statics and deflection limits to size the diameter of the rod.

Forces

$F_x = 75$ [lbf]

$F_y = 75$ [lbf]

$F_z = 75$ [lbf]

Weights

$W_{module} = 12$ [lbf]

$W_y = 4.1$ [lbf]

Lengths

$L_y = 32$ [in]

$L_{AB,z} = 4$ [in]

$L_{AF,x} = 5$ [in]

$L_{AF,z} = 8$ [in]

$L_{BF,z} = L_{AF,z} - L_{AB,z}$

$L_{AW,x} = 2.8$ [in]

Newton's Second Law of Motion - Solve for reaction forces acting on guide rod.

Forces in the X-Axis

$F_{x,net} = 0$

$F_{x,net} = F_x - A_x - B_x$

Moment about the Y-Axis at Point A

$M_{A,y,net} = 0$

$M_{A,y,net} = L_{AW,x} \cdot W_{module} + L_{AF,x} \cdot F_z - L_{AF,z} \cdot F_x + L_{AB,z} \cdot B_x$

Forces in the X-Axis

Figure F-7. Y-Axis Calculation (Page 2 of 3)

$F_{y,net} = 0$

$F_{y,net} = P + F_y$

Forces in the Z-Axis

$F_{z,net} = 0$

$F_{z,net} = A_z + B_z - F_z$

$A_z = B_z$

Maximum Radial Force on X-Axis Guide Rod

$R_A = \sqrt{A_x^2 + A_z^2}$

$R_B = \sqrt{B_x^2 + B_z^2}$

$R_{max} = \text{Max}\left[R_A, R_B\right]$

Stiffness Calculations (Max Deflection cannot exceed 0.125in)

Maximum Deflection due to radial load and weight

$E_{steel} = 3 \times 10^7$ [lbf/in^2]

$\delta = 0.125$ [in]

$$\delta = \left[\frac{R_{max}}{192} + \frac{W_y}{384}\right] \cdot \frac{\frac{L_y^3}{E_{steel}}}{\pi \cdot \frac{D_y^4}{64}}$$

SOLUTION

Unit Settings: Eng F psia mass deg

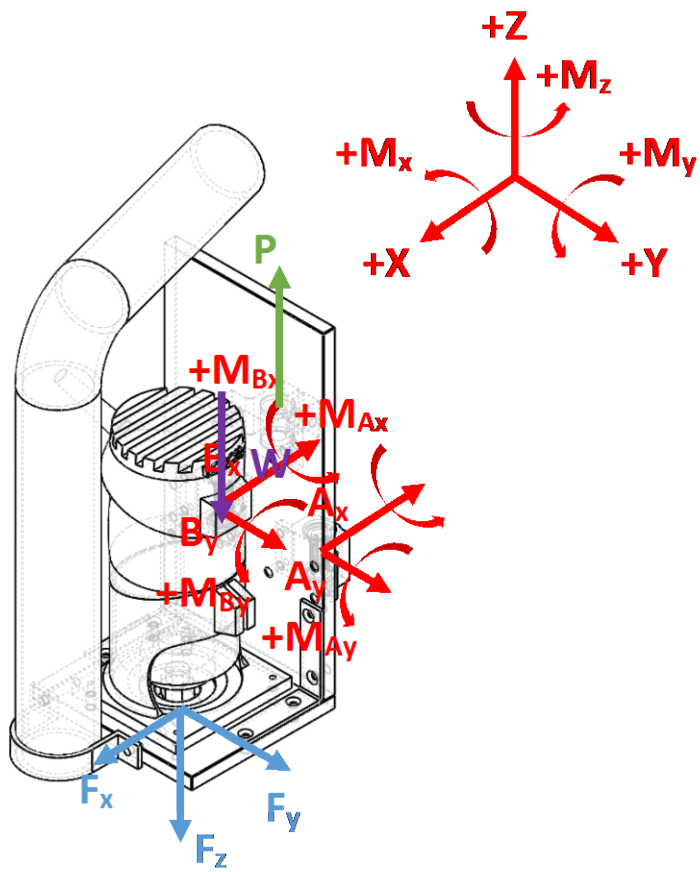
A_x = 27.15 [lbf]	A_z = 37.5 [lbf]
B_x = 47.85 [lbf]	B_z = 37.5 [lbf]
δ = 0.125 [in]	D_y = 0.4913 [in]
E_{steel} = 3.000E+07 [lbf/in^2]	F_x = 75 [lbf]
$F_{x,net}$ = 0 [lbf]	F_y = 75 [lbf]
$F_{y,net}$ = 0 [lbf]	F_z = 75 [lbf]
$F_{z,net}$ = 0 [lbf]	$L_{AB,z}$ = 4 [in]
$L_{AF,x}$ = 5 [in]	$L_{AF,z}$ = 8 [in]
$L_{AW,x}$ = 2.8 [in]	$L_{BF,z}$ = 4 [in]
L_y = 32 [in]	$M_{A,y,net}$ = 0 [in-lbf]
P = -75 [lbf]	R_A = 46.3 [lbf]
R_B = 60.79 [lbf]	R_{max} = 60.79 [lbf]
W_{module} = 12 [lbf]	W_y = 4.1 [lbf]

No unit problems were detected.

Figure F-8. Y-Axis Calculation (Page 3 of 3)

Free Body Diagram – Z-Axis Motion

Red = Bearing Forces
Blue = Cutting Forces
Purple = Weight
Green = Lead Screw Forces



Analysis
See the attached Engineering Equation Solver (EES) file for the analysis required to determine the appropriate design Z-Axis guide rod diameter, D_z.

Results
After running the EES simulation, the design guide rod diameter for the x-axis came out to be $D_z = 0.17$ *in*, which is very close to the standard size of 3/16". However, to maintain a conservative factor of safety, a y-axis guide rod diameter of $D_z = 0.375$ *in* will be used.

Figure F-9. Z-Axis Calculation (Page 1 of 3)

File:GuideRodSizing_Z.EES 2/15/2015 4:35:53 PM Page 1
EES Ver. 9.699: #552: For use by Mech. Engin. Students and Faculty at Cal Poly

Cal Poly Forest Friends
Victor Espinosa
Appendix F

Z-Axis Guide Rod Diameter Sizing

Static analysis parameters extracted from SolidWorks.
The cutting forces were approximated using studies posted in the peer-reviewed journal BioResources.

The objective is to use statics and deflection limits to size the diameter of the rod.

Forces

$F_x = 75$ [lbf]

$F_y = 75$ [lbf]

$F_z = 75$ [lbf]

Lengths

$L_z = 7$ [in]

$L_{AB,y} = 3$ [in]

$L_{AF,x} = 2.75$ [in]

Newton's Second Law of Motion - Solve for reaction forces acting on guide rod.

Forces in the X-Axis

$F_{x,net} = 0$

$F_{x,net} = F_x - A_x - B_x$

Moment about the Z-Axis at Point A

$M_{A,z,net} = 0$

$M_{A,z,net} = -L_{AB,y} \cdot B_x + L_{AF,x} \cdot F_y$

Forces in the Y-Axis

$F_{y,net} = 0$

$F_{y,net} = F_y - A_y - B_y$

$A_y = B_y$

Maximum Radial Force on X-Axis Guide Rod

$R_A = \sqrt{A_x^2 + A_y^2}$

$R_B = \sqrt{B_x^2 + B_y^2}$

Figure F-10. Z-Axis Calculation (Page 2 of 3)

$R_{max} = \mathbf{Max}\left[R_A , R_B\right]$

Stiffness Calculations (Max Deflection cannot exceed 0.125in)

Maximum Deflection due to radial load and weight

$E_{steel} = 3 \times 10^{7}$ [lbf/in^2]

$\delta = 0.125$ [in]

$$\delta = R_{max} \cdot \frac{\frac{L_z^{\ 3}}{192 \cdot E_{steel}}}{\pi \cdot \frac{D_z^{\ 4}}{64}}$$

SOLUTION

Unit Settings: Eng F psia mass deg

A_x = 6.25 [lbf]	A_y = 37.5 [lbf]
B_x = 68.75 [lbf]	B_y = 37.5 [lbf]
δ = 0.125 [in]	D_z = 0.166 [in]
E_{steel} = 3.000E+07 [lbf/in^2]	F_x = 75 [lbf]
$F_{x,net}$ = 0 [lbf]	F_y = 75 [lbf]
$F_{y,net}$ = 0 [lbf]	F_z = 75 [lbf]
$L_{AB,y}$ = 3 [in]	$L_{AF,x}$ = 2.75 [in]
L_z = 7 [in]	$M_{A,z,net}$ = 0 [in-lbf]
R_A = 38.02 [lbf]	R_B = 78.31 [lbf]
R_{max} = 78.31 [lbf]	

No unit problems were detected.

Figure F-11. Z-Axis Calculation (Page 3 of 3)

The following set of calculations is to determine an adequate motor for the Forest Sign Maker.

MOTOR SELECTION

Problem

It has been determined that a DC motor coupled to a gearbox will be the power source for the lead screw systems. In order to meet the performance requirements defined by the sponsor of the Forest Sign Maker, the DC motors that are selected must provide adequate continuous torque output at the desired feed speed velocity. The motor power dissipation must be determined as to facilitate motor driver selection. Since all three axes of motion use the same motor and lead screw configuration, the following analysis will use the x-axis as an example, see the schematic below. Finally, it is widely known that DC motors run most efficiently at high RPMs, however, the lead screws on the Forest Sign Maker should not rotate at such velocities. It is anticipated that a gearbox will be required, so motor selection will be limited to DC gearmotors. The gear ratio will be a result of motor selection, not design.

Given

Lead Screw

ated assuming the guide rods were not present.

Figure F-12. Motor Selection Calculation (Page 1 of 3)

Free Body Diagram and Kinetic Diagram

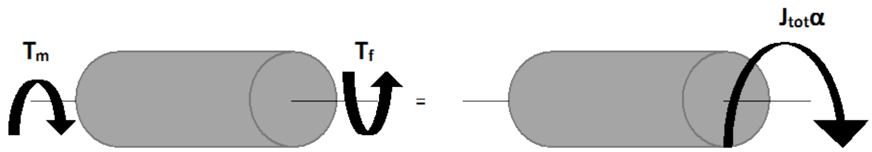


FIGURE 3. FBD AND KD OF THE LEAD SCREW AND GANTRY MECHANISM DRIVEN BY THE MOTOR TORQUE.

Solution

The first step is to apply Newton's Second Law of Motion applied to the FBD shown above:

$$\sum T_x = J_{tot}\alpha$$

$$T_m - T_f = J_{tot}\alpha$$

$$T_m = J_{tot}\alpha + \frac{F_{tot,axial}L}{\eta}$$

Next, it is necessary to determine the total inertia of the lead screw and gantry mass system. The total inertia mass is comprised of the lead screw inertia and the gantry inertia reflected through the lead screw.

$$J_{tot} = J_{screw} + J_{reflected}$$

$$J_{screw} = C\left(\frac{1}{8} m d^2\right)$$

$$J_{screw} = (2)\left[\frac{1}{8}(3.1\ lbm)(0.45\ in)^2\right]$$

$$J_{screw} = 0.157\ lbm - in^2$$

$$J_{reflected} = \frac{ML^2}{(2\pi)^2}$$

$$J_{reflected} = \frac{(50\ lbm)\left(0.125\ \frac{in}{rev}\right)^2}{\left(2\pi\ \frac{rad}{rev}\right)^2}$$

$$J_{reflected} = 0.020\ lbm - in^2$$

$$J_{tot} = (0.157\ lbm - in^2) + (0.020\ lbm - in^2)$$

$$J_{tot} = 0.177\ lbm - in^2$$

Now that the rotational inertia has been determined, we must quantify the maximum acceleration of the gantry mass. This can be solved by assuming constant acceleration bringing the gantry mass up to the feed speed within a small time frame, t_{feed},

$$\alpha = \frac{a}{L}$$

$$a = \frac{v_{feed}}{t_{feed}}$$

$$\alpha = \frac{\left(0.5\ \frac{in}{sec}\right)\left(2\pi\ \frac{rad}{rev}\right)}{\left(0.125\ \frac{in}{rev}\right)(0.1\ sec)}$$

$$\boldsymbol{\alpha = 251\ \frac{rad}{sec^2}}$$

Figure F-13. Motor Selection Calculation (Page 2 of 3)

All that is left to be defined is the resistive torque due to friction. Courtesy of Pittman Motors:

$$T_f = \frac{F_{tot,axial} L}{\eta}$$

$$F_{tot,axial} = F_{axial} + \mu F_{radial}$$

$$F_{tot,axial} = (75\ lbf) + (0.4)(90\ lbf)$$

$$\boldsymbol{F_{tot,axial} = 111\ lbf}$$

$$T_f = \frac{(111\ lbf)\left(0.125\,\frac{in}{rev}\right)}{(0.37)\left(2\pi\,\frac{rad}{rev}\right)}$$

$$\boldsymbol{T_f = 5.97\ in - lbf}$$

The first motor characteristic we must solve for is the total continuous motor output torque by using the values above:

$$T_m = J_{tot}\alpha + T_f$$

$$T_m = \left[(0.177\ lbm - in^2)\left(251\,\frac{rad}{sec^2}\right)\left|\frac{1\ ft}{12\ in}\right|\left|\frac{1\ slug}{32.17\ lbm}\right|\left|\frac{1\ lbf}{1\,\frac{slug-ft}{sec^2}}\right|\right] + (5.97\ in - lbf)$$

$$\boldsymbol{T_m = 6.08\ in - lbf}$$

Lastly, we must determine the continuous motor power:

$$P_m = T_m \Omega_{feed}$$

$$P_m = \frac{T_m v_{feed}}{L}$$

$$P_{m=} = \frac{(6.08\ in - lbf)\left(0.5\,\frac{in}{sec}\right)\left(2\pi\,\frac{rad}{rev}\right)}{\left(0.125\,\frac{in}{rev}\right)}\left|\frac{1\ ft}{12\ in}\right|\left|\frac{1\ W}{0.7376\,\frac{ft-lbf}{sec}}\right|$$

$$\boldsymbol{P_m = 17.3\ W}$$

After considering the desired low continuous output speed, and the calculated torque and power requirements, the Pittman Gearmotor GM9236S014-R1-SP was selected for the x-axis actuation.

Product Details

ADD TO CART | REQUEST MODIFICATIONS | BACK TO SELECTOR

DC Gearmotor
GM9236S014-R1-SP

Note: Product photo is for illustrative purposes. Please refer to Engineering Drawing for specifics.

Motor Series	Series GM9000 LO-COG Brush Commutated DC Gearmotors
Price (USD)	$175.19
Frame Size (Mounting Face) (in)	2
Motor Frame Size (in)	1.58
Gear Frame Size (in)	2.000
Overall Body Length (in)	4.326
Supply Voltage (V)	24
Continuous Output Torque (oz-in)	50
Output Speed @ Cont. Torque (RPM)	663
Current @ Cont. Torque (A)	1.9
Continuous Output Power (W)	25
No Load Current (A)	0.24
No Load Output Speed (RPM)	810
Peak Current (A)	9.6
Peak Output Torque (oz-in)	320

FIGURE 4. DATASHEET SNIPPET OF THE SELECTED DC GEARMOTOR GM9236S014-R1-SP.

NOTE: The gearmotor above will be used for all axes due to similar loading between the axes, and for the relatively low cost of the motor.

Figure F-14. Motor Selection Calculation (Page 3 of 3)

9.7. **Appendix G: Operator's Manual**

This operator's manual outlines how to create a suitable G-Code File for the designated CNC Machine. Note, that the G-Code file contains a set of instructions that the CNC Machine will read and translate into motor-signals which will then be cut into the wooden sign.

1. Safety - There is not direct interaction with the machine during this portion and thus no safety precautions related to Wood Carving need to be taken.

2. Opening Fusion 360 – Power on the designated personal computer, pre-loaded with Fusion 360, a Cloud based CAD/CAM Tool. Open Fusion 360 (on the designated computer, this process takes 30 – 45 seconds to load). One Fusion 360 has opened, start a new project.

3. Creating the Sign Base – Know the length, width, and height of your sign. You will use these dimensions to create the base of the sign, the wooden board which will be cut in to. (Note, the CNC will not actually be cutting this portion, but it is necessary to provide this information for Fusion 360 to generate the appropriate instructions during the engraving step.

Select the "Model" tab on the left-hand side of the screen as shown in Figure 7-1.

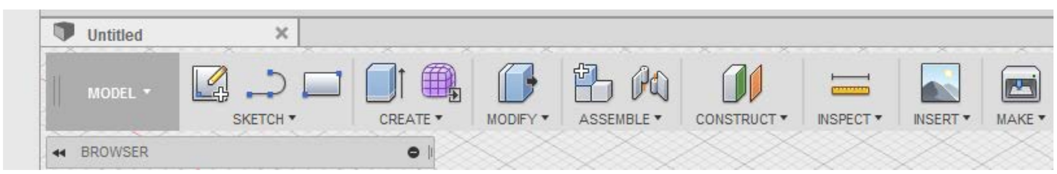


Figure 7-1: The Modelling Sequence

Mouse over the "Create" tab and wait for the drop-down, as shown in Figure 7-2. Select "The Box" option, as shown in Figure 7-2.

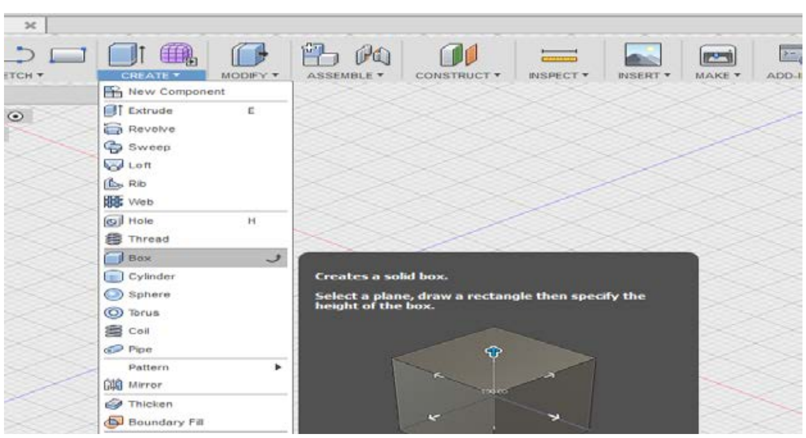


Figure 7-2: The Solid Box

When this mode is select, Fusion 360 will ask the user to select a plane to interact with, as shown in Figure 7-3. Select the X-Y Plane. Then, the mouse will display a 4x4 selection grid as shown in Figure 7-4. Use that grid to draw a 2D Square (or Rectangle). Do not worry about getting the exact dimensions as Fusion 360 will generate a text box that allows you to enter this information for better precision. Make sure to draw the box on the positive X- and Y-axes.

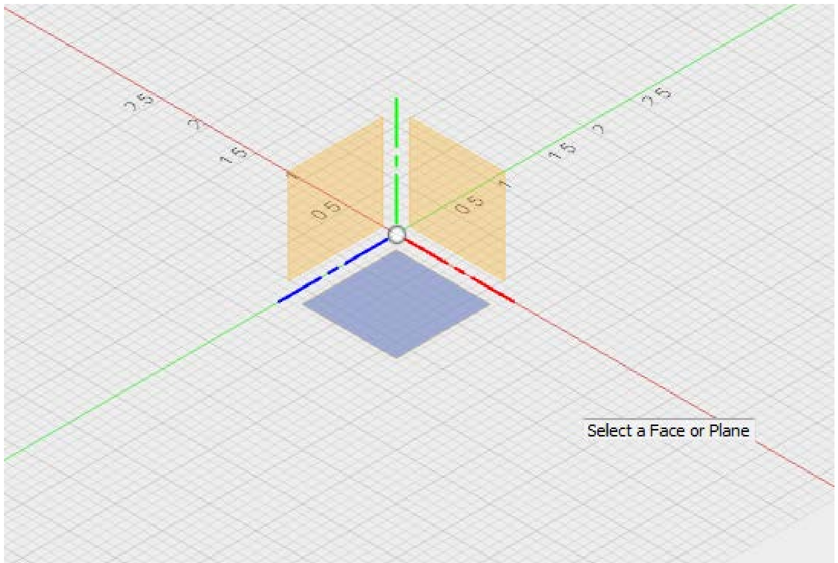


Figure 7-3: After Select "The Box"

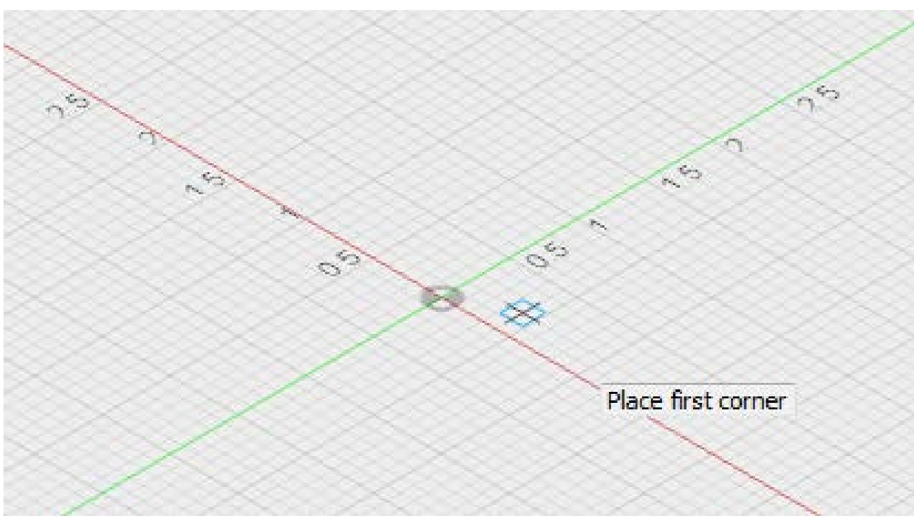


Figure 4: The 4x4 Selection Grid

After drawing the initial box, the screen should look like the image in Figure 5. As the box is created, a dialogue pops up displaying the exact dimensions of the box. When selecting this dialogue, Fusion 360 will ask you to select a generalized unit of measurement for your entire project. Select inches, as shown in Figure 6. (Note: this dialogue box will show up for every new project that the user creates).

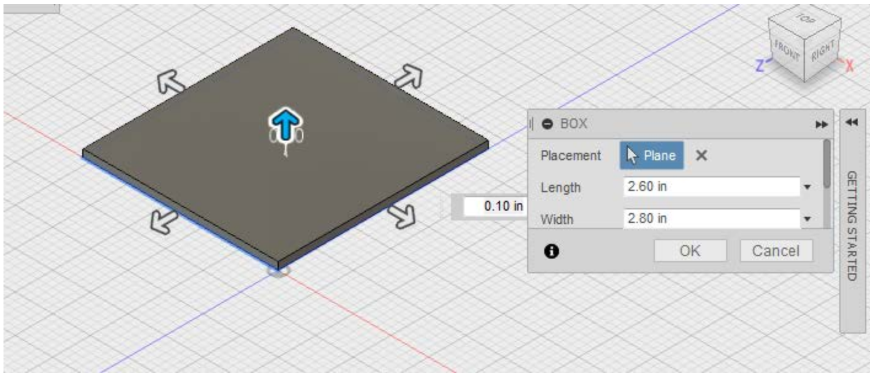


Figure 7-5: After Selecting a General Area

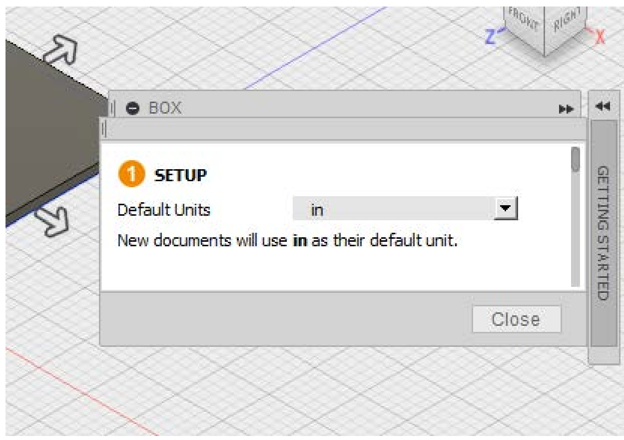


Figure 7-6: Unit Measurement Selection

Once the general unit of measurement is selected, set the appropriate length, width, and height of the sign which the CNC machine will carve on. Fusion 360 defaults to a smaller view, so the user must zoom out to see the entire sign-box once it is created. The zooming out function can be found at the bottom of the Fusion 360 screen, depicted in Figure 7-8.

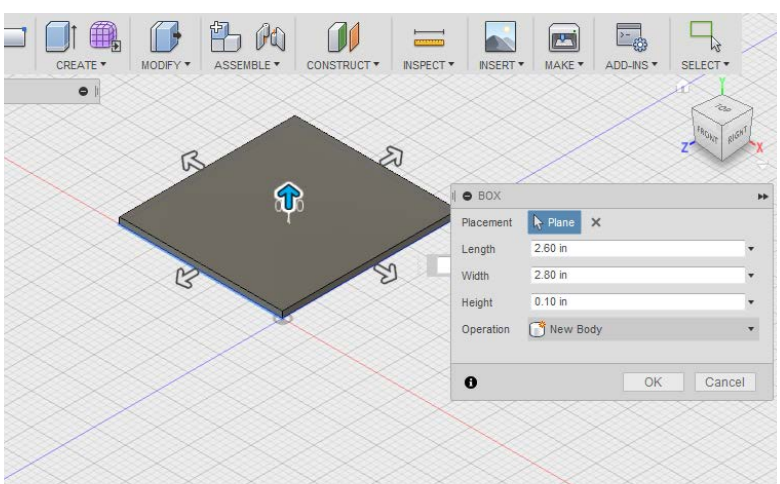


Figure 7-7: Dimension Selection

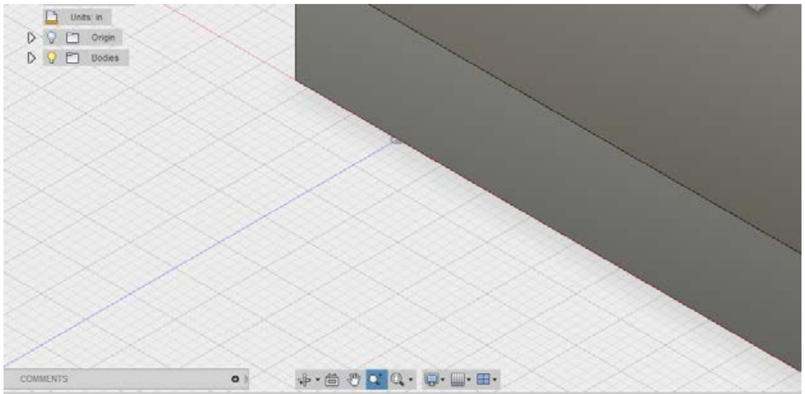


Figure 7-8: Zooming Out

At this point, the wooden sign's box base has been created! Figure 7-9 shows an image of what the result should look like.

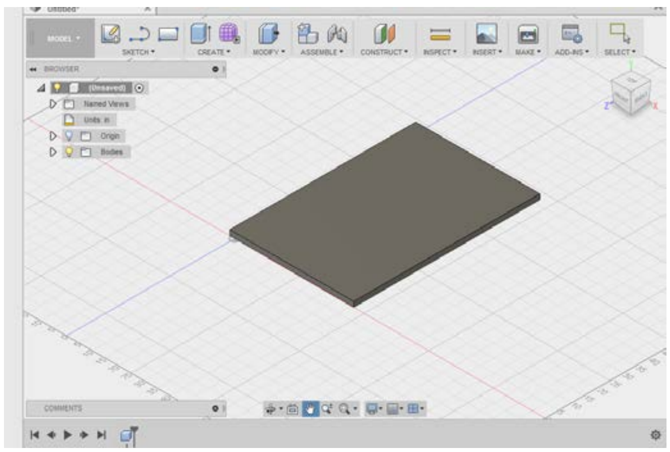


Figure 7-9: The Final Box

__Creating the Sign Text Outline__ – Modify the view such that the user has a top-down view of the box surface and the selected text. Go to the Sketch tab under the Model Mode and Select the "Text" option as shown in Figure 7-10.

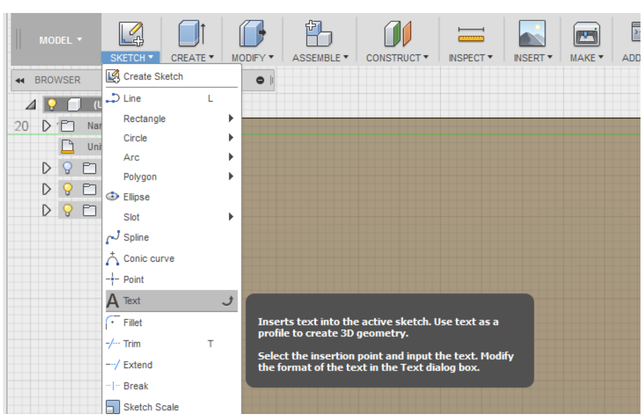


Figure 7-10: Selecting the Text Mode

Choose the location that the text will begin on the sign. One might have to adjust the angle of the text to correctly align with the sign. The cursor to place the text is shown in Figure 7-11. When a location has been chosen, the corresponding dialogue pops up (as shown in Figure 7-12) where the user can enter the text of choice, size it accordingly, and choose the desired font (among other fields). When satisfied, select okay.

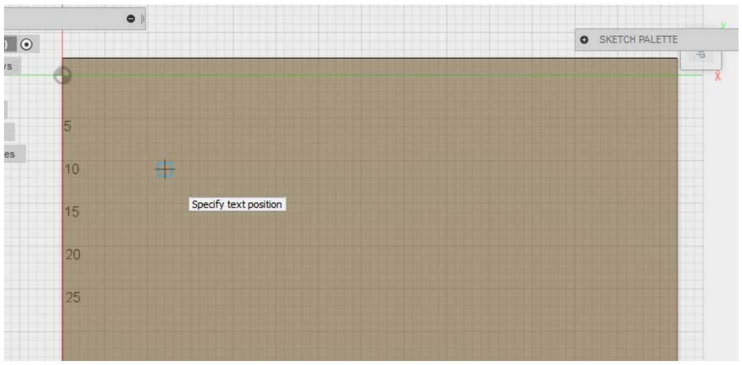


Figure 7-11: Placing the Text

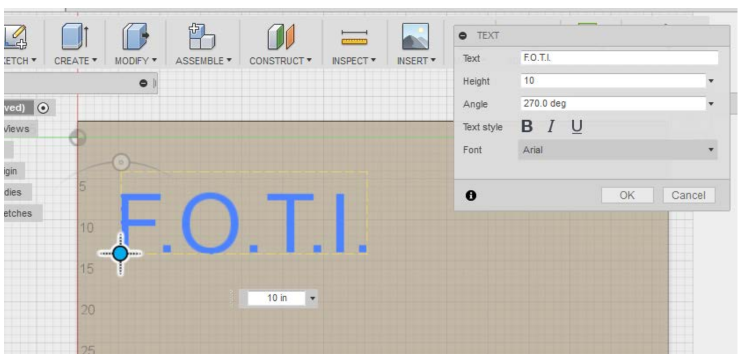


Figure 7-12: Writing the Text

Right click the highlighted text and select the "Explode Text" option. Figure 7-13 shows what the drop down looks like in Fusion 360. Figure 7-14 shows what the text looks like after the "Explode Text" option has been selected.

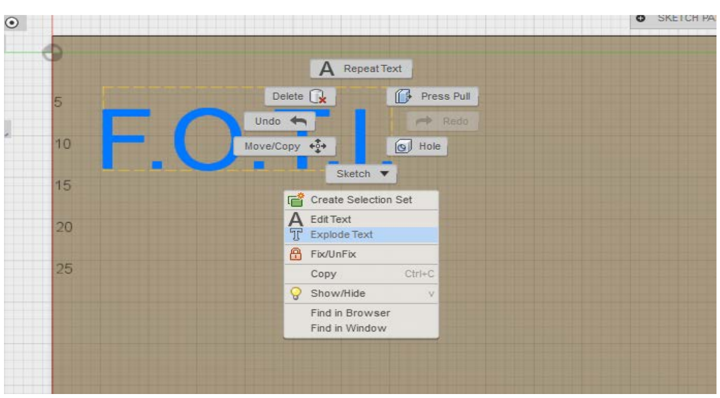


Figure 7-13: Exploding Text

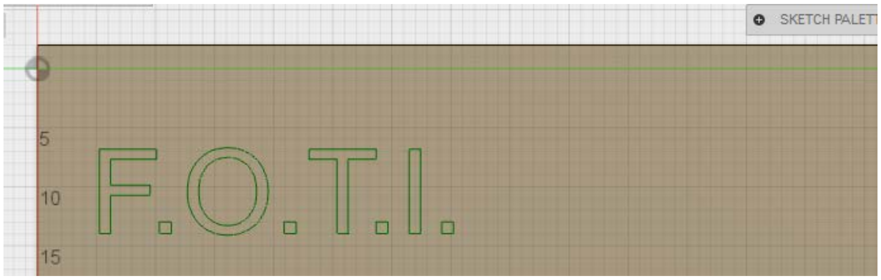


Figure 7-14: After Exploding the Text

Mouse over each letter until it is the entire shape is highlighted in light blue. Left-click to select the shape. To select more than one shape, hold down the “shift” key and repeatedly select the rest of the text. Figure 7-15 shows a period highlighted in light-blue before it is selected. The letters F and O have already been selected and this can be seen by the darker blue shading and the red outline. Figure 7-16 displays the entire text after being entirely selected.

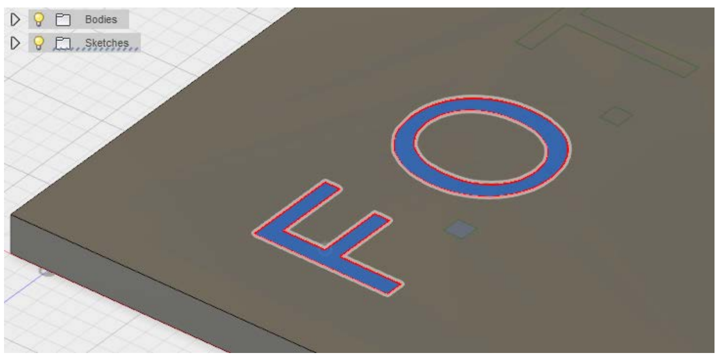


Figure 7-15: Select the Text Curves

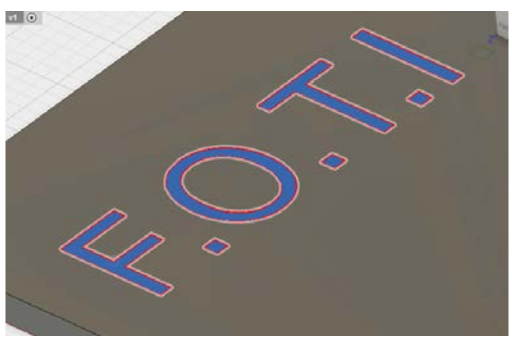


Figure 7-16: All Text Curves Selected

Now that all the text is high-lighted, go back to the create tab and select extrude. See Figure 7-17 for a visual example. After selecting the extrude function, a dialogue will pop up requesting the several fields. The only field that matters is the distance field. Select a negative distance (meaning the carve will go into the wooden board). Figure 7-19 shows the final result of an extrusion of the text at -0.5 inches.

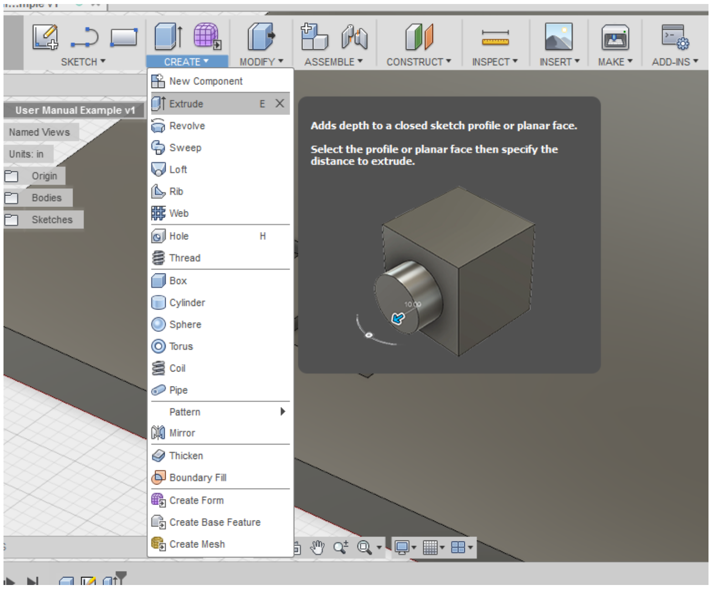


Figure 7-17: Extrude Mode

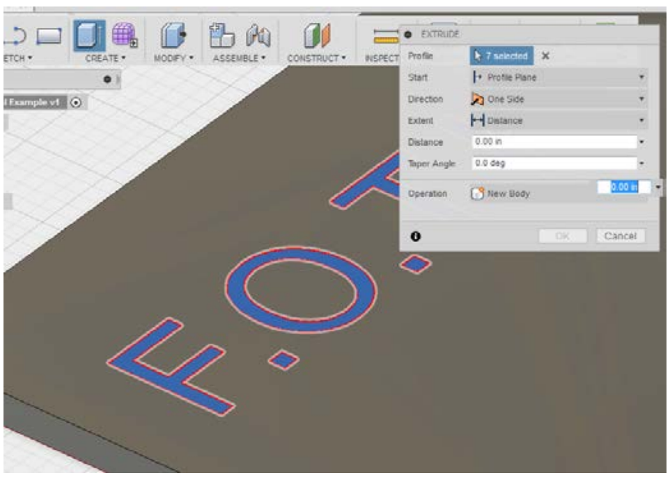


Figure 7-18: Extrude Mode Dialogue

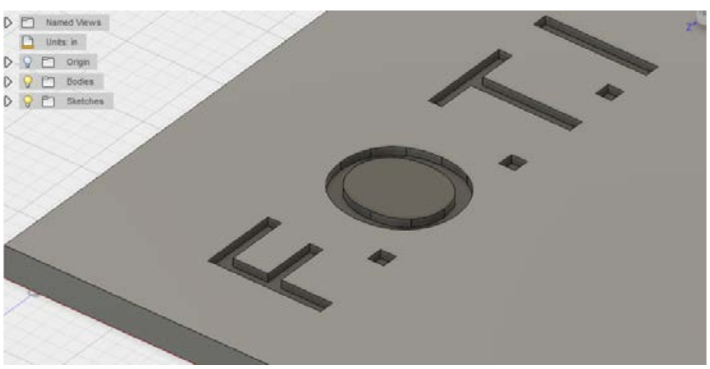


Figure 7-19: After Extruding the Text

(or) Creating the Sign Image Outline –

Creating the Engraving – to create the sign using a pre-designed image save as an SVG file and drop it onto the sign. Follow the shape-selection and the extrusion steps detailed in "*Creating the Sign Text Outline"* to add an image to the sign. Figure 7-20 details the "Insert" tab where a user can import an existing SVG file.

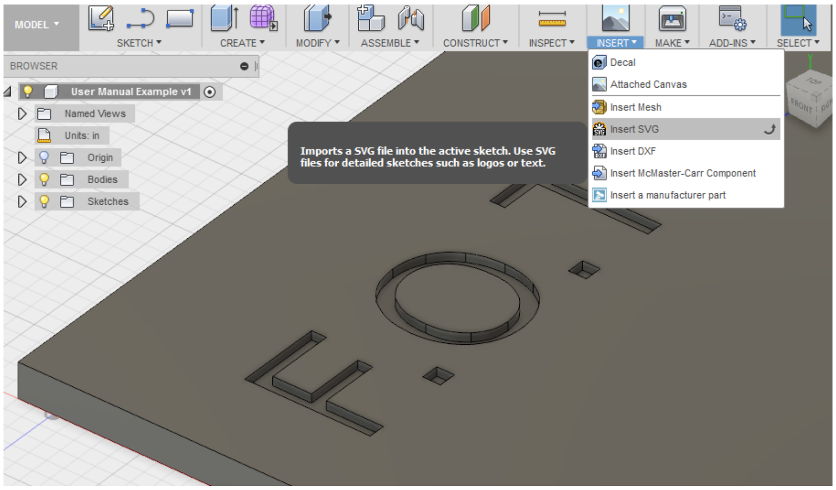


Figure 7-20: Importing an Image

Creating the Actual G-Code – Now that the sign base has been created and the related text and image have been place on the sign, it's time to generate the G-Code which the CNC machine will read to carve the corresponding image.

To do this, change the mode from "Model" to "CAM" as shown in Figure 7-21. In Cam Mode, Fusion 360 will analyze the corresponding CAD/CAM drawing and generate a relevant G-Code of the user's choice. In the case of the Forest Sign Maker, the CNC file to be generated will be for GRBL-supported CNC Machine.

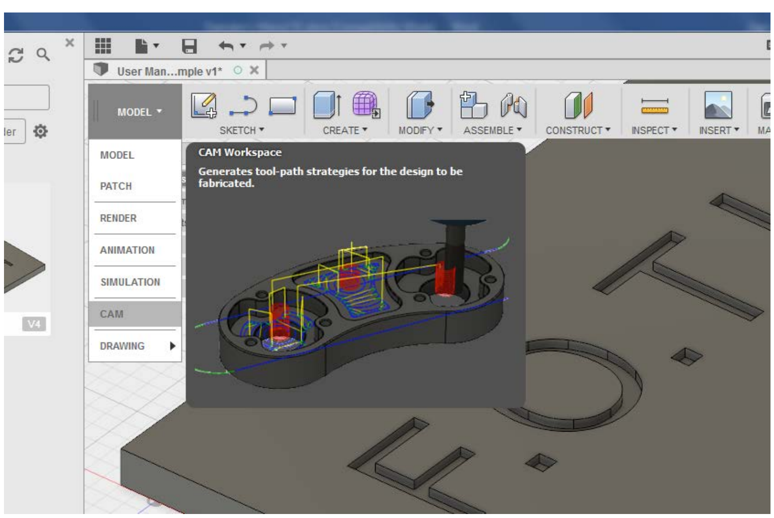


Figure 7-21: Switching to Cam Mode.

After navigating to Cam mode, select “Setup” as shown in Figure 7-21. This is where you will create tool paths for the CNC Machine. Select a stock point at the top bottom corner of the model. In the corresponding dialogue box, select the stock tab and define the size of the stock L x W x H. Make sure to set the offset if necessary for your sign. Once your stock values have been set, select Pocket Clearing from the 3D tab. See Figure 25 for reference.

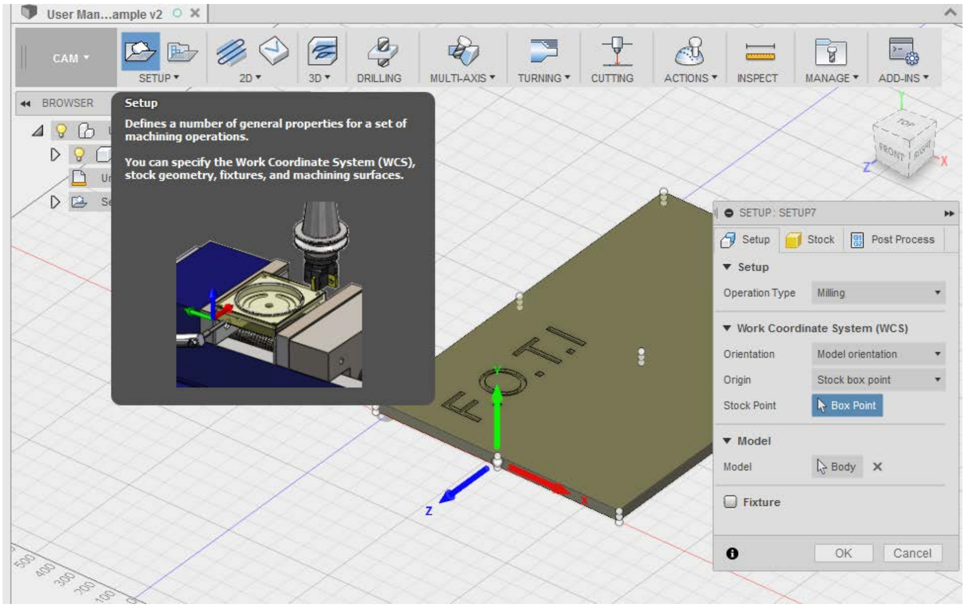


Figure 7-22: Setup

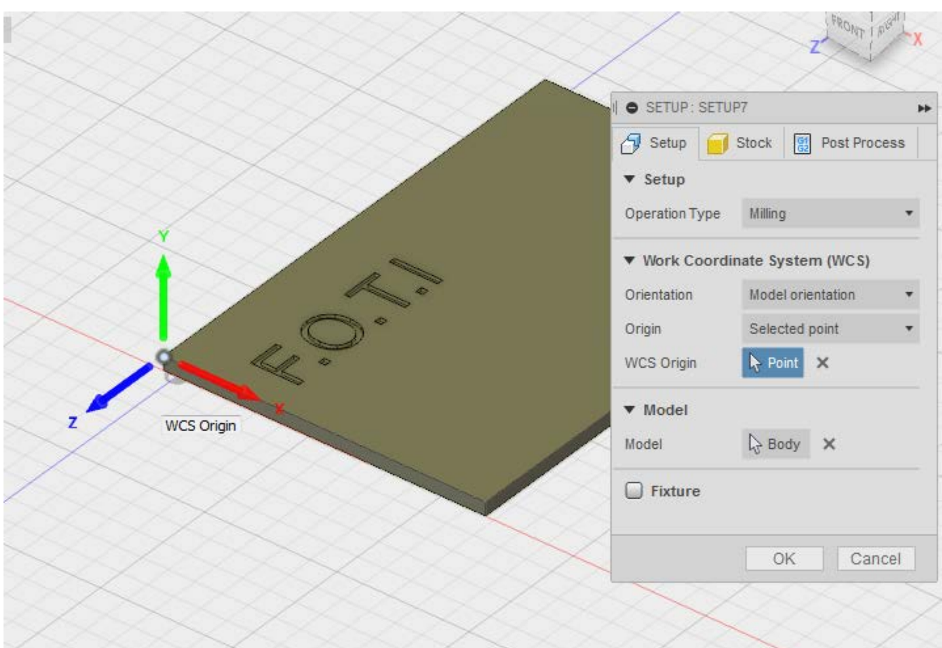


Figure 7-23: Setting a Stock Point

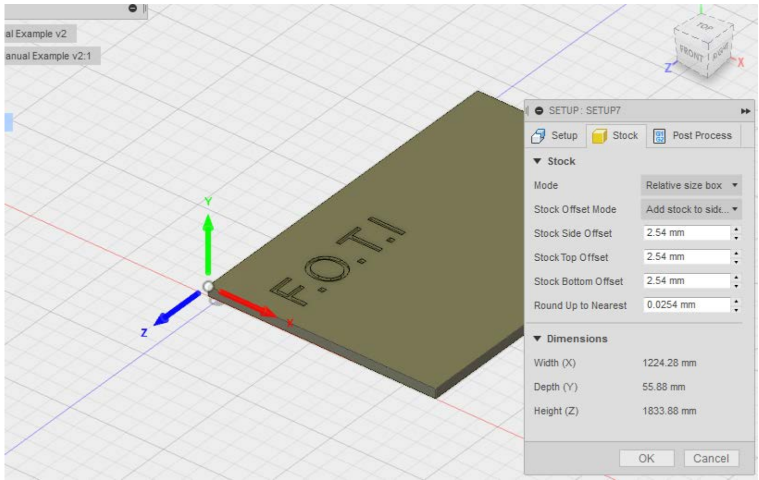


Figure 7-24: Set at the Stock Offset

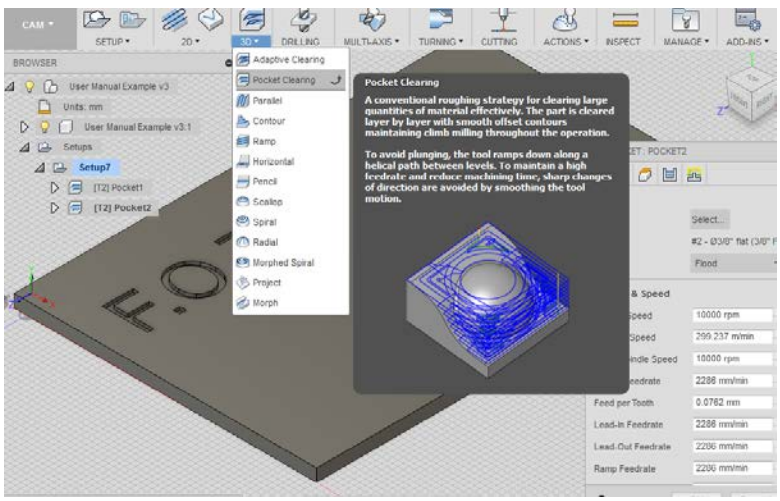


Figure 7-25: Pocket Clearing

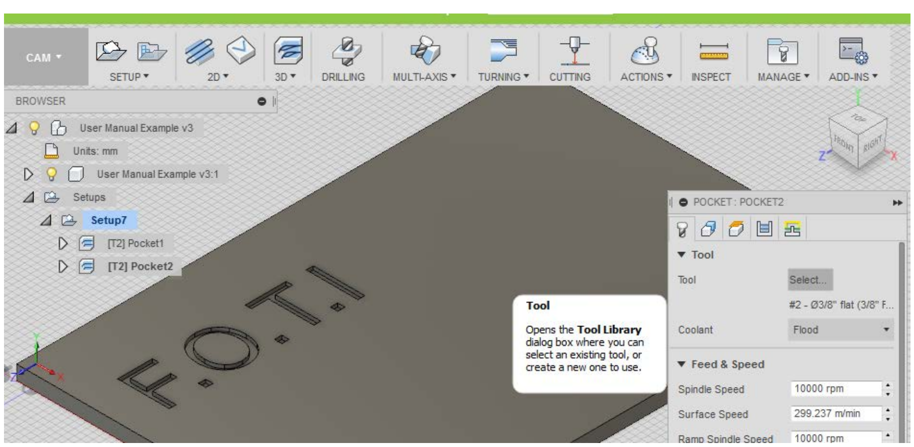


Figure 7-26: Selecting Tool Path

Once you've set up your Stock Point and Stock Offset, go to the Setup tab select the "Tool" selection (See Figure 7-26) to select the appropriate drill bit. You can also fill out the specs related to the selected end mill such as size, diameter, shaft, etc. In Figure 7-27, the 3/8" Flat Endmill has been selected. Press okay. In the pocket dialogue, select the fourth tab labeled "Passes" and fill out the information related to your CNC carve. Once all the specs are pressed, select OK.

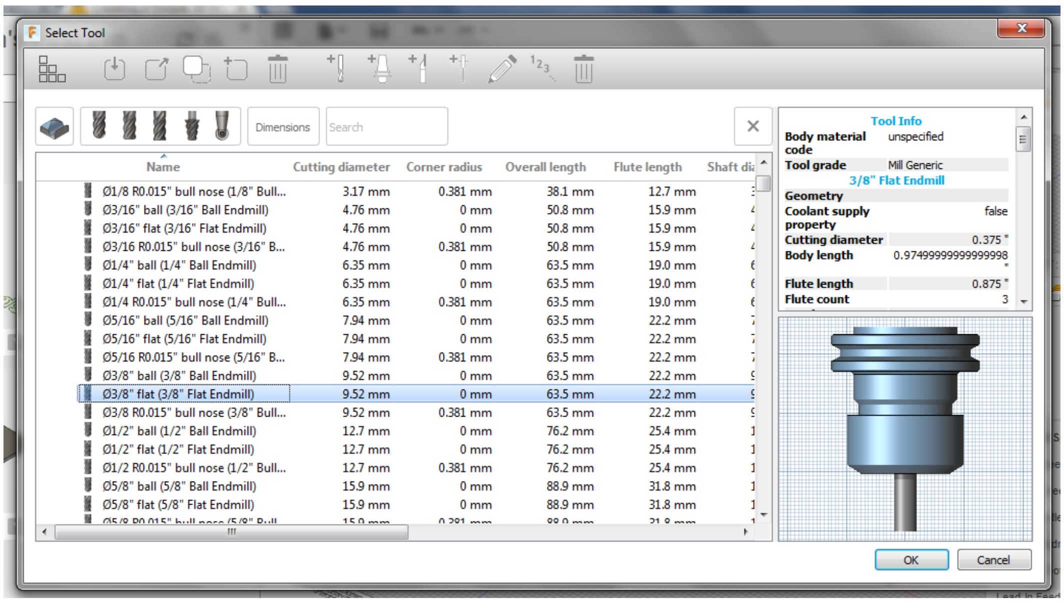


Figure 7-27: Select Your Tool

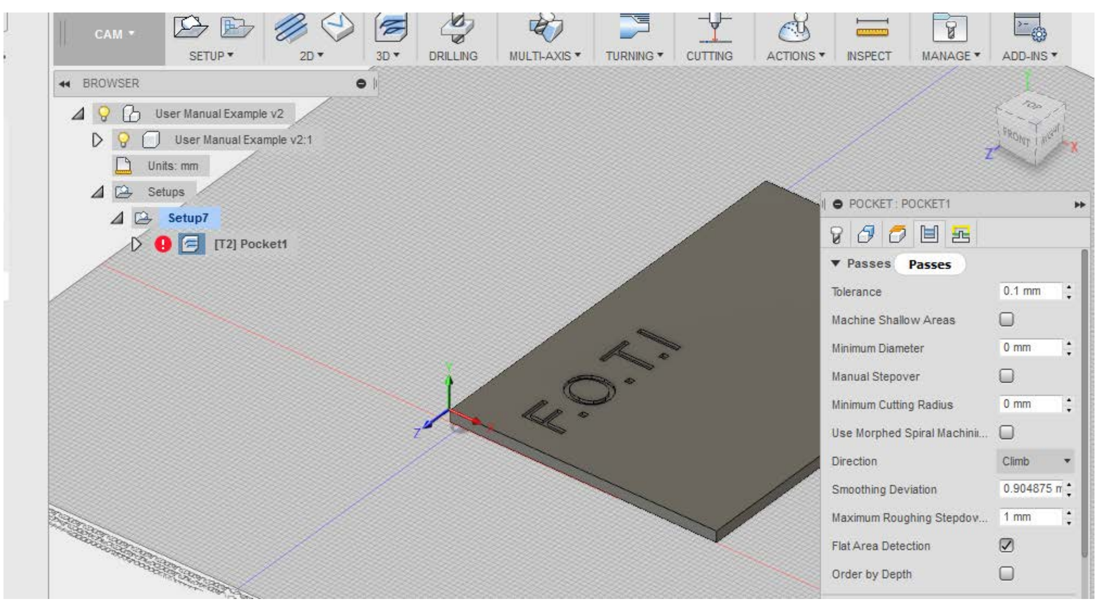


Figure 7-28: Set Your Passes

Once all those steps have been completed, find the "Actions" tab and wait for the drop down. Select "Post Process" when the option appears. For this CNC Machine, modify the file-save to a memorable output location. In the post configuration drop down, select the CNC machine type as Grbl, as shown in Figure 7-29. The G-Code corresponding to your image will be generated and loaded on screen, as shown in Figure 7-30.

At this time, creating the project's corresponding G-Code has been completed!

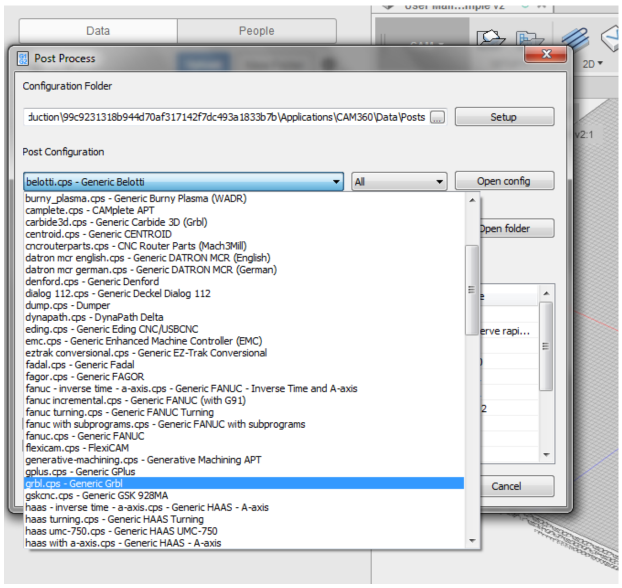


Figure 7-29: Save G-Code Type as Grbl

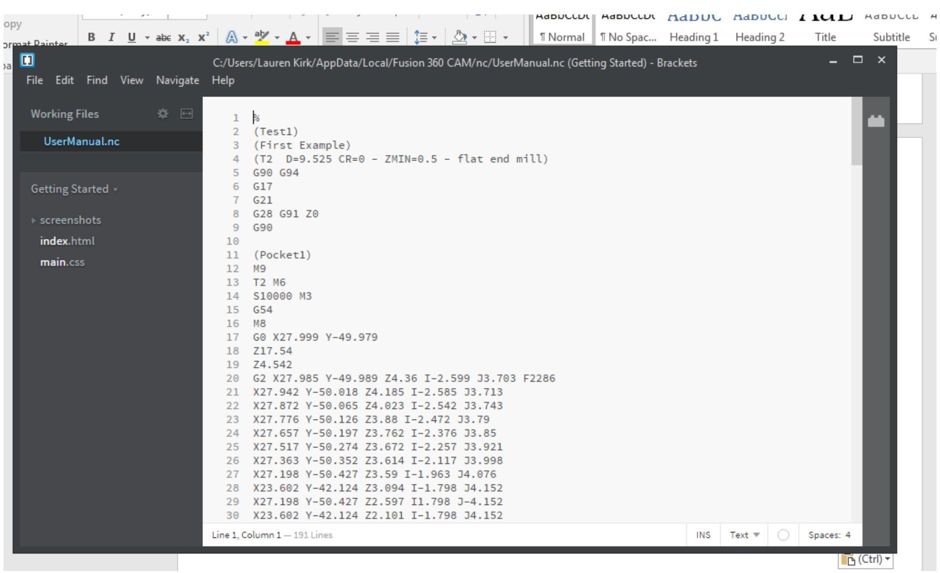


Figure 7-30: Sample G-Code

Creating a Sign with the CNC

This portion of the operator's manual outlines how to take a valid G-Code File and give it to the designated CNC Machine such that it can read those instructions and generate the expected wooden sign.

Safety - As the user will be interacting with the machine during this portion, it is advised the user takes the appropriate steps to protect themselves from injury during the wood cutting process. Of these safety measures, the user is advised to wear (1) safety glasses, a (2) face-mask, and a (3) set of ear-covers. These items will ensure that the user is not negatively affected by and wooden dust, wooden chips, or wooden particles that result from the carving of the sign.

Prepare the Forest Sign Maker – Place the wooden plank on the foundation and clamp it down securely using the T-slot clamps.

Power on the Forest Sign Maker – Plug in the CNC and flip the power switch on.

Power on the Raspberry Pi B – Plug in the Pi and power it on. Plug in the Monitor and power it on. Connect the keyboard and the mouse to the USB inputs on the Raspberry Pi. Navigate to the Pi's home-screen. Plug in the related USB (flash-drive or wire) to the Pi and drag and drop the G-Code generated in the previous step to the computer. Press play and let it begin.

9.8. Appendix H: Figures and Tables List

9.8.1. Section 2

9.8.2. Section 3

9.8.3. Section 4

9.8.4. **Section 5**

9.8.5. Section 6

9.8.6. Appendix B

9.8.7. Appendix C

9.8.8. Appendix D

9.8.9. Appendix F

10. References

10.1. Original References that Have Been Revisited

Aguilera, A., P. J. Meausoone and P. Martin. "Wood Material Influence in Routing Operations: the MDF Case." 2000. 2014.

Bermudez, Julio, Boleslaw Porankiewicz, and Chiaki Tanaka. "Cutting Forces by Peripheral Cutting of Low-Density Wood Species." BioResources (2007): 671-681.

Budynas, Richard G. and J. Keith Nisbett. Shigley's Mechanical Engineering Design, Ninth Edition. McGraw-Hill, 2011. Print. January 2015.

CNC Concepts, Inc. The Basics of Computer Numerical Control. n.d. January 2015. <http://www.cncci.com/resources/articles/CNC%20basics%201.htm>.

Digikey Corporation. Online Ordering. 2015. <http://www.digikey.com/classic/Ordering/AddPart.aspx?site=us&lang=en>.

Digital Wood Carver. Featured Products. n.d. Website. 2014. <http://www.digitalwoodcarver.com/gear-1.html>.

Epilog Laser. Epilog Fusion Laser Series. n.d. Website. 2014. <https://www.epiloglaser.com/products/fusion-laser-series.htm>.

Forest Service. Sign and Poster Guidelines for the Forest Service EM-7100-15. Administrative Document. Idaho Falls, ID: North Wind, Inc., 2005. Website. 2014. <http://www.fs.fed.us/eng/pubs/htmlpubs/htm12512818/em7100-15/pdfindex.htm>.

Friends of the Inyo. About Friends of the Inyo. n.d. 2014.<http://friendsoftheinyo.org/foiD7/about>.

Goli, Giacomo, et al. "Measurement of Cutting Forces, in Routing Wood at Various Grain Angles. Initial Results with Douglas-Fir." White Paper. n.d. Document. 2014.

Haydon Kerk Motion Solutions / Pittman Motors. "Applying Motors in Linear Motion Applications." n.d. Pittman Motors. Ed. Dan Montone. Document. January 2015. <http://www.pittman-motors.com/Brush-DC-Motors.aspx>.

Nise, Norman S. Control Systems Engineering. 6th. John Wiley & Sons, Inc., 2011. Pittman Motors. Applying DC Motors in Linear Motion Applications. n.d. Website. 2014. <http://www.pittman-motors.com/Brush-DC-Motors/DC-Motors-in-Linear-Motion-Applications.aspx>.

Hiwin. "Ballscrews: Technical Information." n.d. Document. January 2015. <http://www.hiwin.com/html/ball%20screws/index.html>.

Honeywell. Hall Effect Sensing and Application. Honeywell. Freeport, IL, n.d. February 2015.

Porankiewicz, Boleslaw, Bengt Axelsson, and Birger Marklund. "Main and Normal Cutting Forces by Machining Wood of Pinus Sylvestris." BioResources (2011): 3687-3713.

Record, Samuel J. "The Mechanical Properties of Wood, Including a Discussion of the Factors Affecting the Mechanical Properties, and Methods of Timber Testing." 2004. eBook. January 2015. <http://www.gutenberg.org/files/12299/12299-h/12299- h.htm>.

Rockler. CNC Shark HD with Extended 63" Bed. n.d. Website. 2014.<http://www.rockler.com/cnc-shark-hd-20-with-extended-63in-bed>.

Rowell, Derek and David N. Wormley. System Dynamics: An Introduction. Upper Saddle River: Prentice Hall, 1997. Print. January 2015.

Sheehy, Donna and Kurt Krueger. "A User Guide for the Sign Sizing Program." General Technical Report. Forest Service, 1999.

ShopBot. The ShoptBot Buddy. n.d. Website. 2014.<http://www.shopbottools.com/mProducts/shopbot_buddy.htm#Top>.

10.2. Unique References Specific to This Report

Automation Technology. "KL-6090 Desktop CNC Router Desktop (24 X 36 X 8 Inch) for Mach3, 3HP Air Spindle." *Stepper Motor Stepper Motor Driver CNC Router Laser Machine 3D Printers For Sale RSS*. Automation Technology, Inc., Jan. 2016. Web. 20 Oct. 2016. <http://www.automationtechnologiesinc.com/products-page/cnc-router/kl-6090-desktop-cnc-router>.

Citation used during the evaluation of competitor products that meet a majority of the customer’s needs defined within the project.

CNC Concepts, Inc. "The Basics Of Computer Numerical Control." *Interactive Article: The Basics of CNC*. CNC Concepts, Inc., 2007. Web. Oct. 2016. <http://www.cncci.com/resources/articles/CNC%20basics%201.htm>.

Citation used to specify basic functionality of a three dimensional CNC machine. In particular, this citation is used to examine the effects of controlled actuation along three linear axes.

CNCShop. "CNCShop CNC Router Engraving Machine Engraver Machine 6040Z 3 Axis Desktop Wood Carving Tools Artwork Milling Woodworking with 1.5kw VFD (6040Z 3 Axis)." *Amazon.com*. Amazon.com, Inc., Jan. 2015. Web. 20 Oct. 2016. <https://www.amazon.com/Engraver-Drilling-milling-Engraving-Machine/dp/B012CFPL3G?th=1>.

Citation used during the evaluation of competitor products that meet a majority of the customer's needs defined within the project.

Forest Service. "Sign and Poster Guidelines for the Forest Service." *Forest Service: U.S. Department of Agriculture*. U.S. Department of Agriculture, Nov. 2012. Web. Oct.2016.<http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprd3810021.pdf>.

Citation used to clarify national standards for displayed text on forest signs as well as construction materials for forest signs.

Rockler. "CNC Shark HD4 with Extended Bed." *Rockler: Woodworking and Hardware*. Rockler Companies, Inc., Jan. 2016. Web. Oct. 2016. <http://www.rockler.com/cnc-shark.hd-20-with-extended-63in-bed>.

Citation used during the evaluation of competitor products that meet a majority of the customer's needs defined within the project.

ShopBot. "The ShopBot Buddy®." *ShopBot Buddy*. ShopBot Tools, Inc., 2006. Web. 20 Oct. 2016. <http://www.shopbottools.com/mProducts/shopbot_buddy.htm#To>.

Citation used during the evaluation of competitor products that meet a majority of the customer's needs defined within the project.

By the Use of Passive Damping Elements, Integrated in the Boring Bars, the Dynamic Behavior of the Tools Can Be Optimized. "Minimizing Vibration Tendencies In Machining." *Modern Machine Shop*. Gardner Business Media, Inc., 2016. Web. Oct. 2016. , http://www.mmsonline.com/articles/minimizing-vibration-tendencies-in-machining>.

Citation used during research of vibration isolation methods on Industrial CNCs

Friends of the Inyo. "About Friends of the Inyo." *Friends of The Inyo: Preservation, Exploration, Stewardship*. Web. Oct. 2016. http://friendsofhteinyo.org/foiD7/about>.

Citation used to discuss the project’s main customer, the Friends of the Inyo.

"ELZ External Roller Bearing Guided, External Belt Driven Modular Linear Actuators | Nook Industries." *ELZ External Roller Bearing Guided, External Belt Driven Modular Linear Actuators | Nook Industries*. NOOK Industries, INC, n.d. Web. Nov. 2016. <http://www.nookindustries.com/Product/ProductCategory/4210>.

Citation used to discuss the belt driven actuator and receive the belt driven actuation image

"ELK Screw Driven Modular Actuator | Nook Industries." *ELK Screw Driven Modular Actuator | Nook Industries*. NOOK Industries, INC, n.d. Web. Nov. 2016. <http://www.nookindustries.com/Product/ProductCategory/4111>.

Citation used to discuss the power screw actuator and receive the power screw actuation image

"DLZA Internal Roller Bearing Guided, Rack and Pinion Driven Modular Linear Actuators | Nook Industries." *DLZA Internal Roller Bearing Guided, Rack and Pinion Driven Modular Linear Actuators | Nook Industries*. NOOK Industries, INC., n.d. Web. Nov. 2016. <ttp://www.nookindustries.com/Product/ProductCategory/4510>.

Citation used to discuss the rack and pinion actuator and receive the rack and pinion actuation image

Autodesk. “Fusion 360.” Autodesk Inc. Web. Nov. 2016 <http://www.autodesk.com/products/fusion-360/overview>.

Citation used to briefly explain the decision to use Fusion 360 over Adobe Illustrator when request an individual to design the appearance of a standard forest sign.

Rohm Semiconductor. Controlling DC Brush Motors with H-bridge Driver ICs. ROHM Semiconductor USA, LLC, San Diego, CA: 2009. Web. Nov. 2016. <http://www.rohm.com/documents/11405/851233/100260.H-BRDG_WP_Jan09.pdf>

Citation used to discuss the requirements for PWM control and H-bridge characteristics.

“ARMv8-A Architecture.” ARM Ltd.,1995. Web. Nov. 2016. <https://www.arm.com/products/processors/armv8-architecture.php>

Citation used to discuss the ARMv8-A family of devices and their capabilities.

“Cortex-M Series Family.” ARM Ltd.,1995. Web. Nov. 2016. <http://www.arm.com/products/processors/cortex-m>

Citation used to discuss the Cortex-M series of devices and their capabilities.

“megaAVR Microcontrollers.” Atmel Corporation: 2016. Web. Nov. 2016. <http://www.atmel.com/products/microcontrollers/avr/megaAVR.aspx>

Citation used to discuss the megaAVR family of devices and their capabilities.

Mouser Electronics. “STMicroelectronics VNH Automotive H-Bridge Drivers.” Mouser Electronics, Inc., Mansfield, Texas, USA: 2016. Web. Nov. 2016. <http://www.mouser.com/new/stmicroelectronics/stm-vnh5xx/>

Citation used to discuss VNH automotive bridge drivers and the capabilities of that family of devices.

“The Basics of Noise Filtering.” Electronics Systems Protection, Inc., Zebulon, NC. n.d. Web. Nov.2016. <http://espsurgex.com/downloads/white-papers/ESP-White-Paper-The-Basics-of-Noise-Filtering.pdf>

Citation used to discuss power and signal line filtering to prevent digital noise.

Raspberry Pi. “Raspberry Pi B+ Mechanical Schematic.” Raspberry Pi Foundation, July 2014. Website. 2017 <https://www.raspberrypi.org/wp content/uploads/2014/07/ mechanicalspecB%2b.png>

Citation for mechanical schematics of the Raspberry Pi.

Hensen, Kelly. Rasbperry Pi B+ GPIO Pinout Diagram. Element14, July 2014. Website. 2017. <https://www.element14.com/community/docs/DOC-73950/l/raspberry-pi-3-model-b-gpio-40-pin-block-pinout>

Citation for GPIO Pinout Diagram.

Raspberry Pi. “Raspberry Pi Rev 1.0 Model AB Schematics.”Raspberry Pi Foundation, July 2014. Website. 2017.<https://www.raspberrypi.org/documentation/hardware/ raspberrypi/schematics/Raspberry-Pi-Rev-1.0-Model-AB-Schematics.pdf>

Citation for the electrical schematics of the Raspberry Pi.

"VNH5019 Motor Driver Carrier." *Pololu*. Pololu Corporation, n.d. Web. Jan. 2017.

Citation for the motor driver boards, from pololu.

Harton, Resistor. James. "OSH Park." *OSH Park ~ An Electric Ecosystem*. N.p., n.d. Web. Jan. 2017.

Citation for the pcb fabrication.

"Mouser Electronics - Electronic Components Distributor." *Mouser Electronics - Electronic Components Distributor*. Mouser Electronics, Inc., n.d. Web. Jan. 2017.

Citation for the controller parts supplier.

"McMaster-Carr." *McMaster-Carr*. N.p., n.d. Web. Jan. 2017.

Citation for the one of the mechanical parts suppliers.

Metals, Online. ONLINEMETALS.COM, n.d. Web. Jan. 2017.

Citation for the one of the mechanical parts suppliers.

Grbl. https://github.com/grbl/grbl/wiki, n.d. Web. April 2017.

Citation for Grbl motion control software

Syntheos. https://synthetos.myshopify.com/products/gshield-v5, n.d. Web. April 2017.

Citation for the gshield motor driver for Arduino