Final Design Report

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1 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.

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4 Nomenclature

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 for 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 on machines that display position 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.

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 wood cut 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.

5 Executive Summary

The Inyo National Forest is arguably one of the most beautiful locations in California, containing natural masterpieces such as Mount Whitney and the Ancient Bristlecone Pine Forest. Despite its magnificence, the Inyo National Forest can be a treacherous region. The Friends of the Inyo take pride in being able to facilitate the viewing experience for all outdoorsmen by maintaining the mountain trails, which includes providing adequate trail signage.

Unfortunately, there is a fundamental issue with the recent state of trail signage in the Inyo National Forest: the rate at which signs are being vandalized or naturally destroyed is greater than the rate at which signs can be produced. More specifically, the problem is that the current sign production process is completely manual; the process of routing the necessary letters and symbols consumes the majority of the production time, since it takes approximately two days to complete. Without adequate signage on the mountain trails, hikers and explorers are at a heightened risk for injury.

We, the Cal Poly Forest Friends, have been commissioned by the Friends of the Inyo to resolve the issue of manufacturing trail signs. We plan on designing, building, and testing a prototype CNC machine for Paul McFarland, an employee of the Friends of the Inyo whom is responsible for replacing signs. This CNC machine can automatically produce a trail sign from a wooden blank so as to expedite the sign replacement process. By comparing different industry methods of etching letters into a wood substrate, researching all applicable signage guidelines for compliance, and optimizing the prototype design for the intended use cases, we have developed a low cost, high capacity CNC router that can be installed directly in Paul McFarland's workshop.

There has been much work done in the field of CNC machinery, so we believe it is feasible to design a functioning prototype that has been optimized for this purpose. The positional accuracy range of the machine will be broadened from the industry standard of *±0.0005 in* to our requirement of *±0.063* inches. This optimized accuracy will allow for emphasis on increased workpiece capacity at a lower total cost. Additionally, by building the prototype CNC router as part of the Cal Poly Multidisciplinary Senior Project class, we will be able to adhere to the revised *$3,500* budget. With a successful prototype in hand by June 2015, the sign production rate for the Friends of the Inyo will potentially increase tenfold, and provide the Friends of the Inyo with the ability to replace illegible trail signs within the Inyo National Forest.

6 Introduction

6.1 Problem Definition

The problem that the Cal Poly Forest Friends have set out to resolve is the issue of a low trail sign production rate at the Friends of the Inyo. Recently, our sponsor, Paul McFarland, has been burdened with the responsibility of manufacturing all of the replacement signs required for the Inyo National Forest, a task that a single person cannot complete by themselves.

6.1.1 Objective

This Multidisciplinary Senior Project will attempt to resolve this problem through machine and software design of a final product, as to aid Paul McFarland in the sign production process and meet the budget set for sign production.

6.2 Project Motivation

The Friends of the Inyo work hard to keep the forest well maintained for visitors. The trails, signs, and markers are always under careful observation to prevent accidents or disorientation. The routed wooden signs in particular take a sizable amount of skilled manual labor and time to produce. At the moment, the Friends of the Inyo create the wooden signs by tracing letters onto a blank wooden board, and then cut the stenciled letters and symbols using a palm router. Depending on the board size and the amount of letters that need to be etched on to the board, this process generally requires two or three days to complete. This project aims to shorten the length of time it takes to create a sign, allowing the Friends of the Inyo to replace the worn trail signs quickly.

6.3 Scope

The goal of Cal Poly Forest Friends is to assist the Friends of the Inyo with expediting the trail sign production process. In order to do so, the team is going to design and build an automated 2½ axis CNC machine to produce wooden signs as big as two feet wide and four feet long in less than two hours. Developing the machine in its entirety, both on the hardware and software level, will allow the Cal Poly Forest Friends to fully optimize the system and carefully work with the budget. Upon completion, this project will help eliminate the majority of manual labor required to produce large signs, as well as produce signs with more consistent quality at a higher production rate.

The scope of this project encompasses the majority of the design process that extends from initial problem definition to developing a functional prototype of the final design. All the intermediate steps, such as conceptual ideation, design development, fabrication, and prototype testing, will be executed in accordance to the requirements outlined by the ENGR 459-460-461 class series, in addition to those needed to satisfy the customer requirements outlined below. Any derivatives of or improvements made to the final prototype developed by the Cal Poly Forest Friends extend beyond the scope of this project.

6.4 Stakeholders

This impact of this project extends past those who are involved directly with the production and operation of the Forest Sign Maker; the hikers and visitors that will be reading our signs ultimately benefit from this endeavor. A successful prototype will ensure that the people who rely on the trail signs will be able to safely explore the Inyo National Forest. With that said, the stakeholders involved in this project are: the Friends of the Inyo, the Cal Poly Forest Friends, Paul and Lee McFarland, Dr. Ridgely, and the visitors of the Inyo National Forest.

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.

The Cal Poly Forest Friends is a team of three Cal Poly senior engineering students: Victor Espinosa, Kevin Ly, and Lisa Yip. The first part of the team name, "Cal Poly", was chosen because the senior project will be designed, built, and engineered at California Polytechnic State University, San Luis Obispo. The second part of the name, "Forest Friends", because the senior project is working with the Friends of the Inyo to create a better and more efficient way of creating a wooden sign. Potentially, this project could be advertised to broader national forest organizations to promote a more efficient method of generating trail signs for the thousands of miles of forest trails and roadways within the United States.

Paul McFarland is an employee of Friends of the Inyo, and sponsor of this project. He works during the summer to help maintain the forest after the winter season has finished. Currently, he uses a hand router to carve letters into the sign, typically taking two to three days, and would like the assistance of the Cal Poly Forest Friends to develop a better solution.

Lee McFarland, father of Paul McFarland, is the co-sponsor of this project, as well as an interdisciplinary senior project advisor. Lee McFarland will be able to assist the Cal Poly Forest Friends with communication with the sponsor and development of the project.

Dr. John Ridgely is the advisor for Forest Sign Carver interdisciplinary senior project. He will be mentoring the Cal Poly Forest Friends during the year-long project to ensure that the Cal Poly Forest Friends are applying the fundamentals of the design process and are progressing the project properly.

The visitors and hiker that trek through the mountain trails rely on indicator signs to safely explore the wilderness. Nearly 4 million people visit the Inyo National Park each year. The wooden signs that the Forest Sign Maker will need to produce will only populate wilderness trails, meaning that the visitors that will be reading them will have the luxury to stop and read the sign up close if need be. By adhering to the trail sign guidelines provided by the United States Forest Service, the Cal Poly Forest Friends will help visitors be able to readily understand the sign and continue with their exploration without issue.

6.5 Customer Requirements

The objective of this endeavor is to design, prototype, qualify and document a machine that can be used by Paul McFarland, or other members of the Friends of the Inyo, for the purpose of creating trail signs for the Inyo National Forest.

The following outlines the customer requirements as perceived by the Cal Poly Forest Friends[1]:

6.5.1 Machine Capabilities

- Must be able to route letters and symbols on a rectangular, flat blank of redwood or equivalent density lumber
- Maximum board dimensions: 2’ x 4’ x 1.5”
- Minimum board dimensions: 1’ x 1’ x 0.75”
- Must be able to handle knots and other internal deformities in the blank sign
- Must be able to completely route a sign faster than a single person could
- Must mount on top of an indoor workbench of dimensions: 3’ x 8’ x 40”
- Must be able to operate year-round

6.5.2 User Interface

- Must have an integrated computer system to store and load electronic files
- Must have a monitor screen and keypad to manipulate the electronic files
- Interaction with the mechanical system must be kept at a minimum

6.5.3 Operation

- A user’s manual must be provided upon completion of final prototype

[1] There are several customer requirements that take the form of engineering specifications directly. They will be listed both as customer requirements as well as engineering specifications in this document.

- Must be simple to use
- Must be low maintenance
- Must be easy for a person to load and align a blank board

6.5.4 Standards and Regulations

- Must adhere to the requirements listed in the Forest Service Wilderness Guidelines provided by Lee McFarland[2]
- Should adhere to OSHA guidelines for acceptable noise levels

6.5.5 Safety

- Must be quick to shut off
- Moving components must not be exposed during operation
- Must minimize the quantity of pinch points
- Operator must wear proper safety equipment during operation

The final prototype for this project, the Forest Sign Maker, must satisfy all of the above customer requirements in order to consider the endeavor a success. Any additional requests made by the sponsor, or any other stakeholder, are considered to be beyond the scope of the project, and the Cal Poly Forest Friends are not obligated to satisfy them. However, every reasonable request will be discussed and evaluated to produce the reliable product the customer deserves for their sponsorship.

[2] See Appendix A for a list of PDF documents referenced to generate engineering specifications that abide by the regulations outlined by the USDA Forest Service.

7 Background

7.1 Guidelines for Trail Signage

Due to the purpose of this project, it is essential to understand the human factors that are involved in the experience of the end user. In order to benefit the end user (the hikers) the most, the words must be easy to read without impeding the wilderness experience. An example of such a human factor that was considered in trail sign design letter height that is sufficiently large for the average person to easily read it from a safe hiking distance. Unfortunately, quantifying these characteristics requires an exhaustive amount of metadata analysis on the involved human factors.

Conveniently, the FS has published standards for the creation of signs that specifies the aesthetics and geometric constraints of the signs, refer to Appendix A for a copy of said guidelines. These guidelines cover a wide range of signs, from highway road sign to small trail signs, with the primary focus being clarity and readability. On the same note, 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 the hiker.

The scope of this project is concentrated on the wooden trail signs that measure from 1’x1’ up to 2’x4’. The guidelines published by the FS provide suggestions for the layout of the text, including font, stroke size, spacing, and symbol sizes. Fortunately, the wooden signs that are to be produced by the Forest Sign Maker are intended to be located in “Primitive” and “Non-motorized” National Forest System Trails (NFSTs), so solid wood is the only base material the Forest Sign Maker will be required to accommodate, see Figure 1 below (Forest Service).

		Semiprimitive			
Item	**Primitive**	**Nonmotorized**	**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 1. FS guidelines snippet confirms sign is to be made of wood, not metal.

In addition to suggesting a base material for the trail signs, the FS also categorizes three different style trail signs that can be seen on NFSTs, see Figure 2 (Forest Service). Due to the scope of this project, the Forest Sign Maker must only accommodate trail signs of shape "TD" (Trail Directional), which are rectangular in design. It will not need to handle odd-shaped signs, such as those of shape "TDW" (Trail Directional / Wilderness).

Furthermore, the FS guidelines indicate a minimum letter height of one inch for the trail signs, which is in accordance to 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 text 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.

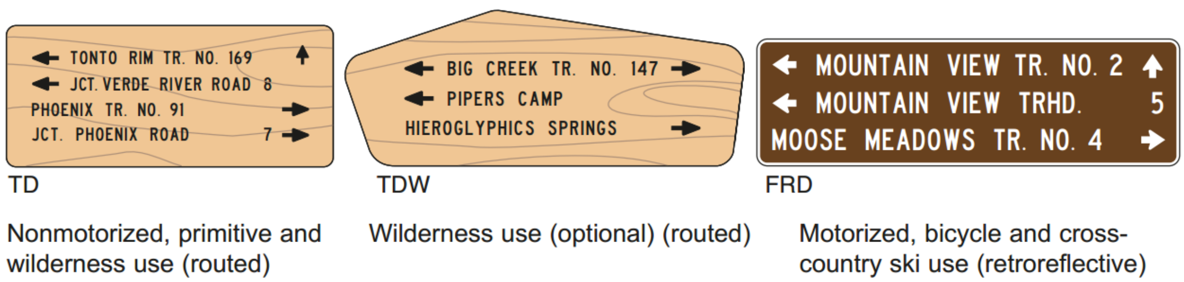

Figure 2. FS Guidelines snippet shows various trail sign shapes, TD being the only shape to be used with the Forest Sign Maker.

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 3. FS Guidelines also specify the standard font to be used for routed signs.

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

7.2 Fundamentals of CNC Machinery

Computer Numerical Control (CNC) implements digital control algorithms in order to control the physical location of an object in three-dimensional space. This can be done without the use of closed-loop position feedback, but that requires the use of stepper motors. If DC servo motors are the actuators of choice, then the CNC depends heavily on measuring the position of the object in order to propel the object in the correct direction. However, in order to accurately measure location, it is critical that the supporting mechanical components are sufficiently rigid, else 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 was not very rigid--then the motor controller will have a difficult time positioning the object accurately. Rigid systems facilitate accurate measurement of the controlled device.

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

The Cal Poly Forest Friends will be considering the rigidity and perpendicularity of the physical prototype while finalizing the detailed design of the CNC prototype for the Friends of the Inyo.

7.2.1 Stepper vs. DC Motor

In addition to rigidity and other geometric constraints required by a CNC machine, the method of actuation is also of great concern. Almost invariably, CNC machines use DC motors connected to a power transmission unit to actuate the system appropriately. This is due to the fact that DC motors are relatively small and can provide continuous motion; 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 a stepper or servo DC motor. By identifying the differences between the two types of motors, it is possible to select the one that is most appropriate for the project:

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, alternating the magnetic field that actuates the stepper motor. These steps are of a precise angle of rotation, and are 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 reliably. Since steppers operate in open-loop control—this means the stepper motor controller cannot verify the actual position of the controlled object; there is no feedback information—there is the risk that the motor could be overloaded, stall, and skip *steps*, resulting in inaccurate and unacceptable performance. The designer must carefully size the stepper motors for the desired application.

Servo motors are brushed DC motors that rotate continuously based on the applied voltage at the two motor terminals, and 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, which means the motor voltage is the only input to the motor, unlike the two pulse trains seen in stepper motors. DC servo motors are most commonly used for closed-loop position control, which ensures the positional accuracy of the machine. The controller would be able to detect if the motors are temporarily overloaded because of the encoder information, and in turn, it would help the motors push through the obstacle, which may be a heavy knot. Furthermore, in comparison to stepper motors, the power dissipated by similarly sized servo motors is less because steppers operate a full power continuously, whereas 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 Forest Friends will consider the performance and power requirements, as well as control interfacing, when selecting the appropriate actuating motors.

7.3 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 (PCBA), 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.

7.3.1 Components

Microcontrollers are designed with practicality in mind: the computing components are usually situated in the center of the PCB, and the interfacing peripherals are located on the edges so that they are most accessible.

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, clock crystal, motor drivers, and communication ports.

7.3.2 Power

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

As mentioned above, power dissipation needs to be considered in order to protect the microcontroller from overheating. There are various techniques to microcontroller board design that can aid in heat dissipation, however, those decisions are controlled by the board designer. Aside from modifying the microcontroller, the most common method of increasing the heat transfer capacity of the board is to use forced convection, or in other words by using a fan. 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.

7.4 Traditional Solutions

With every design endeavor, it is beneficial to research current products or designs that satisfy the problem. If there already exists an appropriate solution, then designing an equivalent product would be an inefficient use of time for all parties involved. After several weeks of investigation for machines that could automatically produce a wooden sign quickly, we had not found a single product that was appropriate. However, the closest two contenders are the Rockler CNC Shark and the ShopBot Buddy. The following is a description of each, and a brief explanation as to why it is inappropriate for this project.

7.4.1 Rocker CNC Shark HD 3.0

The Rockler CNC Shark HD 3.0 has already been considered by the sponsor of this project, but it is not appropriate for the project for two reasons: cost and capacity. This machine costs $4,000, which is slightly over the budget (see Engineering Specifications), and 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 (Rockler).

7.4.2 ShopBot Buddy

Further research into possible CNC routers led us to discover another possible solution: the ShopBot Buddy. The ShopBot Buddy Model BT48 Buddy has a size capacity that is sufficient for this project: 2’ x 4’. However, it is delivered pre-assembled with their proprietary CAD/CAM software, which limits the amount of personal modification the sponsor or future engineering students may be able to perform. Not only are these features and services superfluous, they come at a high cost of $15,954, which is too high for the customer (ShopBot).

7.4.3 Outsourced Labor

Finally, 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 including shipping, labor, and the shop’s profit margins. Having a personal CNC machine to make signs is an economical approach to create faster and cheaper signs that are not meant for large volume production, which we expect from the Forest Sign Maker.

7.5 Alternative Solutions

7.5.1 Laser Cutting

An alternative to producing trail signs using a wood router is a high power CO2 laser cutting system. Interestingly, despite the high price tag and design implications of a high power laser cutting system, the laser cutter method may be more appropriate for this application. Laser cutting is naturally limited to a two-dimensional plane, which is ideal for sign making. As well, 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 the charred etchings that remain on the board. Additionally, laser cutters can operate on a wide range of soft materials, such as acrylic or Medium Density Fiberboard (MDF), not just redwood. There are two main consequences working with laser cutting systems: high capital and operating costs, and low production rate.

The laser cutting system itself is an assembly of many optical components, such as the laser tube, electron source, focal mirrors, CO2 ducting, and a cooling subsystem. All of these components are required to operate a high-power laser safely and efficiently for long durations of time, and the total investment is steep. For example, a standard 40 Watt CO2 laser tube costs approximately $240 on EBay, and the lens and mirrors can cost $120, reaching a total of $360 for just the glassware itself. With the addition of the refrigeration, CO2, and ventilation systems, the entire cutting system would cost several hundreds of dollars, which is unacceptable for this project when compared to the single 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 high immediate costs, the power consumption and operating costs would also be steep. The high power laser, of course, consumes a larger amount of energy, but the majority of the power consumption comes from the support system, i.e. the motors and pumps required for the refrigeration, CO2, and ventilation systems.

7.5.2 Two-Dimensional Printing

As an alternative to removing material from a blank sign, one could print their own signs. It is possible to print letters on many materials, not just wood. However, the environmental conditions present during the lifetime of the sign may cause wear and tear on the printed images, resulting in premature fading of the letters and symbols. Using a sign material like metal makes it durable, but it detracts from the natural environment of the forest. As well, according to the National Forest Specifications for signage, metal signs are reserved for motorized trails while wooden signs are reserved for walking trails.

7.5.3 Chemical Etching

The last unconventional option for putting letters on a wooden blank is through a chemical etching process. Commonly known as a pulping through its usage in the paper industry, the process of using complex chemical solutions to degrade the cellulose and, eventually, erode the wood is widely used and has been optimized over the centuries. Normally, pulping chemicals are used in large batches to dissolve all grain structures in the wood. Using chemicals to dissolve specified regions of a board in order to generate letters may be difficult to control since the grain pores act as capillary tubes, and the chemical tends to disperse in the wood rather than remain in deposited area. Another uncontrollable factor in this process is the grain density, which has great influence on the time it takes to dissolve the wood. Due to these reasons, chemical etching may not be an acceptable solution.

7.6 Performance Risks

As with any high speed cutting device, there are a considerable risks involved in the machine design, such as wood chip management, structural rigidity, knot densities, and climate variations. These risks are detailed below.

7.6.1 Wood Chip Management

With all woodworking processes, the production of wood chips is inevitable, and it tends to become a performance issue when it comes to routing applications. For a CNC machine powered by precision lead screws and using 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 is small and lightweight and has the tendency to float in the air. Due to this tendency, sawdust has the capability of coating hard-to-reach areas that larger wood chips would not usually reach. Therefore, all components of the Forest Sign Maker that are not enclosed 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 surface so that they are protected from wood chips accumulation. Secondly, by enclosing the electronics and motors in a plastic shroud, sawdust will be prevented from clogging the internal components. Thirdly, the foundation of the work surface will be designed to try and contain the wood chips on the bed of the CNC machine, which will facilitate clean up or vacuuming.

7.6.2 System Rigidity

The system rigidity is essential to the accuracy of the CNC machine. If the components have a lot of compliance, the feedback information gathered by the measurement sensors will not be accurate, and 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 legible text that matches the desired image.

This rigidity will be achieved through a mostly metal construction, and careful designing of the supporting components. For each component, the mechanical loading will be considered, and the optimal geometry will be implemented. For example, long, horizontal members will be required to have high bending moments about its neutral axis 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 routing, so the rigidity of system will contain the motion of the CNC machine. Routers are especially prone to gouging and tearing of the wood, which exerts very high forces on the support mechanism, so securing all the moving components is essential.

7.6.3 Knot Density

The presence of knots in the blank signs is a potential performance risk due to the increased grain density. These regions will exert a much higher resistive force on the Forest Sign Maker, and also pose the threat of dislodging itself 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 the knot. As well, all components must be able to withstand the impact of a projectile knot without failure. These risks would be addressed by oversizing the support and actuator components of the Forest Sign Maker, and by shielding sensitive equipment with an impact-resistant cover.

7.6.4 Climate Variations

Another unique consideration that must be made for the Forest Sign Maker is that of climate variations. Normally, the machines operate in closed, stable environments such as a machine shop or warehouse. The Forest Sign Maker will reside and 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 materials selected and system design must accommodate this temperature range so that operation remains consistent during all seasons.

A successful Forest Sign Maker project will address each of these performance risks directly, as to ensure proper satisfaction of the customer requirements. Refer to the following section, Section 6: Engineering Specifications, to see how these risks have been translated into engineering specifications, or refer to Section 9: Final Design Concept for an explicit description of how the Forest Sign Maker design addresses the above performance risks.

8 Engineering Specifications

From the listed customer requirements in the Introduction, a working table of engineering specifications could be made. Refer to Appendix B for the Quality Function Deployment (QFD) Table that served as a tool to produce the tabulated engineering specifications.

A more detailed perspective on the testability of each engineering specification can be found in Table 1, which lists the formal engineering requirements. To be able to interpret the information, the concepts of risk and compliance must be explained.

Table 1. Formal Engineering Requirements

Index	Parameter Description	Requirement or Targets	Tolerance	Risk	Compliance
1	System Weight	200 lb	Max	H	T
2	Width	3.5 ft	Max	H	T
3	Length	6 ft	Max	L	T
4	Height	4 ft	Max	L	T
5	Cost	$3,500	Max	H	A
6	Sign Production Time	2 hrs	Max	L	T
7	Max Blank Size	2 ft x 4 ft	± 1/4"	L	T, I
8	Positional Accuracy	Target dimension	±1/16"	H	T
9	Cutting Depth	3/16 in	± 1/16"	L	T
10	Graphical User Interface	Web Application	--	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

A few of the requirements outlined above in Table 1 have been quantified by the sponsor in the customer requirements because they pertain to the physical packaging of the machine. The operating location for the Forest Sign Maker is inside Paul McFarland's workshop, on top of his current workbench, which is approximately 3' x 6' x 40" (width x length x height). Lee McFarland has noted that there is a little less than a foot of clearance behind the workbench, so the width of the machine must be no wider than 3.5 feet. The length of the machine must not exceed the total length of the workbench. The height of the ceiling is approximately eight feet, so the maximum allowable height for the machine is four feet.

Aside from the physical constraints due to the operation location of the machine, there are regulations laid out by the United States Forest Service, see Appendix A, which have influenced the engineering specifications. For example, Specification #9 in Table 1 describes the cutting depth requirement, which is specified US Forest Service document EM 7100-15, see Appendix A. This cutting depth is also preferred by the sponsor because it will ensure that the letters remain visible on the sign after being passed through a planer, which is the process of making a wooden surface very flat. The planer removes approximately 1/16" – 1/8" of material, so a relatively deep cut is preferred. Furthermore, Specification #8 is also governed by the US Forest Service for trail signing.

Regardless of the chosen cutting method, Lee McFarland has purchased a Bosch Colt Palm Router, which weighs approximately 3.3 lbs. The mechanism that holds the cutting device must be able to interact readily with the Bosch Colt. Since the Forest Sign Maker must endure many hours of continuous operation, the router will become worn relatively quickly, so the mounting scheme must be designed for simple swapping of the router, in case one fails.

Additional engineering specifications are inspired by the moral emphasis on safety. It is our responsibility to design for safe use and operation of any machine, hence the motif in Specifications #15 - #19. The vacuum hose will reduce the quantity of airborne particles that can harm the operator; the clamps are required not only for accuracy, but to prevent the wood from spinning off the machine; the emergency shut off capability allows the user to assume control of any situation.

Further development of the Forest Sign Carver will reference the specifications outlined above. Due to the dynamic nature of this document, engineering requirements may be added or removed on a case-by-case basis, with clear approval of all the stakeholders. See the implemented revisions below.

8.1 Revisions

There have been a few notable revisions that have been made to the list of specifications, including changes made to Specifications #1, #5, and #10, as well as the removal of previous specifications after discussions with the sponsor.

The overall weight specifications was relaxed from the previous maximum value of 100 lbs. to a more reasonable 200 lbs. There were two reasons for this change: the previous limit was not a hard specification, and the CAD model developed suggests that the weight of the system is to be closer to 150 lbs. The main concern with weight is transportation of the machine from the Cal Poly campus, where it is to be fabricated and assembled, to Paul McFarland's workshop in Inyo County, where it is to be installed. With the revised specification, it will still be possible to readily transport the machine, while remaining structurally sound.

In addition to relieving the weight specification, we have also agreed to relieve the project budget. Through the detailed design process, it became evident that the desired capacity of the machine is a driving factor for the cost of the machine. For longer travel distances, the support components must be enlarged, resulting in high material costs alone. These increases in size also tend to propagate further into the design, forcing other components to be oversized as well. Furthermore, it has been decided between the Cal Poly Forest Friends and Lee McFarland that the Forest Sign Maker design should focus more on robustness and durability, rather than low cost.

Another major specification that was changed was the user interface program in which the operator would design the sign. Previously, it was suggested that Adobe Illustrator (AI) be the input file program due to Paul McFarland's familiarity and accessibility to AI. However, constraining the Forest Sign Maker to interact solely with AI quickly became a large obstacle that did not warrant the effort. A custom graphical user interface (GUI) was designed and approved by Lee McFarland, more detail on the GUI and reasons for switching away from AI can be found in the Final Design section of this document.

The fourth specification change that warrants explanation is the removal of the total enclosure requirement. Previously, it was desired to have a total enclosure that would cover the Forest Sign Maker during operation, ensuring the safety of the operator and facilitating debris management within the workshop. After initial cost analysis and CAD modeling of the total enclosure, it became evident that the enclosure itself would cost approximately $400 for the materials and features. Discussion with Lee McFarland resulted in the conclusion that the benefits of the total enclosure would not be worth the time and money to implement. The vacuum system will be the primary form of wood chip management; the router mounting plate will be intentionally oversized in order to make the router bit as inaccessible as possible during operation, as to decrease the possibility of accidental injury.

Lastly, the loudness specification was removed from Table 1. It was removed because of two reasons: 1) it would be difficult and impractical to attempt to control the sound level of the machine, and 2) it would be simple enough to require the operator to wear ear plugs if the operating noise is too great.

9 Design Development

The primary objectives of the brainstorming sessions were to define the various subsystems of this project, as well as generate as many solutions as possible. The subsystems, and the various options for each subsystem, are outlined below.

9.1 Subsystems

9.1.1 Movement

Movement is the action of moving the cutting tool relative to the board. The movement subsystem options below reflect various options of high-level cutter movement schemes, varying from linear motion to rotational motion. These movement configurations will govern future programming commands of the CNC controller, because linear motion lends itself well to programming in a Cartesian coordinate system, and rotational motion lends itself well to cylindrical coordinates. The cutting tool will etch symbols such as letters onto the board and eventually produce a sign.

9.1.1.1 Gantry

A gantry is a rigid bridge that moves horizontally and in this case, would be suspending the cutting tool, see Figure 4. The horizontal movement of the gantry allows movement in x-axis, while an additional actuator on the gantry will move the cutting tool in the y-axis direction, allowing an additional axis of motion. This setup is the industry standard for CNC routers, as it allows simple linear motion, but can reach every point on the workpiece without sacrificing rigidity.

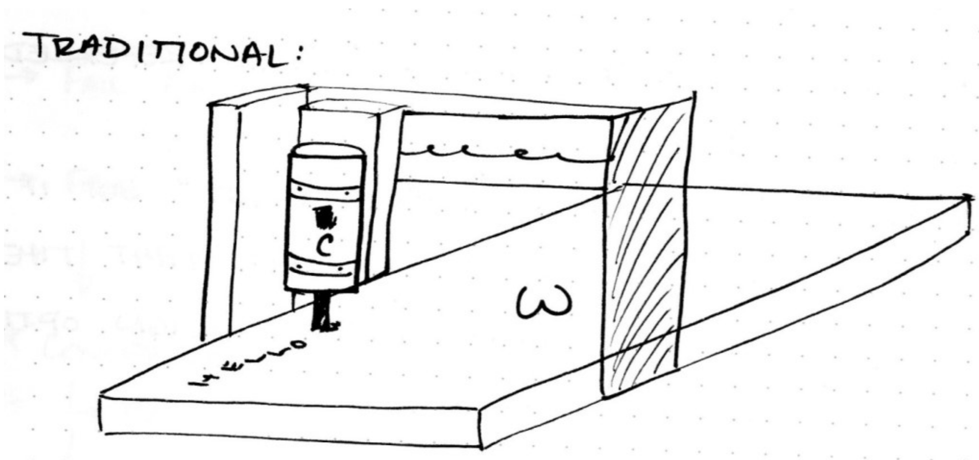

Figure 4. Traditional Gantry Layout

9.1.1.2 Drawstring

The drawstring method requires that the cutting device is suspended above the workpiece by a network of cables attached to pulleys located on the edge of the sign making machine, see Figure 5. This design is inspired by aerial cameras of football fields. By pulling cables towards one direction, the suspended cutting device will follow the direction of the increased tension, thus the cutting tool moves across the board. The major drawback is the lack of control in the vertical height of the tool, it is not trivial to raise or lower the cutting tool.

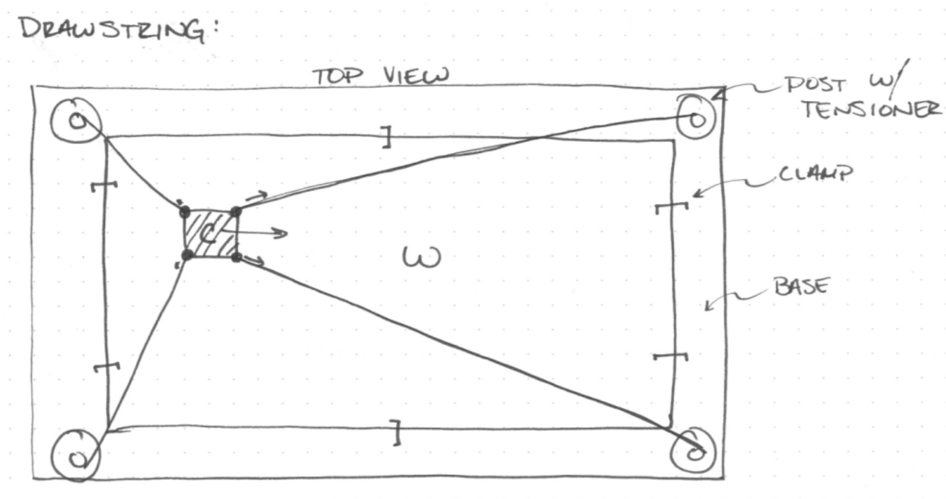

Figure 5. Drawstring Top-Down View

9.1.1.3 Tower

The tower design is similar to the gantry option, except instead of the workpiece positioned horizontally, it is positioned vertically standing up, see Figure 6. This will save floor space, but potentially limits the feasibility of workbench mounting. The drawback is the influence of gravity when the router needs to be raised or lowered, despite that resolving the debris management issue in part.

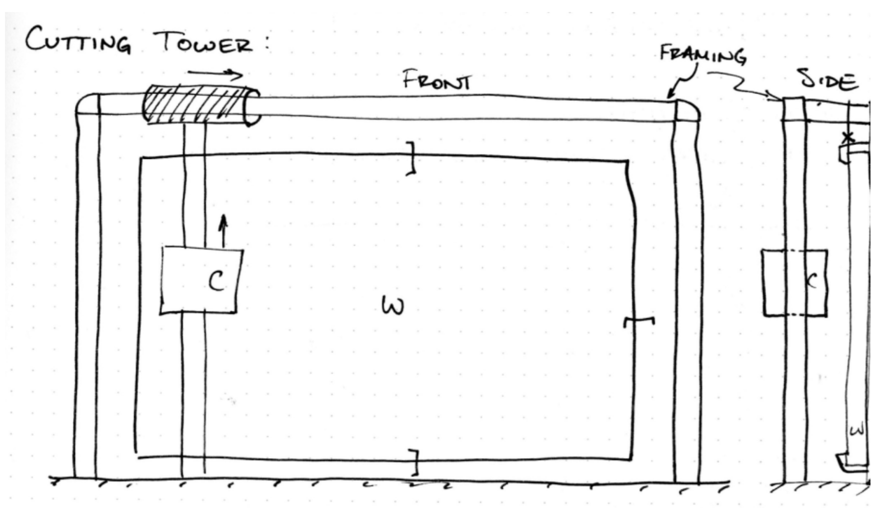

Figure 6. Cutting Tower Layout

9.1.1.4 Strong Arm

The strong arm design uses the cutting device attached to the end of an arm with 2 pivot points that provides rotational motion, see Figure 7. The two pivot points provides enough range to every point of the board. The advantage is that only 2 motors, albeit large motors, are required, one for each pivot point. The disadvantage is that the arm system needs to be heavy in order to support its own weight across the 4ft of the workpiece.

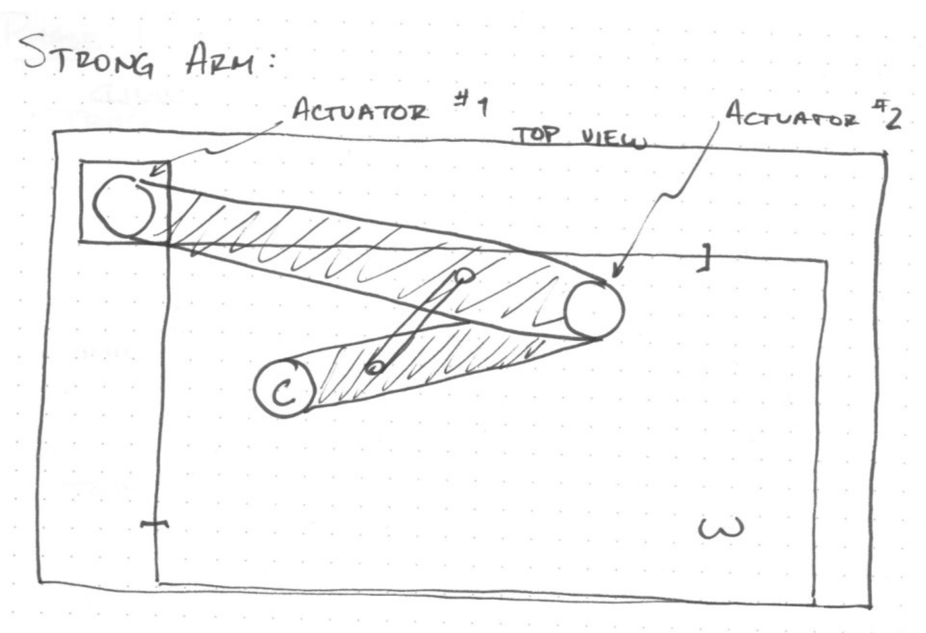

Figure 7. Strong Arm Top-Down View

9.1.2 User Interface

The user interface is the space where interactions between humans and machines occur. The interaction is to allow effective operation and control of the machine from the human end. Some aspects include data input methods such as touch screens and graphical user interface (GUI). A user interface is required in this project to ease the use of our customer's interaction with the prototype. To fit with the customer requirements, this workstation is required to have a digital display and be able to run a design program. A personal computer (PC) was used as a benchmark for the user interface. It was used because most companies and family households own a personal computer.

9.1.2.1 Tablet PC

A tablet is a portable station that can be brought anywhere to increase the productivity. Specifically, a tablet PC will be able to provide a high level of user interaction without the risk of sawdust clogging the mechanics, since they are void of physical buttons. This will allow the design computer to be adjacent to the Forest Sign Maker in Paul McFarland's workshop, providing a modular product.

9.1.2.2 Personal Computer

A personal computer is a computer that is meant to be used by an individual at a time, rather than a mainframe computer. It is traditionally either a desktop or a laptop, both featuring a keyboard, a cursor, or a trackpad. PCs are built powerful enough for general everyday tasks, including data processing from Adobe Illustrator files or other design programs to CNC instructions.

9.1.2.3 Custom Display

A custom display would require Cal Poly Forest Friends to design, build, and engineer non-keyboard method to input data. Custom displays feature limited buttons and options, but the limitations makes the purpose of the display precise. It is designed specifically for the purpose of the Forest Sign Maker. Examples of other custom displays are the microwave timer and buttons or a car's navigation system.

9.1.3 Microcontrollers

A microcontroller is a simple, versatile, lower-powered computer processor that can execute programs. It is small in size and inexpensive, enabling it to be a good starting point for different projects. The three most readily available, affordable and similarly sized popular microcontrollers are: Arduino Uno, Raspberry Pi Model B+, and BeagleBone Black. Using any one of these microcontrollers will enable us to take advantage of the open-source software, allowing us to reference and build on.

9.1.3.1 Arduino Uno

Arduino consumes very little power and is great for simple projects such as interacting with objects in the deal world, see Figure 8. However, as a minimalistic board, it lacks a graphical interface. Since it is inexpensive and small, the Arduino cannot handle complicated projects that require a lot of computing power.

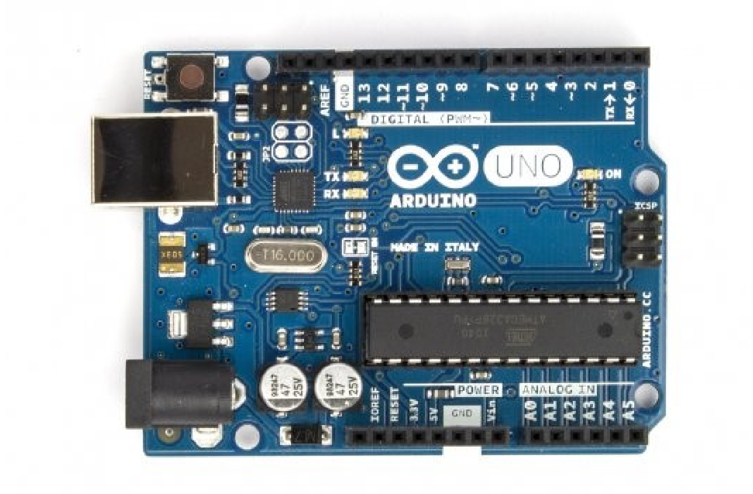

Figure 8. Arduino Board

9.1.3.2 Raspberry Pi B+

The Raspberry Pi is a tiny, low-powered computer that runs Linux from an SD card and can run all sorts of projects that requires a graphical interface or the internet, see Figure 9. Its advantages include a 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 is as powerful as a 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 the other microcontrollers.

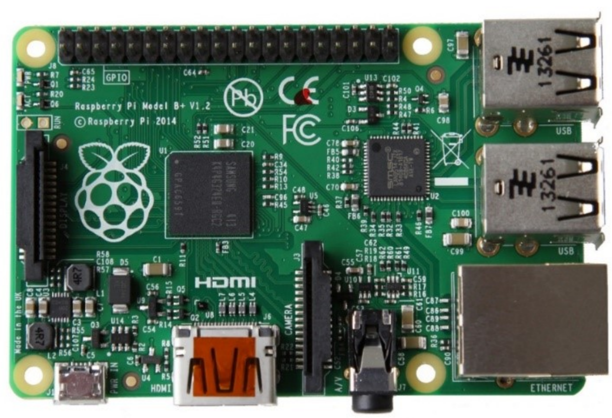

Figure 9. Raspberry Pi B+ Board

9.1.3.3 BeagleBone Black

The BeagleBone Black is a combination of a Raspberry Pi and an Arduino, see Figure 10. It is best suited for projects that are too complicated for an Arduino, but don't require the graphics of Raspberry Pi. It can connect to the internet and unlike the Raspberry Pi, there are ways to connect to external sensors. However, since BeagleBone isn't as popular compared to the Arduino and Raspberry Pi, there won't be a lot of open-source ideas and materials to reference from.

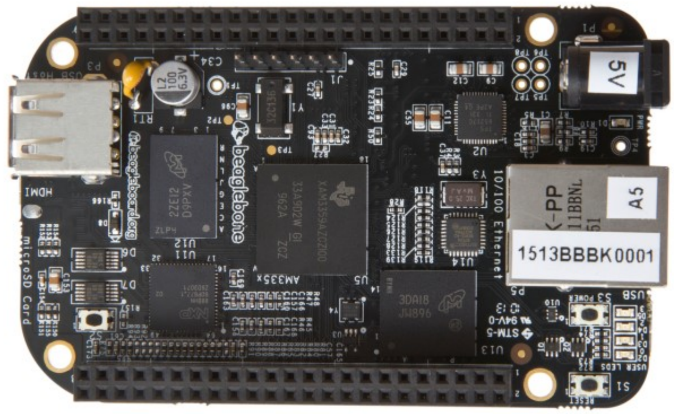

Figure 10. BeagleBone Black Board

9.1.3.4 Custom Microcontroller

Instead of purchasing a pre-made board, a custom PCB can be designed with the microcontroller and other components picked. Then the board's schematic can be sent out to a fabrication shop and the board will be delivered. By designing a PCB by hand, the board will be very specific to its application and has no wasted features.

However, a custom PCB adds more complexity to the overall system than a pre-designed PCB. If the custom board breaks, then a replacement will be more costly than one that's readily available on the market. The effort to design the board will also require time, which could be recovered if a market ready board is used instead. Also, orders to fabricate custom boards are more expensive than buying a pre-build one.

9.1.4 Cutting Module

The cutter is the tool used to mark 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. Below is the comparison.

9.1.4.1 Router

A palm router is a power tool that uses a high speed routing bit to remove material from the workpiece, typically wood. Removing material this way produces a lot of debris and wood chips, which may interfere with the performance of the router and the finish of the 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. Safe operation requires the CNC machine to move the router relatively slowly through the wood, while the feed speed should be able to be adjusted depending on the type of wood that is being cut.

9.1.4.2 Laser

For detail on the construction and investment required to assemble a high power laser cutter, please refer to the Background section 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. Laser cutting requires a substantial amount of electrical energy in order to produce the required flow of electrons, and generate sufficient ventilation for safe operation of the laser. Lasers are also complex by nature and, therefore, expensive.

Since the laser cutter appears to be a valid option, the Cal Poly Forest Friends believed it was warranted to investigate the laser cutter in the Mustang ’60 machine shop on the university campus. During the test run of the laser cutter, a small piece of MDF board was used, and the text “TEST” was to be etched 1/8” deep, see Figure 11.

Figure 11. "TEST" Laser Etch

The laser cutter spent over two minutes to produce this etching. Extrapolating this rate to a time requirement to produce a sign. Laser cutting also burns the wood, producing a burnt odor and an inconsistent quality of cut. Due to the nature of wood fibers, the depth of the cut varied slightly, and did not produce a smooth texture. This slow cutting speed is why they consume more power than a typical palm router: the cutting process is longer, so the laser will run for a longer duration of time compared to the router.

9.1.4.3 Chemical

Chemicals can be deposited to eat away the workpiece material. By carefully applying chemicals on specified areas of the workpiece, the surface will erode and reveal the desired image. Chemicals that can dissolve wood include sodium hydroxide and sulfuric acid. Both chemicals are very dangerous. After the letters are dissolved away, the board must be washed of debris and the dissolving agent.

9.1.4.4 Print

Printing is the action of applying colored ink onto the board to distinguish characters from the difference in color. Print does not involve stripping away material, but instead adds a coat of color. Printing is simple, and works well for metal signs used on motorized roads, however, this project will produce signs for hiking trails.

9.1.5 Actuation

The actuation subsystem will define the method used to locate the cutting module, and it will control its location in three-dimensional space. The chosen actuation subsystem must consider the presence of wood chips, but also consider the required accuracy of the system. Below are the various options for transmitting power and actuating the Bosch Colt router:

9.1.5.1 Belts and Pulleys

For this option, the system will use pulleys to generate tension in the belt, which will pull the attached payload. The payload for this project will be the cutting tool and gantry mechanism. Even though this option allow for 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.

9.1.5.2 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. 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, but the power loss due to friction may be significant. In order to maximize the efficiency of the lead screw, thread profiles other than standard ACME thread could be investigated.

9.1.5.3 Rack and Pinion

The rack and pinion 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. 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.

9.1.6 Foundation

The foundation of the CNC machine will serve two purposes: it must provide a structural base for the gantry mechanism, and it must be able the affix the desired wooden board is the bed which the workpiece will rest on. It will feature clamping spots for the workpiece to hold on to, as well as include mounting features for fastening the entire system to a work bench.

9.1.6.1 Wooden Board with T-Slots

A hand assembled board where a wooden board bigger than 2’ x 4’ will be purchased, then grooves will routed in order to situate the T-slots extrusions flush with the top surface. The simplicity of the design will facilitate fabrication and assembly, however, it will not be durable and may break down prematurely.

9.1.6.2 Metal Plate with T-Slots

The metal plate with T-slots option is similar to the concept above, however, in efforts to increase the durability of the design, the wood would be replaced by metal, most likely aluminum. The total weight of the system may increase too much due to the heavy weight. Furthermore, due to its size, the quality of the aluminum plate, such as its flatness and perpendicularity, are not controllable and will be governed by the fabrication process.

9.1.6.3 Prefabricated Bed

A pre-made bed could also be purchased, saving time and effort to build one. Upon research, finding a bed at least 2’ x 4’ large is difficult online, and can be expensive. Although a prefabricated bed is an easy solution, it may not perfectly satisfy the requirements.

9.1.6.4 T-Slotted Extrusions

Instead of manufacturing an entire foundation surface using a large piece of material, stacking multiple t-slotted extrusions next to each other is another option to produce a slotted work surface. These extrusions vary in size, and are relatively inexpensive for the quality of the parts. However, each piece needs to be fastened to the machine, so the quantity of screws increases significantly.

9.1.6.5 Cast Aluminum Foundation

An entire bed can be made by making a using a mold then casting aluminum into the mold. This process is complex and not easily feasible. This will allow the entire bed to be made out of one piece, which is structurally beneficial. Casting cannot accommodate intricate shapes, so casting T-slots may be difficult.

9.2 Safety and Risk

Due to the nature of moving parts and the usage of devices to cut wood, there is the risk of accidental injury to the customer due to the impact of moving parts or sharp fast moving blades. It is a hazardous machine and can cause injury if the machine is not used properly. For the general well-being, safety options have been deliberated to reduce the risk of injury.

9.2.1 Vacuum Capabilities

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 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 and can coat the rotating parts in a film of dust. Sawdust is the biggest risk to safety and performance, but it will be mitigated through the vacuum system.

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

9.2.2 Emergency Shutoff Switch

The emergency off switch is an easily accessible mushroom button on the machine that when pressed, will shut down the entire machine. In the event of a malfunction or if the user wishes to turn off the machine, then the button can be pressed, and the current job will terminate. This will eliminate the potential for accidental injury if something goes awry during the cutting process.

9.2.3 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, and the copper material will be completely shielded. 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 in order to mitigate fatigue stress and cracking of the copper.

9.2.4 Overheating

Overheating of any electronics and hardware raises much concern because it often leads to component failure if not addressed properly. The motors have been oversized so that the load torque maximum is comparable to the continuous load rating of the motor, which is 25W. The motor drivers can easily provide this power continuously, due to a hefty factor of safety while using the VNH3SP30 drivers. The rest of the electronics have the risk of overheating due to the enclosed design of the impact cover. If testing shows that some of the electronics or the power supply is overheating, then it is always possible to install a small computer case fan on the side of the cover to force more heat dissipation.

9.2.5 Operator Pinch Points

To ensure the safety of the operator and other passersby in Paul McFarland's workshop, it is essential to mitigate the severity and quantity of pinch point present on the machine. A pinch point is a location where gaps close quickly, sometimes forcefully. Throughout the design iteration cycle, it is beneficial to locate potential pinch points and provide a solution if possible. Many times, gaps are critical to the performance of the machine, so it is best to address pinch points as early as possible.

10 Final Design Concept

By comparing the perceived performance of each system to the engineering requirements that they are intended to satisfy, the final conceptual design for the Forest Sign Maker was developed. The decision matrix used, refer to Appendix B for a complete weighted decision matrix for all subsystem outlined previously, shows a combination of successful subsystem options that may be the most appropriate conceptual design. In addition, refer to Appendix C for a complete cost breakdown of the mechanical assembly. That bill of materials provides a complete record of the SolidWorks parts list, as well as all necessary vendor information and pricing.

10.1 Results of Weighted Decision Matrix

10.1.1 Movement: Gantry

After consolidating and evaluating the four potential movement schemes outlined above, it was decided that the "Gantry" method of movement would be most beneficial for our project, see Table 2 below.

Table 2. Weighted Decision Matrix for the Movement subsystem.

Subsystems	Potential Options	Benchmark	200 lbs	3.5ft x 6ft x 4ft	$3500 Budget	2 Hr Cutting Time	3/16" Routing Depth	Design GUI	Debris Management	Slotted Bed	Positionial Accuracy +/- 1/16"	Holds Bosch Palm Router	Table Top Mounting Feature	Shutdown Time: 0.5 sec	Weighted Sum +	Weighted Sum -	Weighted Sum S	Total Score
	Specification Weight		5	8	8	4	10	11	7	9	11	10	6	11				
Movement	**Gantry**	ShopBot Buddy	**S**	**S**	**+**	**S**	**S**				**S**	**S**	**S**		**8**	**0**	**54**	**24**
	Drawstring		S	S	-	-	-				-	-	-		0	49	13	-45
	Tower		S	S	+	S	S				S	-	-		8	16	38	3
	Strong-Arm		-	-	-	-	S				-	S	-		0	42	20	-36

Using a gantry allows for a strong, stable, and relatively simple way to move the cutting tool. By allowing motion in 2 axis, every point on the board is reachable. It also allows easy raising or lowering of the cutting tool. Compared with all the other options, nothing is as simple as the gantry, and some of them have no means of raising or lowering the cutting tool.

A detailed CAD model of the final design demonstrating the movement scheme and various other subsystems has been generated, see the Figure 12 below.

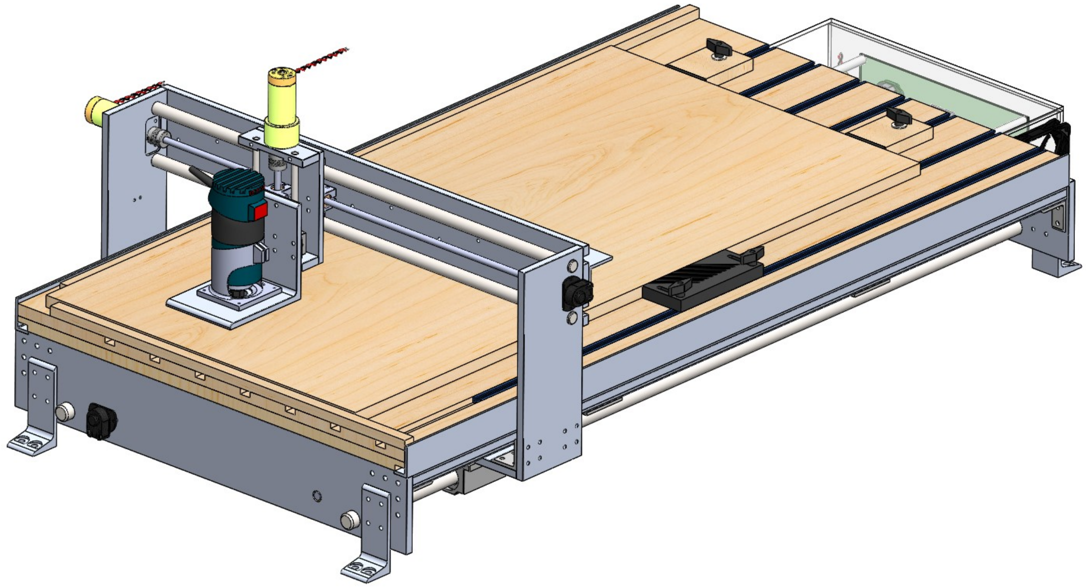

Figure 12. Isometric view of the Forest Sign Maker current SolidWorks CAD design.

10.1.2 User Interface: Personal Computer

The final decision on the hardware to be used to support the user interface is a personal computer. Instead of interfacing with an on-board computer and monitor where the electronics hardware would be exposed to sawdust, Paul McFarland will design the sign layout on his own personal computer inside the house. The design file will then be formatted properly and then installed onto the CNC memory via a USB flash drive, see Table 3 below.

Table 3. Weighted Decision Matrix for the user interface platform.

Subsystems	Potential Options	Benchmark	200 lbs	3.5ft x 6ft x 4ft	$3500 Budget	2 Hr Cutting Time	3/16" Routing Depth	Design GUI	Debris Management	Slotted Bed	Positional Accuracy +/- 1/16"	Holds Bosch Palm Router	Table Top Mounting Feature	Shutdown Time: 0.5 sec	Weighted Sum +	Weighted Sum -	Weighted Sum S	Total Score
Specification Weight			5	8	8	4	10	11	7	9	11	10	6	11				
User Interface	Tablet	PC			+			-							8	11	0	-3
	PC				**S**			**S**							0	0	19	**6**
	Custom Display				+			-							8	11	0	-3

10.1.3 Microcontrollers: Raspberry Pi B+

In the end, the Raspberry Pi B+ was chosen for our application because of its low cost and versatility in an embedded system. It will interface directly with the formatted design file processed on the personal computer via USB, and develop the tool paths necessary for the motor drivers. In addition to the Raspberry Pi B+, the Forest Sign Maker will also house a custom microcontroller that a fellow classmate and colleague, Darren Chan, designed and tested. This microcontroller will be used for its I2C communication capability, serial port compatibility, three VNH3SP30 DC motor drivers, and various general purpose input output pins (GPIO), see Table 4 below.

Table 4. Weighted Decision Matrix for microcontroller selection.

Subsystems	Potential Options	Benchmark	200 lbs	3.5ft x 6ft x 4ft	$3500 Budget	2 Hr Cutting Time	3/16" Routing Depth	Design GUI	Debris Management	Slotted Bed	Positionial Accuracy +/- 1/16"	Holds Bosch Palm Router	Table Top Mounting Feature	Shutdown Time: 0.5 sec	Weighted Sum +	Weighted Sum -	Weighted Sum S	Total Score
Specification Weight			5	8	8	4	10	11	7	9	11	10	6	11				
Microcontrollers	**Raspberri Pi**	CNC Controller Kit			**+**			**+**							**19**	**0**	**0**	**19**
	Ardruino				+			-							8	11	0	-3
	Custom				+			S							8	0	11	11
	Beaglebone				-			+							11	8	0	3

A Raspberry Pi paired with a custom microcontroller was chosen to be appropriate for the scope of the project. A Raspberry Pi comes with an operating system to be able to navigate file systems such as the one found in USB drives. Since the design file is transferred by a USB, a Raspberry Pi is appropriate. If an Arduino was used instead, additional software must be used to interpret the USB's file system.

For this setup, a custom board will be used that combines the microcontroller and motor drivers on a single board. This will have the advantage that less manual wiring is required, as components are already connected by the circuit board.

10.1.4 Cutter: Router

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, but despite that, it is fortunately the most appropriate cutting tool for this project, and was selected via the following decision matrix, Table 5.

Table 5. Weighted Decision Matrix for the cutting tool.

Subsystems	Potential Options	Benchmark	200 lbs	3.5ft x 6ft x 4ft	$3500 Budget	2 Hr Cutting Time	3/16" Routing Depth	Design GUI	Debris Management	Slotted Bed	Positionial Accuracy +/- 1/16"	Holds Bosch Palm Router	Table Top Mounting Feature	Shutdown Time: 0.5 sec	Weighted Sum +	Weighted Sum -	Weighted Sum S	Total Score
Specification Weight			5	8	8	4	10	11	7	9	11	10	6	11				
Working Tool	**Router**	Bosch Router			**+**	**S**	**S**		**S**		**S**			**S**	**8**	**0**	**43**	**21**
	Laser				-	+	-		+		+			S	22	18	11	7
	Chemical				-	-	-		-		-			-	0	51	0	-51
	Print				-	+	-		+		-			S	11	29	11	-15

The current plan for the cutting device on the CNC machine will be a hand router. The machine will accept the Bosch Colt Palm Router, in particular, since Lee McFarland has already purchased that router for this application.

Figure 13. Bosch Colt Palm Router

Figure 13 above shows a Bosch Colt Palm Router with a straight-edge guide attached. The CNC machine will accommodate the router itself, but not any peripheral accessories, such as 90° guide depicted above. 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 is simply a flat plate with a particular hole pattern, which could easily lend itself well to future modifications if need be.

10.1.5 Actuation: Power Screw

After evaluating the above actuation methods, the power screw was selected by means of the following decision matrix, Table 6.

Table 6. Weighted Decision Matrix for actuator selection.

Subsystems	Potential Options	Benchmark	200 lbs	3.5ft x 6ft x 4ft	$3500 Budget	2 Hr Cutting Time	3/16" Routing Depth	Design GUI	Debris Management	Slotted Bed	Positional Accuracy +/- 1/16"	Holds Bosch Palm Router	Table Top Mounting Feature	Shutdown Time: 0.5 sec	Weighted Sum +	Weighted Sum -	Weighted Sum S	Total Score
	Specification Weight		5	8	8	4	10	11	7	9	11	10	6	11				
Actuation	Belts and Pulley	ShopBot Buddy	+		S				+		-				12	11	8	3
	Power Screw		**S**		**S**				**S**		**+**				**11**	**0**	**20**	**17**
	Rack and Pinion		-		S				-		S				0	12	19	-6

Power screws, which can take the form of a lead screw or a ball screw, provide accurate positioning, which is required for the 1/16” tolerance in letter positioning. Belts and pulleys were considered, but through testing and experience with other, were not accurate enough. They will stretch over time, unreliable performance during extreme seasonal weather, and any slack in the belt will manifest itself as backlash in the motor controller. Despite the expense of power screws, their positional accuracy and reliability is worth the investment. The threads of the screws will also be protected by the sawdust because the sleeve nuts will be “hidden” underneath the gantry; it will be impossible for debris to accumulate on the lead screw.

The lead screws will be powered by DC gearmotors using incremental shaft encoder for closed-loop position feedback. For the y- and z-axes, the gearmotor is attached directly to the lead screw shaft. For the x-axis, there are two lead screws that transmit the gearmotor power to the gantry. The rear lead screw, the left screw in the following Figure 14, is driven by the gearmotor, and the front screw is driven in unison via the roller chain mechanism shown. Each lead screw has the same size sprocket, and the spring tensioner retains stiffness during operation. Sample calculations demonstrating the sizing of the gearmotors, lead screws, and shaft encoders can be found in Appendix F.

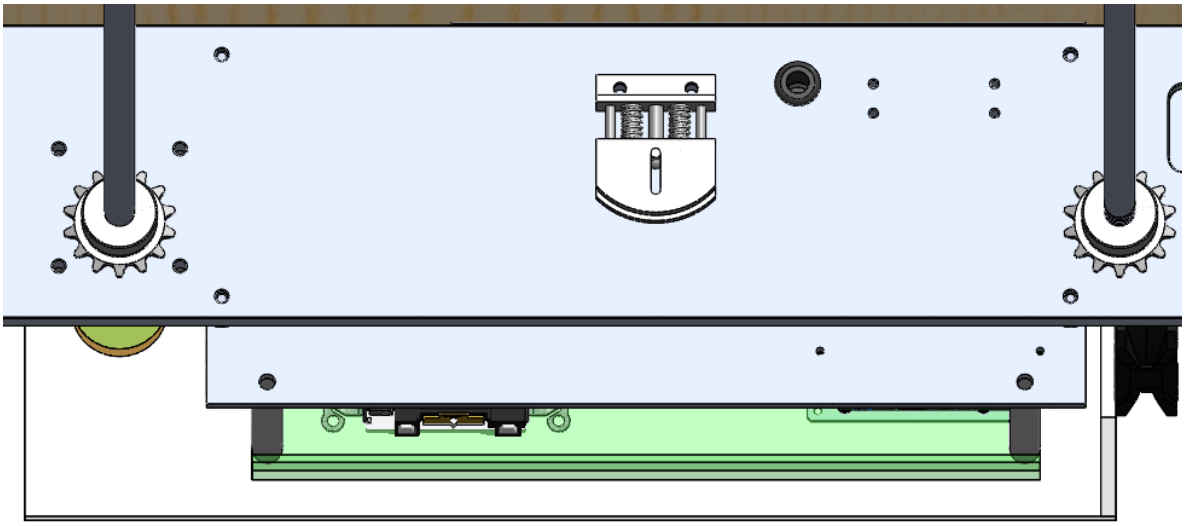

Figure 14. Underside view of the Forest Sign Maker, demonstrating the dual driven x-axis.

10.1.6 Foundation: Wooden Board with T-Slots

Through direct comparison of the foundation surface options described previously, the decision to design a wooden work surface with T-Slots has been made.

Table 7. Weighted Decision Matrix for foundation work surface selection.

Subsystems	Potential Options	Benchmark	200 lbs	3.5ft x 6ft x 4ft	$3500 Budget	2 Hr Cutting Time	3/16" Routing Depth	Design GUI	Debris Management	Slotted Bed	Positional Accuracy +/- 1/16"	Holds Bosch Palm Router	Table Top Mounting Feature	Shutdown Time: 0.5 sec	Weighted Sum +	Weighted Sum -	Weighted Sum S	Total Score
Specification Weight			5	8	8	4	10	11	7	9	11	10	6	11				
Foundation	**Wood w/ T-slots**	Prefabricated Slotted Bed	**+**	**S**	**+**				**S**	**S**					**13**	**0**	**24**	**20**
	Metal w/ T-slots		-	S	-				S	S					0	13	24	-6
	Prefabricated Bed		S	S	S				S	S					0	0	37	11
	Track Extrusions		S	+	-				-	-					8	24	5	-15
	Cast Aluminum		-	+	-				S	-					8	22	7	-12

Even though the wooden board is not the most durable solution to a slotted bed, it is relatively lightweight and inexpensive, see Figure 15. It will also give the sponsor the flexibility to modify it in the future, if necessary.

Lee McFarland was integral in the design of the T-Track design and clamping system. The wooden slots will be cut by Lee McFarland himself, as well as the wooden clamping blocks. The finger clamps will tightly clamp down on the blank sign, and the wooden block clamps will resist any lateral movement of the blank sign during the cutting process. The T-track and the clamp hardware will be purchased from Rockler, per the sponsor's request.

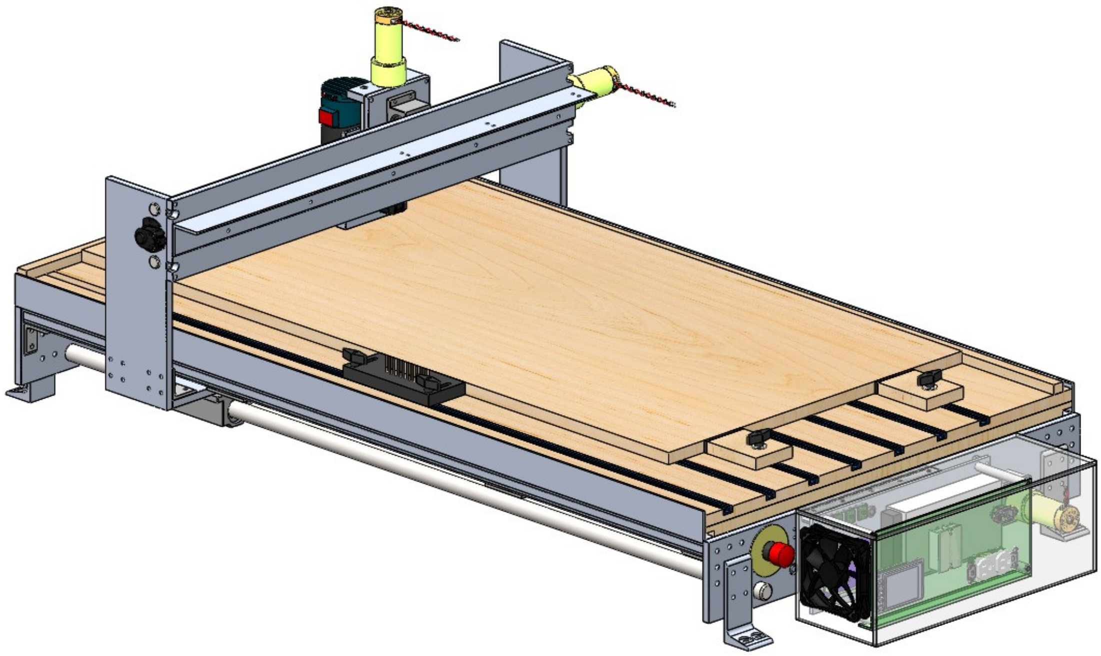

Figure 15. Alternate view of the Forest Sign Maker, revealing the electronics region.

The bulk of the design process was not structured according to the previously outlined subsystem decomposition. The design efforts fell into three different categories: mechanical, software, and electrical design. The mechanical design effort addressed the entirety of the Forest Sign Maker as it would reside in Paul McFarland's workshop; the software design focused on the graphical user interface and tool path generation; the electrical hardware design effort pursued efficient interfacing between the mechanical function and the end user input.

10.2 Mechanical

The final design is comprised of five main subassemblies: the foundation (red), the gantry (yellow), the z-module (green), the cutting module (blue), and the sign clamps (purple), see Figure 16 below. With this decomposition of the subassemblies, it is clear how the CNC motion is composed of x-, y-, and z-travel. Each axis is to be driven by a DC gearmotor that is attached directly to an ACME lead screw. The support guide rods facilitate movement in the prescribed axis by being paired with closed linear ball bearings inside a pillow block. Closed-loop feedback position control will be achieved through the use of low density incremental encoders that will be calibrated before each sign production process.

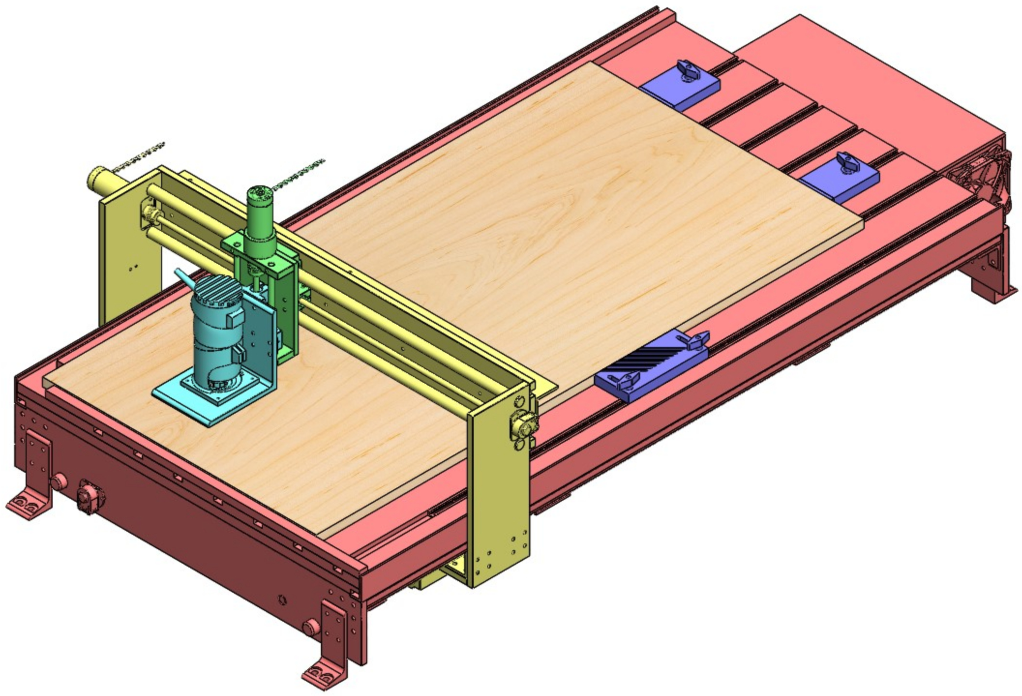

Figure 16. Identifying colors isolate the five subassemblies of the Forest Sign Maker.

10.2.1 Structural

10.2.1.1 System Rigidity

In order to meet the engineering specification of positional accuracy, the entire mechanical system must be sufficiently rigid so that the forces induced by routing wood do not severely deflect the structural components of the machine. If the structural components deflect too much, then it will be impossible to locate the router precisely with respect to the sign regardless of the accuracy of the control system.

Each structural component was sized by using a deflection limit as the primary constraint. The combination of peak load and maximum allowable deflection was used to size all static components. Refer to Section 8.5 for detail on the dynamic components of the system. All sample calculations of load deflection sizing can be found in Appendix F.

10.2.1.2 Foundation

In addition to the wooden work surface described in Section 8.1.6 above, it is comprised of sidewall stiffeners and custom end plates that support the rest of the machine.

These side stiffeners were designed with three important considerations in focus. Firstly, the stiffeners are sized to hold both wooden surfaces, the work surface and the support board. The lengths of the stiffener legs are designed to be long enough to fully encase both wooden boards.

Secondly, the length of the stiffener legs also provide a lip that extends higher than the top surface. This extension will contain a partial amount of the wood chips produced during the cutting process, which assists in protecting the dynamic components from becoming clogged with debris. In Figure 17 below, you can see the z-direction stack-up of the wooden boards and the side stiffeners, as well as see an example of the side T-slot extrusion that unites the end plates and the side stiffeners. The side stiffeners are to be mounted to the T-slot aluminum extrusions via dual end-feed T-slot fasteners; the T-slot extrusions span the two extreme end plates and, when anchoring the side stiffeners, provide the rigidity necessary for proper operation.

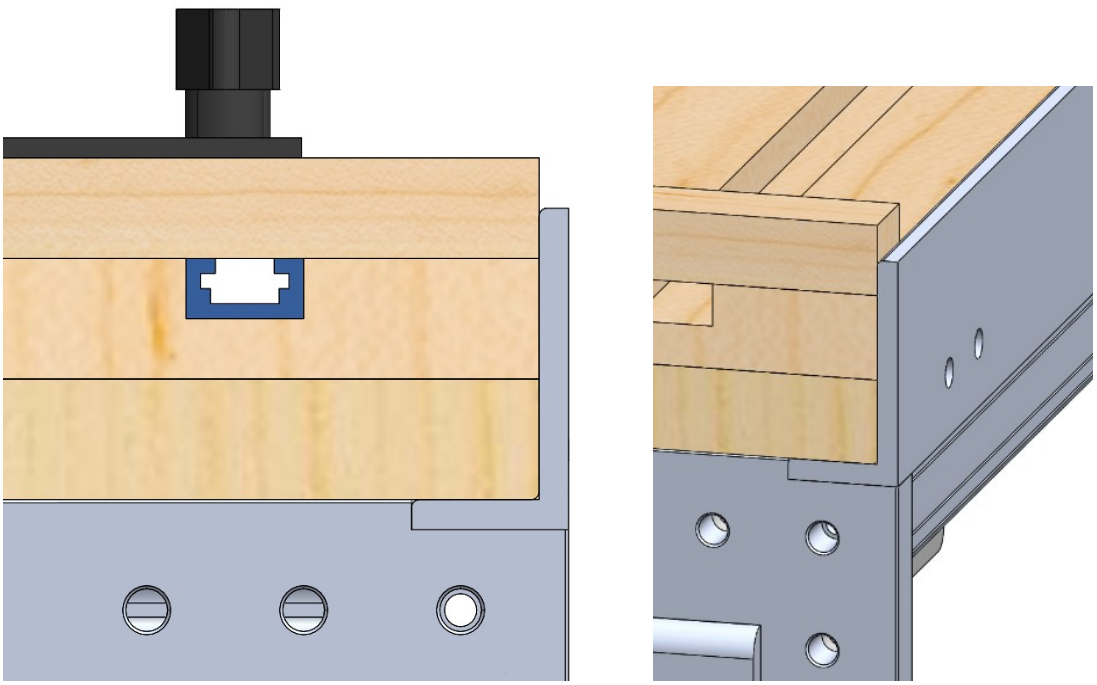

Figure 17. The screenshots show a zoomed-in side view of the board and stiffener stack-up.

Thirdly, these side stiffeners provide anchoring features for fastening the wooden work surface onto the foundation, which in turn provides 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; designing for a solid, rigid foundation ensures the router position tolerance will meet the engineering specification.

10.2.1.3 Guide Rods

The second critical component group that facilitates smooth and accurate performance of the Forest Sign Maker is the guide rods. 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, see 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. In order 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 in order 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.

10.2.1.4 Structural Plates

The third and final major structural system is comprised of the structural plates that construct the gantry and z-module subassemblies. All of these plates are aluminum 6061-T6 flat rectangular bar, and are 5 in wide. The gantry structure is comprised of four ½ in thick aluminum plate to ensure sufficient rigidity for router accuracy. The z-module has two ½ in thick bars as end plates, and a 3/8 in vertical back plate. A final note: to ensure longevity of the aluminum joints, all threaded holes will be fitted with HeliCoil thread inserts. See Figure 18 to clearly view the structural plates.

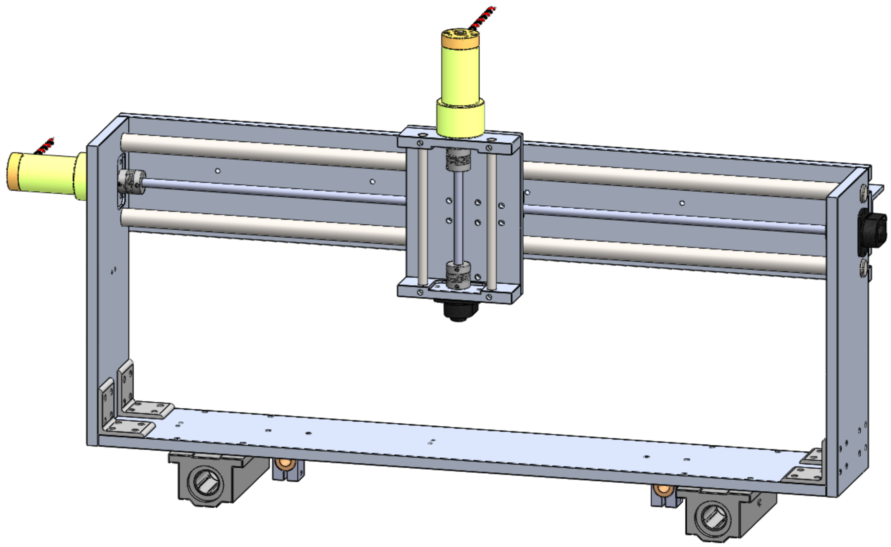

Figure 18. The gantry and z-module subassemblies are shown.

10.2.1.5 Impact Cover

On the operator side of the Forest Sign Maker resides the electronics region. The benefit of consolidating all of the electronic hardware in one region is that it only requires one impact cover to protect all the equipment during operation. The impact cover is intended to serve three purposes: to protect the electronics from impact damage from the surroundings, to shroud the electronics from sawdust accumulation, and to provide a conduit for forced convection heat transfer. Refer to Figure 19 to view the contents of the electronics region that resides underneath the impact cover.

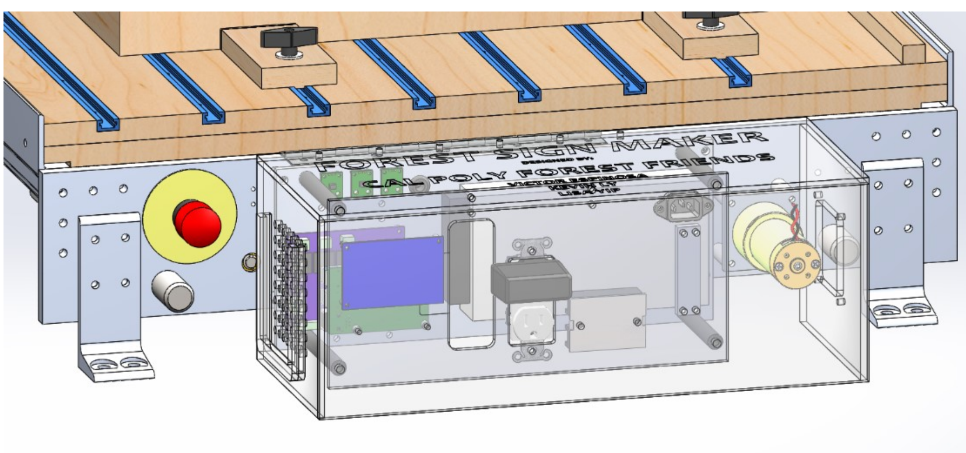

Figure 19. Detailed view of the electronics region.

The material for the impact cover is chosen to be clear acrylic for it resilience and weather resistance. Polycarbonate was considered for this application since it embodies all of the necessary structural properties necessary, but it was rejected ultimately because it cannot be cut with a laser. To facilitate fabrication of the mounting holes and fan port, the impact cover panels will be laser cut instead of machined. Polycarbonate exposed to a laser emits noxious fumes that endanger the operator, whereas acrylic does not.

10.2.1.6 Electronics Mounting Plates

The impact cover ensures the protection of the electronics, however, all the components still need to be mounted in space. Since there are several components that need to be supported, the mounting scheme has been designed to utilize large mounting panels to house multiple components, instead of individually mounting all the components. There are two mounting plates in the electronics region, both being fastened to the Forest Sign Maker via 18-8 stainless steel spacers.

The first mounting plate is the baseplate. The base plate is a 0.25 in thick 6061-T6 aluminum plate, and it will secure the microcontroller board, the current sensors, the AC-DC converter power supply, and the second mounting plate of the electronics region.

The second mounting plate is the green panel. The green panel is transparent dark green acrylic, selected for its aesthetics and ability to be cut on the laser cutter. This panel will support the additional electronic components, such as the Raspberry Pi B+ and the user interface touchscreen.

10.2.2 Actuation

To reiterate, the actuation method of choice is to use a linear lead screw to transmit rotational motion into translational motion. This requires a combination of a power screw and an electric motor, see below for the details on the design of each component.

10.2.2.1 Lead Screw

There are various options for power screws, the two most common forms are ball screws and lead screws. 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. See Appendix F for a sample calculation of the lead screw thread calculation.

10.2.2.2 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 three power domains that exist within this machine; the electrical power is transformed into rotational motion via the dc motors, however, the rotational energy is again converted into a 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, see Appendix F for a the motor selection calculations, 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.

10.2.3 Fasteners

Due to the size of the Forest Sign Maker, a large quantity of threaded fasteners will need to be used to hold the components together with sufficient rigidity. By using fasteners to adhere all the necessary components, it reduces the criticality of each individual piece, providing a final product that is 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 is to be built, so its 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 has been tackled with regard to the fasteners is the complexity of the purchase list. Only two screw sizes will be used for fastening the subassemblies of the Forest Sign Maker, aside from the plastic screws used to mount the electronic components. This greatly reduces the quantity of parts in the Bill of Materials, and facilitates servicing and replacements, if necessary.

10.2.4 Addressed Performance Risks

In the previous Section 7.2 Safety and Risk, five major concerns regarding the safety of the operator and the machine were acknowledged: vacuuming capabilities, emergency shut off, electrical power and conduits, overheating, and operator pinch points.

The Forest Sign Maker will be fitted with large diameter PVC tubing that will be intended to not be removed. It will have an inlet port situated right in front of the debris cavity of the Bosch Colt router, and the outlet port will be oriented behind the back wall of the gantry facing the electronics region. This configuration will allow the majority of the wood chips and debris to be quickly vacuumed during operation, but also provides a detachment point close to the operator. This feature will allow the operator to easily detach the vacuum hose after a trail sign has been produced, and manually vacuum the remaining debris.

The second critical safety feature of the Forest Sign Maker is the emergency shut off switch. The selected switch is a red, plastic, pull-to-reset mushroom switch that will be panel-mounted next to the machine user interface so that the operator can readily press it. It only regulates one circuit, and opens the connection when pressed, therefore, cutting power to the circuit. However, it is not desirable to disconnect power to the entire machine, rather only to the components that control the potentially dangerous equipment: the motors and the router. The Raspberry Pi B+ and the touchscreen need not be turned off in the event of an emergency, so there will be a second circuit that will always be hot, and will be dedicated to powering these components.

However, even when there is no emergency during operation, the Forest Sign Maker as a whole has the capability of dissipating approximately 1000 W under extreme load well beyond the design operating point. Each component of the machine must, therefore, be rated to the appropriate power level to avoid catastrophic failure. The power cables are 18 AWG and will be robust enough to handle the current draw. All the power connections will be rated for up to 15 A, including the power outlet and router extension cord. In addition, hole passageway will be lined with a rubber grommet to ensure that the wires are protected from the vibration metal edges. Lastly, the motor cables will be bundled into a single sleeve, and will be fastened to the machine via zip tie downs to control the motion of the cables and prevent accidental pinching or entanglement.

As with pinching of the cables, it is necessary to eliminate potential pinch points for the operator. This has been achieved by designing gaps that are larger than the average human finger. For example, the distance between the gantry walls and the foundation end plates when at its maximum or minimum position will never descend lower than 1.25 in, which is large enough for a human finger to pass through easily. The gaps are created through strategic positioning of the mechanical limit switches that extend above the surface of the endplates, see Figure 20 below.

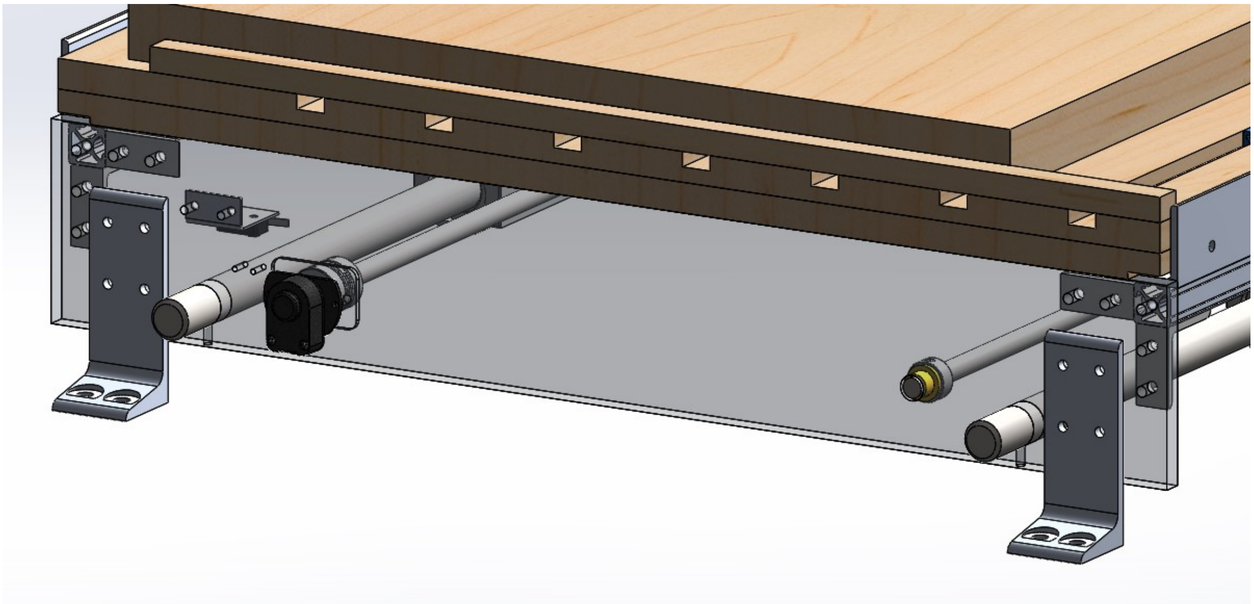

Figure 20. Detailed view of left endplate. Endplate is transparent to view limit switch.

Lastly, the concern of overheating has been addressed using a combination of an impact case and a case fan. The impact has other primary motives for design, but one consequence is that the electronics are contained within the case. By mounting an air filter on the front of the impact, and fastening a case fan to the back, there is now an air flow conduit through which to force convective heat transfer and cool all the components to a safe operating temperature. This case fan will be powered by the motor controller board so that it loses power when the emergency shut off switch is pressed. Despite being a low power component, the fan blades rotate quickly and may cause potential reason for an emergency shutdown.

10.3 Software

10.3.1 Web Graphical User Interface

Following the conceptual design of the GUI, further research and implementation were done to move the project forward. Originally, since we knew that the sponsor knew how to use Adobe Illustrator, the conceptual idea/design was designed around this. We would create a web application that could read and convert an Adobe Illustrator file into motor signals. The Adobe Illustrator file would have the design our sponsor would like to have created. However, complications occurred when we tried to extract information from the Adobe Illustrator file. Seeing that Adobe Illustrator is a proprietary application, there wasn't an easy way to extract information. Since the focus of our project was to create a simple user interface that could be translated to motor signals, we decided that trying to extract information from Adobe Illustrator would require more effort in this aspect of the project.

Furthermore, another idea was proposed. Recycling the idea of using a web application, it would now instead take in user specifications and output a design file that would then be converted into motor signals on the Raspberry Pi.

10.3.1.1 Motivation for Modified GUI

The reason this solution was proposed was because creating an in-house web application without having to use a third party application, such as Adobe Illustrator, would be easier for the user to use, and also have the ability of designing a file on any browser or computer without having to use proprietary software. The application is be interactive to the user using HTML5. This means that while the user edits the dimensions of the board and text boxes, the design of the board will reflect the edits and change in real time. A prototype of this GUI can be found at http://lisayip.com/ForestFriends/. Although the in-house application may be limited to what it can do compared to Adobe Illustrator, the focus of this user interface is for the user to export data in ASCII characters that could be later translated to motor signals rather than having to convert vectors.

10.3.1.2 Description of Modified GUI

The user would specify the thickness of the board, width and length of the board, the height of the letter in inches (e.g. 1”, 2”, 3”). Then, after entering the critical information of the board, the user will then add text to the board until they are satisfied with the design.

The application, Figure 22, will only be able to support between a minimum board size of 0.75” in thickness, 12” in width and height to a maximum board size of 1.50” in thickness, 48” in width and 24” in height. The user will not be able to change the interface to make it so that the maximum board size is 24” in width and 48” in height. This means that there will not be an option to choose the orientation of the board.

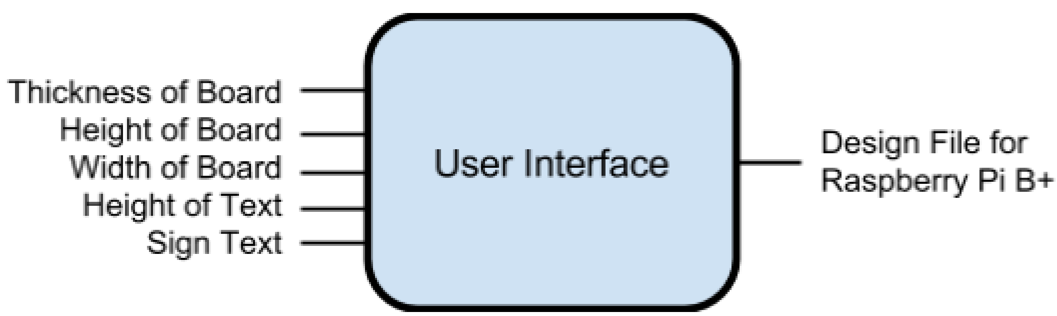

Figure 21. Inputs and outputs of user specifications of a GUI.

Once the user is satisfied with the design, they can save the data by typing the filename on “Filename to Save As” text box, this way the file can have specific names and the file will not disappear. If the user tries to save the file without a filename or on accident, the application will prevent the user from saving and prompt them to add a filename. This application will also allow them to reuse the design file in for future uses through the upload feature. Next, the user would click on "Save Text to File" to save the design file locally to a flash drive, and the data could then be loaded onto the Raspberry Pi B+ to be translated to motor signals. Figure 21 has a more detailed draft of the graphical user interface with specific inputs. A "Choose File" button is created for the user to upload a previously saved file into the GUI. Doing so will ease the use of the interface because it would allow editing of previous work, which will save time.

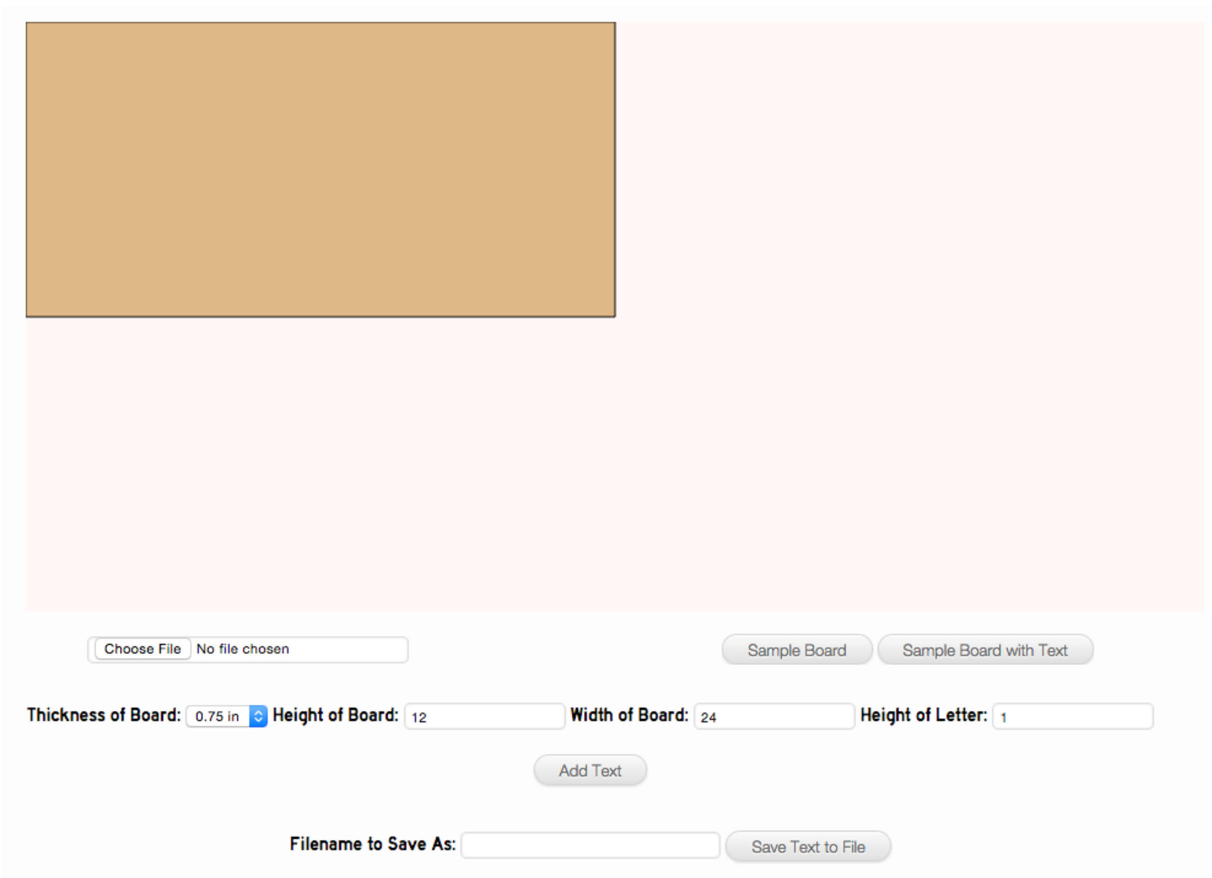

Figure 22. Draft of GUI with specifications.

10.3.1.3 Font Requirements

According to signage guidelines, the letters on signs will all be in capital letters to ensure maximum readability. Highway Gothic is a font used in the signage guidelines and Cal Poly Forest Friends has to adhere to it. To do so, Highway Gothic is displayed in the HTML5 canvas so the user can reference how and where the characters will look like when the letters are routed.

Every inch of the board will be equivalent to 20 pixels. 20 pixels per inch was chosen because we know that the typical monitor resolution is 1024 x 786 (W3Schools). So in order to create an optimally sized canvas, we chose to represent the largest sized board (a 4 ft. x 2 ft. board) to occupy 960 x 480 pixels. in particular, we constrained the width of our digital representation of our board to fit within the width of our resolution. Since 960 pixels is the width of the board and 1 foot is 240 pixels, then the height of the digital representation of 2 ft. tall sign is 480 pixels. Limiting our board to 960 x 480 pixels would allow most of the users to see the board in one screen rather than having to scroll. From the interface, when the user types in “1” for one inch for the font height, width or length, an automatic conversion would be done using JavaScript and correct dimensions would display on the interactive board. They will be limited to select the thickness of the board between 0.75” and 1.50” from a drop down menu.

The reference point of the text is on the bottom left of the word.A better clarification can be seen on Figure 23. The user should be aware of this as it will govern the design of their board when it is being printed.

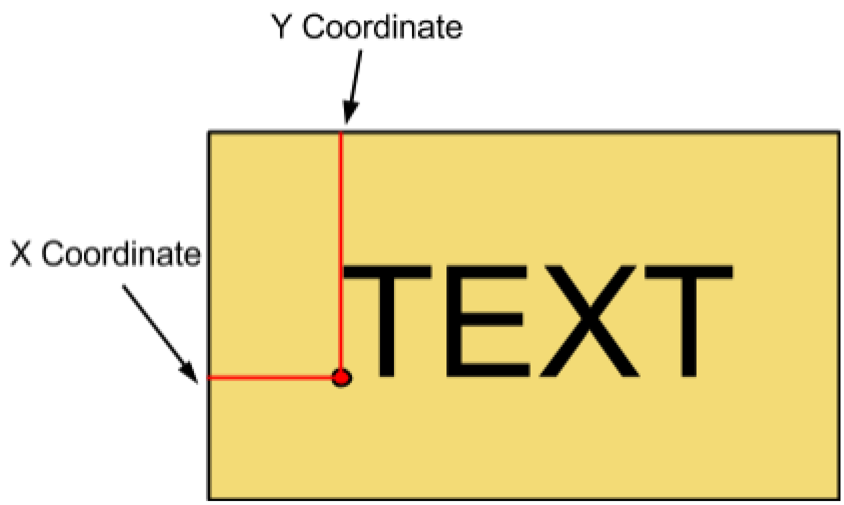

Figure 23. Reference point of the text.

10.3.1.4 Error Checking

Additionally, there will be error checking for the width and height of the board. Since the minimum board size is 12” by 12” and the maximum board size is 24” by 48’, the application perform a check to make sure the board is ideal to fit the machine. The height has a range between 12” to 24” and the width has a range between 12” to 48”. If the user enters a value greater than it’s maximum expected value, the application will automatically change it to the maximum board dimension. This also applies for minimum values, if the a value less than 12”, the application will automatically change the value back to 12”. For example, if the user entered 50” in the height field, the value would automatically change to 24”.

There is also a limitation in the font size. The font size is determined by its height. An input of “1” on the field box would result in a 1 inch tall letter. The font ranges between 1” to 6” high. The font size is limited to the biggest router bit provided, which is ¾”.

Since typical trail signs do not include special characters, the machine will only be routing characters from A-Z, 0-9, space, apostrophe, and underscore. If the user does input a character that is not the previously listed characters, the character will not show up on the design nor will it be saved.

The application also makes sure the text is within bounds of the design. There is a one inch border around the whole design for safety measures. Without the border, the router may accidentally route the clamps or foundation. To prevent accidental routing, the one inch border will be enforced. The application is designed to warn the user if the text overflows the dimensions of the board. A small window will pop up if the text overflows and warns the user, and the text will be highlighted in red. Doing so will allow the user to become aware the mistake in their design. If the warning is ignored and not fixed, the design will not save.

If the user at some point during the design wants to change the font to a bigger size, the coordinates of where the text is located may chance. Since the reference point is located on the bottom left of the character, refer to Figure 23, the application will automatically update the y-coordinate so the text will fit within bounds of the design.

10.3.2 Future Implementation and Consideration

Additionally, we foresee in future iterations of the user interface error checking that will be performed on overflow text. This feature will prevent system failure as well by preventing the router from accessing outside the safety bounds of the board. The user interface will also be able to have a toggle button for “show ruler” as well as “show grids” for ease of use and better reference of the board. As mentioned earlier, the orientation of the board is currently fixed to landscape. Portrait orientated signs could be implemented in the future, however, this feature will add more complexity to the application.

10.3.3 Machine Operator User Interface

From the user's point of view, they would only be interacting with the user interface that is ran with python. Within the python program, during different frames the user goes through, there is backend processing to make machining possible.

When the user clicks on the desired design file, the python program launches a Java program in the background to process the design file and output a render of the design file as well as a coordinate text file for the motor controller board. The design file is parsed and vectors are hand coded to imitate the Highway Gothic Font. An exact duplication is not possible because of how font is normally rendered on a computer screen is fundamentally different than how a router bit with a diameter is marking symbols on a board.

After the Java program is processed, the python program will resume its task. The user will be able to verify their design file and components to confirm before the machine starts. Once the user clicks on “Start Machining”, the user interface will freeze until the machining is finished. To terminate the machining before it is finished, the EMO switched will need to be used. A more detailed description of what the user would be following is located in Appendix I.

A more detailed description of how the letter pathing is processed is located in Product Realization.

10.3.4 Tool Path Translation

After the user has produced an export file containing the data specifying the sign’s design, the next step is to convert those designs into paths in order to be transmitted into the motor controller board.

10.3.4.1 Procedure to Design a Symbol Path

The translation of the design to paths is done on the Raspberry Pi. Essentially, each sign design is a series of symbols which will be routed at a particular location. The symbols are composed of vectors. Take for example the letter “E”. Similar to handwriting, there are 4 vectors involved in scribing the letter “E”. There is the long vertical stroke and 3 horizontal strokes as shown below in Figure 24.

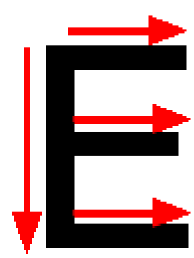

Figure 24. The path used to scribe the letter “E”.

Not all vectors involve symbol strokes, some motion is just used to reposition itself. An example non-scribing vectors is shown in green arrows below in Figure 25 for the letter “E”.

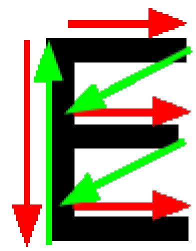

Figure 25. The letter "E" has 7 motions, 4 scribes, and 3 non-scribes.

In this particular example, the cutting tool will start on the top-left then start routing the vertical line. There are other ways to path letters using fewer paths, such as the "E" below starting from the top-right shown below in Figure 26.

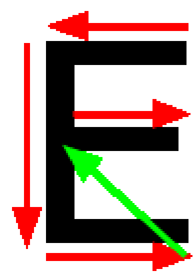

Figure 26. The letter "E" with 5 motions, 4 scribes and 1 non-scribes.

Care will be taken care in designing the paths for each letter to achieve the most efficient path while minimizing non-scribing paths.

Each possible sign symbol will have an associating series of paths. There is also support for arrows. If the user inputs the characters "<", ">", or "^", it will correspond to the actual left, right, and up arrows. The last step of the path conversion is to give each letter's path an origin. The origin will be a coordinate on the board. Assigning the coordinates will take into account the position of the text during the sign design process along with the width and spacing of each letter.

10.3.4.2 Path Simulation

Paths have been made for some letters. Simple straight letters are easily produced and circular letters have been carefully pathed. Since each letter is essentially an ordered collection of vectors, circular paths are made of many small straight lines. The small straight lines will provide enough resolution to appear rounded when they are routed. The figure below shows some sample simulated paths for some letters and a right arrow.

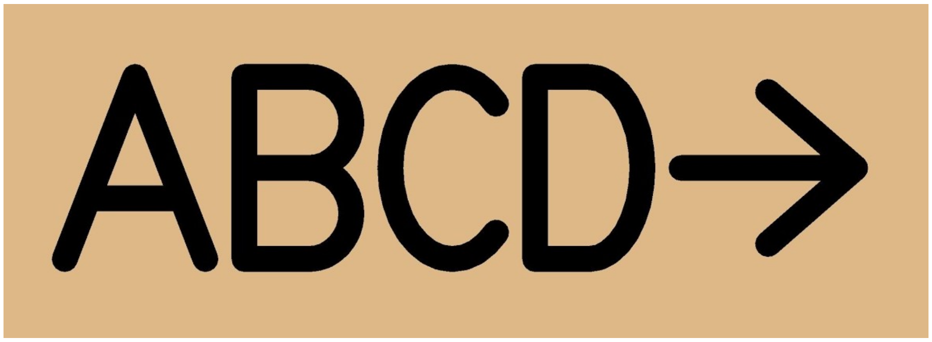

Figure 27. Path simulation of various letters, and an arrow.

Some adjustments will be made to the letter kerning and the stroke width. These initial simulations look good as the letter curves are smooth. For trail signs, the directional arrow is supposed to be filled rather than an outline. To fill the arrow, the router will cut concentric layers inside the arrow until the arrow is filled. The number of layers to cut will be determined using as input the router bit diameter and the side of the arrow.

10.3.4.3 Path Transfer

After determining the positions for each letter, the Raspberry Pi will send the microcontroller the coordinates to move the router. The coordinates are sent as 3 two-byte integer values in the raster coordinate space, representing the x-coordinate, y-coordinate, and then the movement type. The movement type is one of three options: a cut, a non-cutting repositioning movement, and the initial start position of the symbol. An example of the sent information is shown below.

```
(144, 480, 0) // Start position for A
(216, 240, 1) // Cut
(288, 480, 1) // Cut
(168, 400, 2) // Move
(264, 400, 1) // Cut
(318, 360, 0) // Start position for B
(404, 360, 1) // Cut
...
```

Figure 28. Example sequence of path coordinates.

The coordinate numbers are not based on any measurement scale, but instead based on the encoder steps and the guide rod thread to inch ratio. Our encoder will record 32 pulses per revolution and for each revolution, the guide rod will translate is 0.125 in. linearly, so the encoder will record 256 pulses per inch. This is the greatest resolution that can be achieved with the current setup. By using the highest resolution, the vectorised paths will stay as sharp and accurate as possible.

10.3.4.4 Software Design Overview

The structure of the software backend can be modeled using a Unified Modeling Language diagram (UML). Below is a UML diagram of the software structure in Figure 29.

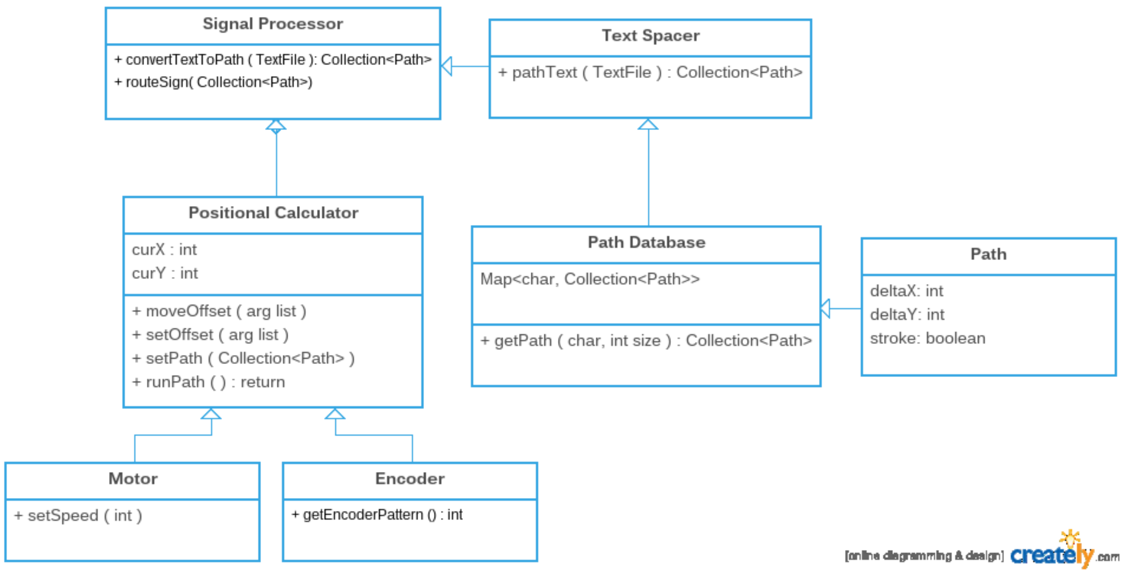

Figure 29. UML Diagram of the software component.

Each box represents a different component in the software system. The starting point is the Signal Processor, which will have as input the design file. The Signal Processor will consult the Text Spacer to convert the symbols into paths, placing gaps between letters as necessary. There is a Path Database which contains pre-generated paths for each letter. The Text Spacer will use this database to convert each letter into a path then output a series of path. The path instructions will be fed in one-by-one to the positional calculator which will move the router to the desired position using the feedback loop created by the motor and encoder.

Different letter heights are also feasible on the system. The letter path can be scalar multiplied for a larger letter. The larger letters will require a larger stroke weight, and so the user will have to install a larger router bit.

10.3.5 Closed-Loop Position Control

The encoder, motor, and motor controller board are all parts of a closed-loop positional control system. For the motor controller board, the encoder is the data input, and the motor voltage is the output. The motor controller board computes the error from the current router position to the desired position. The magnitude of the error is directly proportional to the amount of power applied to the motors in order to correct the router position. As the motor controller board provides the power signals to activate the motor, the encoders report a position of how far the motor moved. A graphical representation of the loop is shown below in Figure 30. For a mechanical controls perspective on the closed-loop feedback loop, see Figure 31 (Forkish).

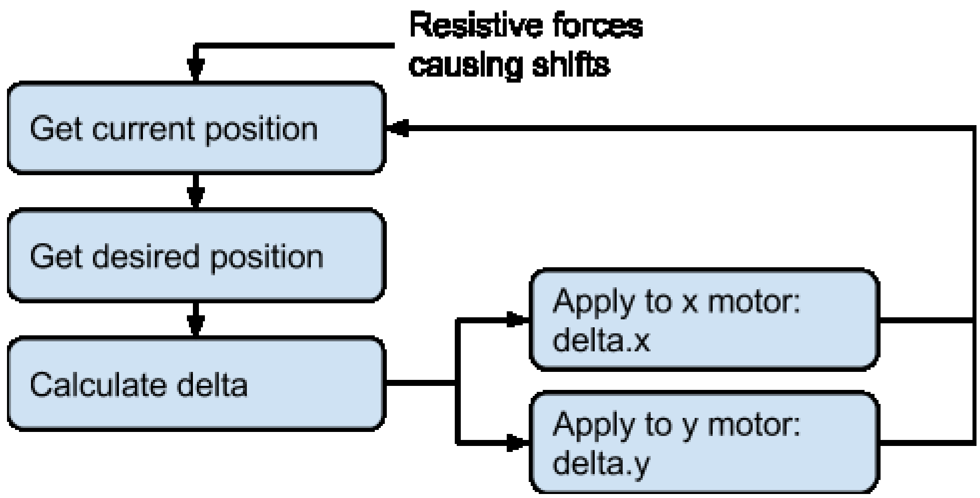

Figure 30. Execution flow of microcontroller.

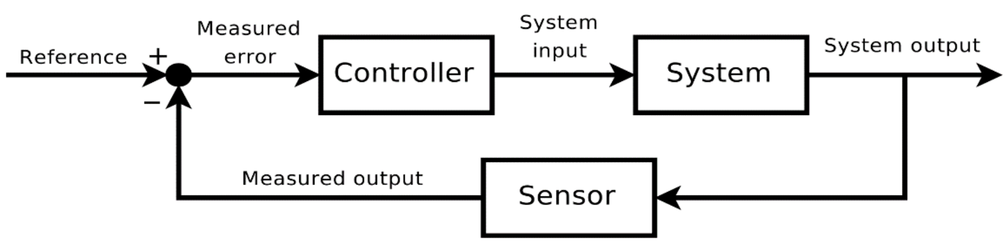

Figure 31. Closed-loop schematic.

Initially, a controller with only proportional action (P-controller) will be tested since it will lead to the least erratic behavior. Any overshoot is unacceptable, since it will lead to a misshaped character in the wooden sign, therefore adding integral action to the P-controller to form a PI-controller is not an acceptable solution to improving performance if a P-controller is insufficient. A proportional-integral-derivative controller (PID controller) will provide controlled movement of the router to ensure that the router will not overshoot any linear motion, but will only be designed if deemed necessary. Once the current character vector has been routed, the motor controller board accepts the next character vector and the closed-loop position control repeats. Refer to Appendix F for preliminary P-controller design calculations.

Using a P-controller lends itself well to ensuring accurate cuts despite the presence of knots in the wood. When the router bit experiences spikes in load forces that attempt to move from its desired path, the P-controller will react to this disturbance error and command the motors to exert more force, correcting the router tool path. This negative feedback loop will ensure the router can correct itself.

10.3.6 User Modes

The Forest Sign Maker supports up to three different modes of operations to provide options on for the user’s desired task. The three modes are: sign making, sign preview, and calibration.

10.3.6.1 Sign Making Mode

The standard operation is a cutting job, where given as input a sign design file, the machine will route the symbols onto the wooden board. This mode is considered to be used the most frequently, as it is the mode used to produce a wooden sign.

10.3.6.2 Sign Preview Mode

Another option is the preview, where given a sign design file, the machine will follow the paths, but not cut symbols into the sign. The X and Y axis motors will activate, linearly moving the router parallel to the board, but the router will be turned off and will not plunge into the wooden board. This mode of operation gives the user a chance to test the movement capabilities of the Forest Sign Maker without having a sign routed. The user also has a chance to check if the board size is correct and estimate if the design is satisfactory.

10.3.6.3 Calibration mode

This mode will exercise the boundary limits of the Forest Sign Maker. By activating this mode, the router will follow the paths to create a border on a 2’ by 4’ board without plunging the cutting tool. This mode is used to estimate the maximum limits of the board dimension and detect if any clamps used to hold down the board could interfere with the cutting tool. If the user estimates that the clamp may interfere with the cutting tool, then the clamp will have to be moved or adjust the design file to not route in that area.

10.4 Electrical

The final subdomain of the Forest Sign Maker is the electrical hardware components. The following provides insight on the final design for the electronics region, including explanations for microcontroller design, power supply selection, custom cabling, and interfacing with the various sensors present in the system.

10.4.1 Microcontrollers

The Forest Sign Maker relies upon a system of computing devices used to perform controlled movement of the router and to interpret commands. Below are the key computing components needed to run the Forest Sign Maker.

10.4.1.1 Raspberry Pi B+

The Raspberry Pi B+ was chosen for its compact size, its operating system, and its support for a touch screen user interface. Having a compatible Linux operating system allows the navigation of file systems and the execution of the programming languages Java or Python, both of each can interface the motor controller board. The Raspberry Pi 2, a recent upgrade to the line of Raspberry Pi products, was taken into consideration. The added boost of processing speed is not a downside, but it is unnecessary. In addition, the touch screen interface is currently only compatible with the Raspberry Pi B+, not the Raspberry Pi 2.

10.4.1.2 Touchscreen LCD Interface

The touchscreen interface was chosen to give the user a friendly visual and easy way to input data. Initially, a 2x16 character dot matrix LCD display with 5 input buttons was considered as our primary Forest Sign Maker interface, but the touchscreen would add far greater value to the system. The screen would allow graphical interfacing using icons such as folders and windows. In addition, a preview of the board could be displayed on the screen.

In addition to the software benefits of using a Raspberry Pi B+, there are two significant mechanical reasons for its selection. Firstly, the Raspberry Pi B+ will indirectly aid in managing sawdust in the electronics region. Due to the inevitable presence of sawdust, it is beneficial to use a miniature touchscreen as the local display; this removes the concern of sawdust congesting the buttons of a non-touchscreen display. The most appropriate display for the intended use of the Forest Sign Maker is the PiTFT + Touchscreen sold by Adafruit. This particular model touchscreen currently only interfaces with the Raspberry Pi B+. Secondly, the Raspberry Pi B+ features the necessary USB-B ports which will allow the operator to connect a USB flash drive to the Forest Sign Maker and upload the design file produced by the design GUI. Other competitive options like the Arduino Uno do not have that capability.

10.4.1.3 Motor Controller Board

The motor controller board is a custom microcontroller designed by a fellow Cal Poly Electrical Engineering graduate student, Darren Chan, which will be able to accept the toolpath positions generated by the Raspberry Pi B+ and output the appropriate PWM signal to power the motors. Furthermore, the motor controller board will not only relay the motor commands, but also interpret sensor data during operation.

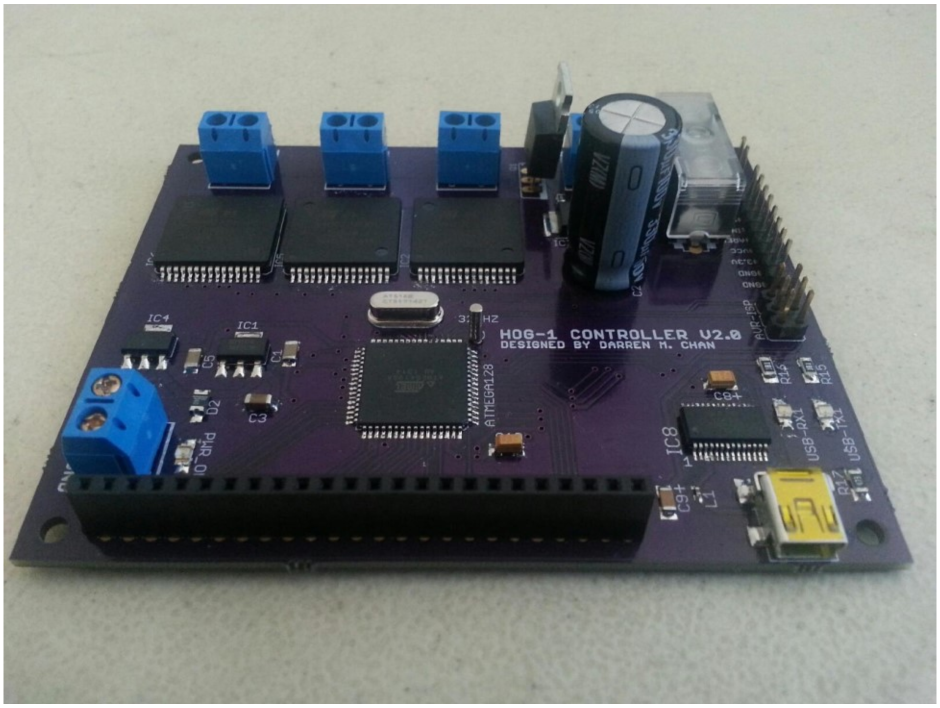

Figure 32. Photo of the motor controller board, courtesy of Darren Chan.

This motor controller board is outfitted with three VNH3SP30 motor drivers that can each output up to 30 A at 40 V, which is appropriately oversized for the selected Pittman gear motors that draw a stall current of 9.6 A at 24 V maximum. The traces on the PCB itself are also oversized to dissipate the large amount of heat. In addition, heat sinking vias are located underneath each high power component as to decrease operating temperature and increase reliability. With twelve GPIO pins, it will be possible to interface with all of the required sensors with some space for a few additional devices if the need arises in the future.

Unlike the Raspberry Pi, the motor controller board can be powered with electricity at a voltage higher than the traditional 5 V. In fact, it must be provided higher voltage power due to the internal DC-DC step down regulators that protect the integrated circuits (IC) from potentially noisy power supplies that could harm the internal circuitry. After consulting with the design engineer himself, it was decided that 24 V could be supplied safely to the motor controller board to power all the components, simplifying the power scheme for the Forest Sign Maker.

10.4.2 Power Supply

10.4.3 Cabling

Despite the clear need for 24 VDC, the primary source of power for the Forest Sign Maker is the AC main line currently present in Paul McFarland’s workshop. Other forms of electrical power, such as battery storage, have been deemed impractical because of the machine power consumption and runtime. The power consumption of the motors alone would draw approximately 6 A continuously, requiring a 48 A-hr battery at a minimum for a full day of operation. The wall AC outlet available in the workshop will provide sufficient power for the motors, as well as the Bosch Colt Router that will be used, so it will be the only source of power for the Forest Sign Maker.

The workshop AC operates at 120 VAC and will be converted to a 24 VDC supply via the selected AC-DC single output 336 W power supply manufactured by Mean Well.

This DC voltage rail will power the motor controller board, which interfaces with the motors, limit switches, current sensors, and the case fan. In addition to this DC voltage circuit, there will be two other AC circuits powered by the workshop wall AC outlet that activate the Raspberry Pi B+ and touchscreen, as well as the router.

To clarify, the Raspberry Pi is not powered by an AC voltage, rather it is powered via mini-USB that provides 5 VDC continuously. A simple USB wall adapter rated up to 2 A and a USB-B/miniUSB cable will be sufficient to provide relatively clean power for the Raspberry Pi.

With regard to cabling, one has already been mentioned above: the USB-B/miniUSB cable that will power the Raspberry Pi. This is a prefabricated cable, so there are not many concerns with its construction. However, the main concern with the Forest Sign Maker cabling is maintaining the integrity of the wire insulation and connection.

There are two other prefabricated cables that will be used for the Forest Sign Maker. Those are the 18 AWG power cable for connecting the Forest Sign Maker to the wall AC outlet, and the 18 AWG extension cable intended for connecting the router to the Forest Sign Maker.

The rest of the cables are custom cables fabricated by the Cal Poly Forest Friends team. The gauge of the wire will depend on the application. For high power applications, 18 AWG wire will be used, and for signal and communication applications, 22 AWG wire will be used. Where applicable, the wire ends will be soldered to a terminal connector, instead of using crimping connectors which will be susceptible to vibration loosening. The terminals that will be used on all stud connections--studs will be used for connecting to the current sensors and the AC-DC power supply--are not going to be fork terminals, but ring terminals to eliminate the possibility of slipping during operation. Furthermore, the soldered joint for each wire will be protected and insulated with heat shrink tubing.

As far as a coloring scheme is concerned, it will be kept as simple as possible. The intention is not to color-code each individual wire, rather group them into three categories: power, ground, and communication. The power and ground cables will be red and black, respectively, but the communication cables will be green to match the aesthetic theme of the machine, and the project as a whole.

At this point, it is clear that a plan for cable management will be necessary. Not only will organized cables facilitate debugging and testing, but it will also decrease restrictive air flow in the electronics region, decreasing component temperature. The cable bundle that extends to the motors and sensors located outside of the electronics region will be secured in as many locations as possible without interfering with the motion of the subassemblies. Tie down holes have been included in the machined walls to allow zip ties to be used, therefore, controlling the motion of the cable. Not only do these tie downs control the cable bundle, but they will also provide strain relief for the connections themselves, increasing the longevity of the Forest Sign Maker.

Sensors play a crucial role for the Forest Sign Maker since they facilitate the automation of the machine. In a way, the sensors are the hands and eyes for the motor controller board, and provide critical position information that makes closed-loop position control possible. There are three different types of sensors used on the Forest Sign Maker: proximity sensors, shaft encoders, current sensors, and the emergency shutoff switch.

10.4.4 Sensors

10.4.4.1 Limit Switches

For the proximity sensor, there are two low-cost, viable options: Hall Effect sensors or mechanical limit switches. The most important benefit of using a Hall Effect sensor is that it is truly solid state, meaning that there is no concern with debris or wood chips interfering with its performance. However, the downside of these sensors is that they require a small amount of power to operate, and require a mating magnet in order to activate the Hall Effect within the sensor, whereas mechanical limit switches do not need power to operate properly and can function without the need to mount magnets in various locations. Standard miniature limit switches are extremely well enclosed and are not at risk for sawdust clogging in the Forest Sign Maker. These switches will be strategically located to constrain the motion of the subassemblies appropriately, and will provide critical calibration data for the motor controller board at the beginning of each cutting process. Each switch will be mounted via #4 machine screws to ensure robustness and repeatability.

It is clear that the switch need only be mounted in the correct location for it to function properly. When the gantry bridge member makes contact with the rigid lever, the switch is pressed and the gantry stops moving. Recall that a Hall Effect sensor would require a magnetic field to function properly, so a small magnet would have to be mounted on the gantry, and the threshold distance would need to be fine-tuned during assembly. In the end, limit switches are the simplest and most reliable option for calibrating the Forest Sign Maker, and preventing accidental damage.

10.4.4.2 Incremental Encoders

While the limit switches provide calibration data, the incremental shaft encoders provides the motor controller board with real-time position data. The encoders will be mounted directly to the far end of each lead screw, measuring the screw angle. This data is essential for accurate closed-loop position control within the motor controller board, since the controller continuously compares the real-time router position to the desired tool path positions. However, it is necessary to interpret the position data accordingly, because the output of the encoder is simply two channels of digital pulses. Each pulse is the result of the shaft encoder incrementing by one division, meaning that the number of divisions is directly related to the resolution of the encoder. This resolution is referred to as encoder density, where high density encoders provide high resolution shaft position information. Due to the relatively large position tolerance for the Forest Sign Maker, it is possible to use a low density encoder from US Digital, which has only 32 divisions on the encoder disk.

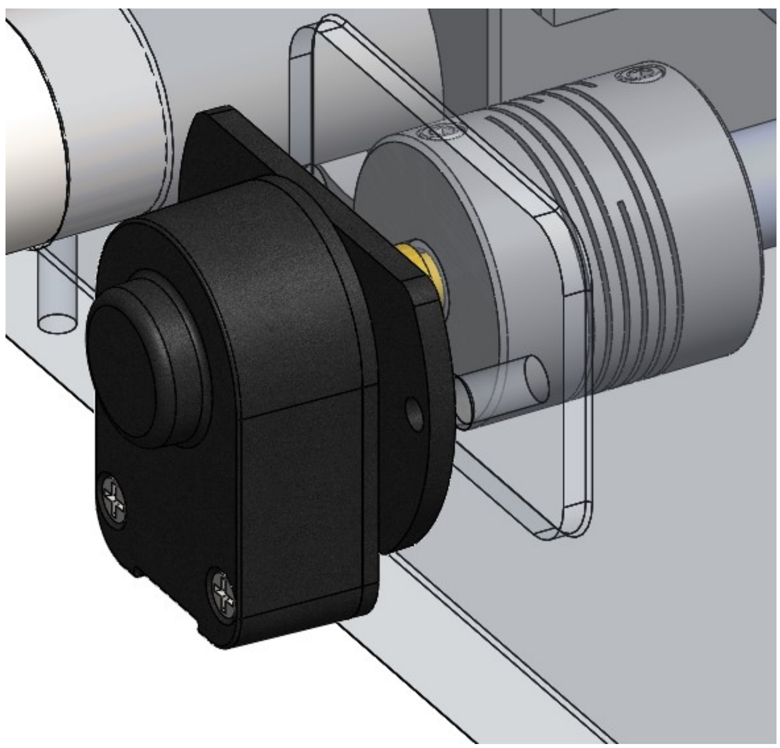

Figure 33. US Digital H5 shaft encoder model, in black.

With this encoder mounted on the lead screws, it will be possible to control the position of the lead screws within 1/32 of a revolution, or approximately 10°. Assuming negligible backlash in the lead screw nut, this corresponds to a linear position controlled range ten times smaller than the required tolerance, which is sufficiently narrow for this application. See Figure 34 below to observe the difference between a low and high density encoder disk (Denney).

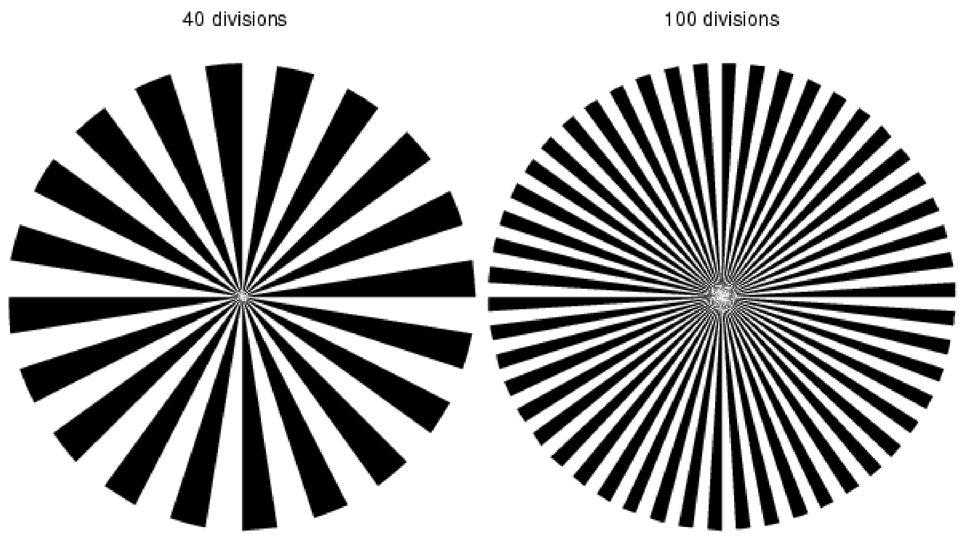

Figure 34. Difference between high density and low density encoders.

Despite the simplicity of interfacing with incremental encoder, the primary ramification is that the Forest Sign Maker will need to calibrate the router position frequently, especially after power to the machine has been disconnected. Absolute encoders maintain the position reading after reconnecting power, however, they require more complex interpretation algorithms and are more expensive than incremental encoders. Refer to Appendix F for the derivation of the minimum encoder resolution allowable for this project.

10.4.4.3 Emergency Shutoff Switch

The emergency shutoff switch is used for an immediate system power down. Electrically, activating the switch will cut off the power for the Forest Sign Maker motors and the router. By cutting off the power, the entire system will come to a halt. The Raspberry Pi will still be powered and can report the last command performed before the switch has been activated. The system will remain on Emergency Off mode until the emergency shutoff switch has been reset to its connected state by pulling on the switch.

11 Product Realization

During Spring of 2015, the Forest Sign Maker's prototype underwent construction and assembly. The entire prototype can be broken down into 2 discrete components, the mechanical side and the software side.

Victor Espinosa has completed the Cal Poly machine shop Yellow Tag certification, so he has the capability to use the vertical mill to machine the custom components. All components that need to be machined on the vertical mill have been optimized for it, considering single setup and minimal tool changes.

Both Kevin Ly and Lisa Yip have their Red Tag certification, so whenever holes need to be tapped, or when we are ready for spray painting, they will be able to assist and expedite the process.

11.1 Mechanical

11.1.1 Wooden Components

There are four wooden components present in the Forest Sign Maker assembly: the slotted work surface, the support layer, the two wooden clamps. These four components were fabricated by Lee McFarland in his garage, since he has all the necessary woodworking tools to fabricate them quickly and accurately.

11.1.2 On-Campus Machining

In efforts to reduce prototyping costs, all machining processes of the raw materials, such as the aluminum angle bars and flat plates, were completed by Victor Espinosa in the Cal Poly machine shops. Due to an unfortunate hand injury, the machining processes were delayed until the second week of the Spring Quarter, leaving eight weeks total for fabrication and assembly. Fortunately, all the components were designed in such a way to minimize part setup and tool changes on a vertical mill, which significantly relieved pressure on the production deadline.

11.1.2.1 Power Machinery

Out of the 33 custom components that comprise the Forest Sign Maker, the vast majority of them were fabricated on the vertical mills in the Cal Poly machine shops, both the Aerohangar and the Mustang '60 shop. The vertical mill facilitated the process of machining faces and features within tight tolerances. Each part setup was preceded by vise calibration using dial calipers, and using a mill edge finder and a DRO to calibrate the machine to each part. In retrospect, it is much more reliable to start and complete a part on the same machine, since each one has its own particular misalignment. Since these machines in the Cal Poly machine shops are available to all students, it was common to use parts that were either dull or compromised due to necessity.

In addition to using the vertical mill to produce the tightly toleranced cuts and precise features, the bandsaw and drill press were utilized for rough cuts and basic drill holes, respectively. The bandsaw, both horizontal and vertical, allowed for the raw material to be decomposed into the rough cut parts quickly. The horizontal bandsaw was used to cut the thick plates of aluminum and large angle bars, and the vertical bandsaw allowed for the raw Delrin plastic and thinner aluminum components to be cut with ease.

The abrasive chop saw was used to cut the steel lead screws, both the ½" and ⅜" diameters, to the proper length. A grinder and jeweler's file were used to deburr and clean the edges so that the bronze sleeve nuts could be threaded onto the screw without marring the inner surface. All the guide rods could have been cut to a proper length as well, but it was decided to not do so since the resulting end would be discolored and the case hardened steel would greatly wear the tool.

11.1.2.2 Presses

Aside from the power tools available in the machine shops, the sheetmetal press and finger break allowed for quick production of the few custom brackets required to mount the x-axis limit switches and the vacuum tubing. The manual hole punch was also used to add offset holes to the continuous hinge of the impact case.

11.1.2.3 Laser Cutter

The laser cutter in the Mustang '60 shop proved to be extremely useful for producing the various acrylic components that comprised the electronics panel and the impact cover subassembly. By saving the desired SolidWorks drawings as Adobe Illustrator files, it was possible to cut the components on the laser cutter at the appropriate scale. Not only could the laser cutter cut the outline of the acrylic parts, but it could also etch certain regions by taking advantage of different color settings. This made it possible to etch the team and product names into the top impact cover panel, as well as produce a rough surface on other panels that made it ideal for adhering joints.

One effect that the high power laser had on the edge finish was that it left a slight draft angle on the edge. Of course, this angle was very small, but it made for unreliable solvent welding, since there was a small gap between two pieces. The result was the formulation of small cracks visible inside each joint, reducing the overall strength. Ideally, each edge would have been routed flat prior to assembly; future iterations would include this step.

11.2 Software

Within the software field, work can be split into 3 stages, sign design, letter pathing, and machine routing.

11.2.1 Sign Design

As described earlier, the design is produced in a web browser using HTML5 and Javascript. An interactive HTML5 component called the Canvas is used as the graphics that will display the sign preview. The Javascript program will interact the Canvas with the Document Object Model (DOM) to dynamically create new canvases and text boxes.

Each line of text is made in its own Context within the Canvas. The space boundaries of the line of text is measured against a computed hard limit of the allowable maximum routing area.

In addition, other inputs such as uploading a file is performed by parsing the chosen file and populating the HTML textbox fields as accordingly. Exporting the design as a file also uses the DOM and its textbox values to construct a string of text which will be saved as a blob on a file.

11.2.2 Letter Pathing

Letter pathing is performed on the Raspberry Pi after the user selects a file through the Raspberry Pi's graphical user interface. The interface library used is Tkinter, which will eventually execute a Java program to perform letter to path conversion.

The vectors are hand coded to imitate the Highway Gothic Font. An exact duplication is not possible because of how font is normally rendered on a computer screen is fundamentally different than how a router bit with a diameter is marking symbols on a board.

Pathing is performed per symbol by specifying the starting point, followed by motions to either produce a line, or instead move to the next coordinate. Strokes with curves such as the letter "O" are produced by many small line segments. To ensure good accuracy in router X and Y movement, diagonal lines are broken into smaller line segments.

At the same time the rendering is generated, a list of coordinates is also being created which specify the movement of the router in order to recreate the sign. When the user confirms the sign dimensions and specifications, the user is prompted to "Start Machining". Upon clicking this button, a serial connection is established with the motor controller board and the Raspberry Pi will send coordinates one at a time to the motor board. The motor board will send notifications back to the Raspberry Pi when the current coordinate is complete and request for another coordinate. At the beginning and end of every cut, the router is instructed to go HOME.

11.2.3 Machine Routing

The control of the motors is performed by the Motor Controller Board. Below is the outline of the entire program of the motor board. Default pin layouts needed for devices to communicate with the board is listed in the appendix.

There are 4 tasks involved to control the Forest Sign Maker: read_serial_task, x_motor_task, y_motor_task, and z_motor_task. Two key state conditions are critical to the order and operation of the machine. zReady and State.

zReady specifies whether the height of the router bit has been achieved yet. The height of the router takes priority over the any lateral motion of the router. So if the z axis is ready, then the x and y axis can move. If the z-axis is not ready, then the x and y axis will wait until the height is ready.

There are 2 modes of movement the gantry will take, either NORMAL or HOME. Under the HOME position, the gantry will move towards the home position until all 3 minimum limit switches are activated. When all 3 switches are activated, the Forest Sign Maker has recalibrated and the encoders will reset back to the zero position.

Under the NORMAL State, the machine will travel to the given coordinate fed in through the serial port.

Below is a State Diagram of the machine using zReady and HOME

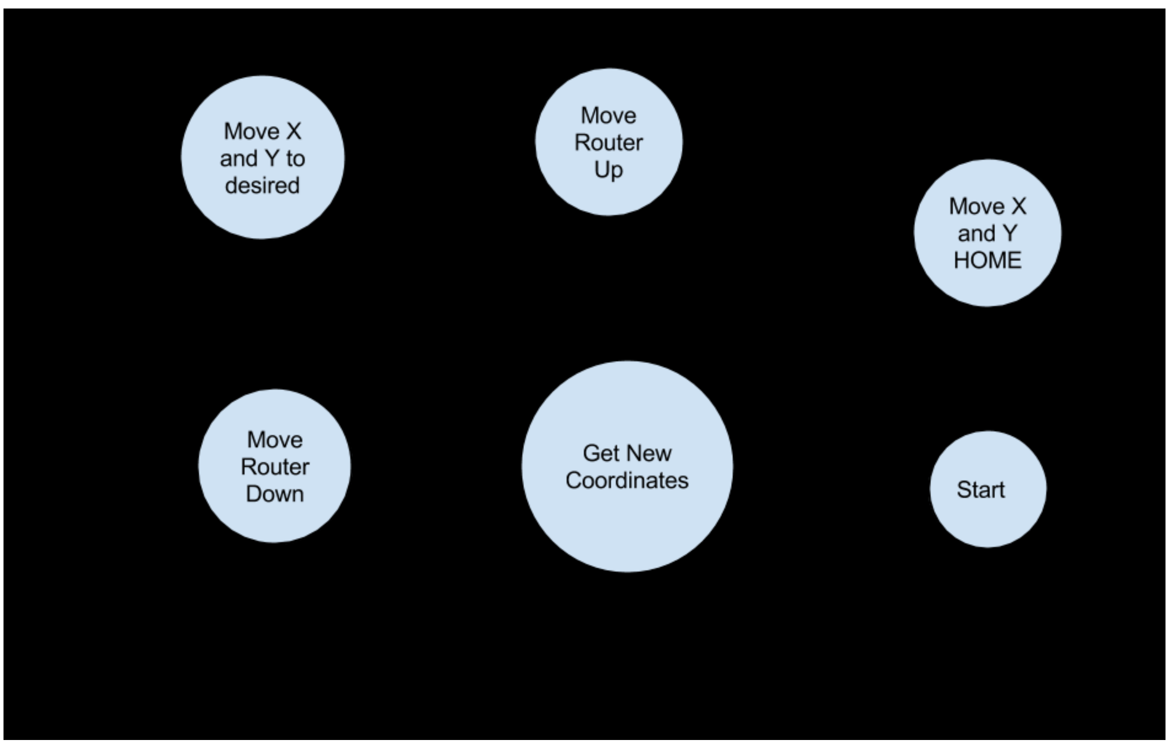

Figure 35. Forest Sign Maker State Machine Diagram

11.2.3.1 Read Serial Task

Read Serial Task is an overarching task that monitors safety and updates the new x, y, and z coordinates. The general program of the read_serial_task is outlined below

```
if all x, y, z positions equals desired:
  retrieve new desired x, y, z
  zReady = FALSE
if any x, y, z maximum limit switch activated:
  shut down machine
if (x, y, z) == (0, 0, 0) or (0, 0, 3) or (0, 0, 4):
  state = HOME
if State == HOME:
  if all minimum limit switches activated:
     state = NORMAL
```

11.2.3.2 Z Motor Task

The Z motor task is in charge of moving the router up and down. Once the router is at the appropriate height, it will set zReady to be true, allowing the X and Y axis to move. The general program for the Z Motor Task is outlined below

```
if zReady == FALSE:
  if State == HOME:
     move in (-) direction until minimum limit switch activated
     zReady = TRUE
  if State == NORMAL:
     move by (desired position - current position)
     zReady = TRUE
```

11.2.3.3 X & Y Motor Task

The X and Y Motor Tasks control the lateral movement of the X axis and Y axis. This is used to move the router across the board and is responsible for scribing the letters. The program for the X & Y Motor Task is outlined below

```
if zReady == FALSE:
  do nothing
else:
  if State == HOME:
     move in (-) direction until minimum limit switch activated
  if State == NORMAL:
     move by (desired position - current position)
```

11.3 Commercial Part Acquisition

On top of the custom parts, there were over 70 component parts that were acquired to complete the final assembly. The primary supplier of these off-the-shelf parts was McMaster-

Carr, however other special suppliers were used when necessary: lead screw parts were purchased from Roton, Inc., raw materials from OnlineMetals, electronic parts from both Adafruit and Digikey, and general hardware parts like screws and acrylic were purchased from a combination of Ace Hardware, Home Depot and Fastenal.

11.4 Temporary Modifications

As with most projects, the Forest Sign Maker prototype contains a few design changes that were not present in the designed model. After initial installation of the bearings, it was clear that there was a mistake in part selection: there was almost no stiffness in the assembly. In particular, the y- and z-axis bearings were too compliant. Each bearing was self-aligning and could accommodate up to 1° of shaft misalignment; with two of these compliant bearings working in tandem, the module was unrestrained and could pivot approximately 2° in all planes. The solution was to replace one of the two bearings with a rigid replacement that would fully restrain the bearing, but then the paired compliant bearing would relieve any residual binding due to shaft misalignment. To clarify, both the y- and z-axis were supported by compliant bearing pairs, but had to be replaced by pairs of compliant and rigid bearings. The replacements were machined from blocks of Delrin plastic to maintain existing tolerance requirements, but allow for smooth performance.

This modification was successful, and has since been implemented into the final design.

Some electrical components also underwent some changes. Through testing of the Motor Controller Board, 2 components were not working as expected. The 24v regulated Vcc power input failed to power the circuit. When attached to a current reader, amperage spiked, suggesting an electrical short. Due to the scarcity in supply of our single motor controller board, a fix is not attempted, but instead the board is powered through a 5v unregulated voltage pin.

Initially as planned, there is a USB serial interface that would allow communication between the motor board and the Raspberry Pi. The serial interface however is not recognized by the Raspberry Pi or any other computer, so it was concluded that it failed. Instead, an FT232 breakout board is used to connect the 2 serial pins RX1 and TX1 to allow serial communication. This adds another $15 part, but otherwise a doable workaround.

The ATmega128A only contains 4 toggle interrupt pins. To ensure maximum encoder accuracy, each encoder requires 2 toggle pins. Since the Forest Sign Maker contains 3 encoders, 2 more toggle interrupt pins are required. Instead, 2 rising edge interrupts were compromised and the position can be estimated with the additional information of knowing beforehand which direction the encoder shaft should be spinning in. To fix, a replacement from the ATmega128A to the ATmega1281 would supply 8 more toggle interrupts. Plus, the pin layouts between the ATmega128A and ATmega1281 are nearly the same, so a quick unsolder and solder of the new chip is sufficient.

11.5 Manufacturing Estimate

With regard to mass production, this machine may not be a viable solution compared to the existing products in the market. The largest cost factor is the labor cost due to the high demand for machined parts in the assembly. The amount of time spent in the Cal Poly machine shops was documented to be around 100 man-hours, which would lead to a projected labor estimate of $6,000. Coupling this labor estimate with the total material cost of $4,000, the approximate total manufacturing estimate is $10,000.

It is important to note that this estimate assumes no post machining processes are executed, such as material finishes, part assembly, and hardware debugging.

12 Design Verification

This section provides the results of our design verification plan.

Table 8.Design Specifications with Testing Results

Index	Parameter Description	Requirement or Targets	Tolerance	Result
1	System Weight	200 lb	Max	PASS
2	Width	3.5 ft	Max	PASS
3	Length	6 ft	Max	PASS
4	Height	4 ft	Max	PASS
5	Cost	$3,500	Max	FAIL
6	Sign Production Time	2 hrs	Max	PASS
7	Max Blank Size	2 ft x 4 ft	± 1/4"	PASS
8	Positional Accuracy	Target dimension	±1/16"	FAIL
9	Cutting Depth	3/16 in	± 1/16"	PASS
10	Graphical User Interface	Web Application	--	PASS
11	Local Operation	No network connection necessary	--	PASS
12	Multi-platform Capabilities	Function on Chrome, Firefox browsers	--	PASS
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	NO TEST
16	Clamp Rigidity	0.012 in	Max	NO TEST
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	FAIL
20	Electronics Temperature	60 °C	Max	NO TEST
21	AC-DC Power Supply	300 W	Min	PASS

12.1 Prototype Evaluation

System Weight - The weight of the system must be under 200 pounds. A qualitative test was performed where 3 people, Lisa, Kevin, and Victor carried the Forest Sign Maker from one table to another successfully. If the system weighed 200 pounds, then each one would carry roughly 66 pounds each, a feat that would be easily recognized by its difficulty. Instead, the Forest Sign Maker was easily transferred across, marking it under 200 pounds.

Width - The measured width of the system is just at 3.5 ft, making it within tolerance.

Length - The measured length of the system is under 6 ft, making it within tolerance.

Height - The measured height of the system is under 4 ft, making it within tolerance.

Max Blank Size - The Forest Sign Maker must accommodate a 2' x 4' board. Since the router bit can extend all the way across the X and Y axis, the entire 2' x 4' surface is routable.

Graphical User Interface - An interface is provided to the user in both the web application to design a sign, and in the machine interface where the user can command the machine to make a sign. Both of these interfaces are graphical with buttons, therefore passing the requirement of having a graphical user interface.

Local Operation - Due to the remoteness of the worksite, an internet connection may not always be guaranteed. The Forest Sign Maker's operation is not dependent on an internet connection because the web application can be run locally without going on the World Wide Web, making the system local.

Cutting Tool - Our system specifically holds the Bosch Colt Router as the entire router assembly was custom designed to mount the Bosch Colt Router plate.

Mounting Feature - The Forest Sign Maker must be able to securely mount to a workbench. Since each leg on the Forest Sign Maker comes with 4 mounting holes, it comes with a mounting platform, fulfilling this requirement.

AC-DC Power Supply - The Forest Sign Maker comes with a power supply rated above 300W, enough to provide power to all 3 motors and all the electrical components.

12.2 Performance Testing

Sign production time - Given an allotment of 120 minutes, a sign must be routed. Some benchmark tests were performed and a small string was routed "HELLO FRIENDS". The entire process took less than 5 minutes. Extrapolating this rate, at least 24 strings of "HELLO FRIENDS" can be routed. For a sign of at most 24 lines of text, the sign would be completed in 2 hours. Since most trail signs only contain a couple of lines of text, in most cases, the sign will complete in under 2 hours.

Multiplatform Capabilities - The web application must be operable in multiple web browsers because different users have a different preferred web browser. The web application performs under the 2 most popular web browsers: Google Chrome and Mozilla FireFox. Under Safari, upon clicking "Save Text to File", the window will refresh itself and load the cpff design file instead of prompting the user to save the file. This can be remedied by having the user purposefully saving the file. Since the web application can produce a .cpff file under Google Chrome, Mozilla, FireFox, and Safari, the web application meets the multiplatform capabilities requirement.

Cutting Depth - The cutting depth of the bit must be between ⅛" to ¼". A dot test was performed to verify the inaccuracies. A 6 x 6 grid of dots spaced one inch away from each other was designed and routed, the result of which is shown below.

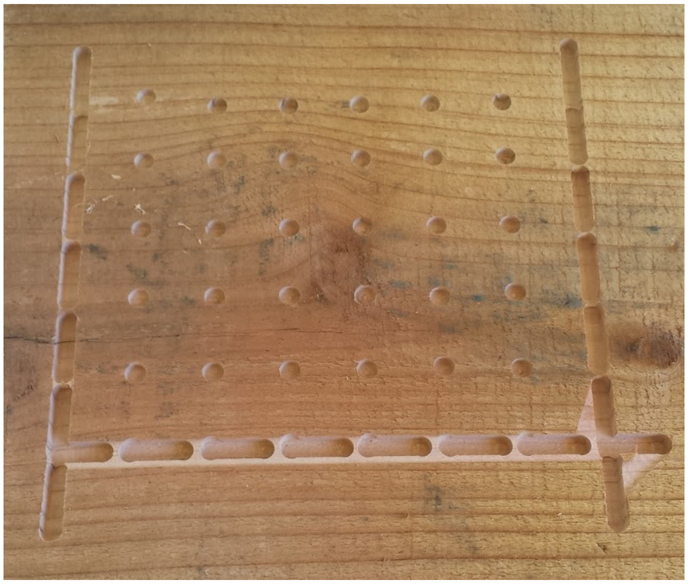

Figure 36. Dot test board sample.

The dot test shows that the depth of the dots were all constant and within the accepted range. During some plunges, if the router was near a wood knot, it may struggle to cut within the accepted range, but once out of the knot, the router plunged further, making a full cut.

Tool Path Errors - To prevent the accidental routing on the foundation or clamps, the web application enforces a one inch border in the design. Once the design is saved, the design file is checked with a java program to make sure each outputted coordinate is within the safe zone. There is also one last check with the user in the machine interface asking them to confirm the inputted design and components. Of course, these errors are only prevented if the user uses the correct design parts materials.

CNC Design Input - The interface hardware can function with sawdust present. Since the vacuum capabilities has not been implemented, Cal Poly Forest Friends tested the machine with sawdust present. The machine is design to work with sawdust. The gantry of the x-axis is designed to be underneath the foundation, preventing any debris on the guide rods and ball bearings. The electronics box is also the farthest away from the origin, limiting the amount of sawdust when small blank boards are routed.

12.3 Failed or untested specs

Cost - The ideal budget the sponsor would have preferred as $3,500. However, due to a unforeseen complications, the budget turned out to be around $3,800 excluding shipping. The main factors that led to the over budget would include misordering parts and ordering individual parts that were forgotten or neglected until the last minute.

Positional Accuracy - The Forest Sign Maker must route symbols within a 1/16" tolerance in positional accuracy. Instead, the positional accuracy can peak to at least ⅛". The problem has been identified as the 2 compliant helical shaft couplings allowing too much play in the Y direction.

The dot test was used to verify the failure. On the 2nd to 6th column of dots, the top row of dots are positioned lower than those in the first column. Our diagnosis of the problem is the slack of the 2 helical coil couplings on the Y-axis lead screw. It allows some lead screw rotation without any linear movement of the router. The first column performed well because the bit was moving from the top left corner of the board. All other dots on the first row were moving from the bottom, causing the error.

The second test executed was the Connect Test. Lines are routed starting at a previously routed dot as seen in the bottom row. If there is good positional accuracy, the bit would plunge where the dot is and leave little evidence that there ever existed a dot. The results of the Connect Test is shown in the same image as the Dot Test.

Using encoders, the router bit plunges at the same position as the dot within the allowed tolerance when creating the horizontal line. There is minimal evidence that a dot existed at all when the line was inspected. This shows that the encoders maintained accuracy overtime, but due to the play in the Y axis, the machine at times can be inaccurate up to ⅛".

Vacuum Capabilities - The vacuum capabilities was not tested due to the lack of time and poor planning. However, the parts for the vacuum fastener were manufactured and could be installed but without access to a shop vac, it prevent Cal Poly Forest Friends from testing the vacuum component. While it may help with the longevity of the project, it was also not a critical specification because the machine could operate without it.

Clamp Rigidity - The clamps did prevent the board from moving when the machine was routing. However, since the specifications states that the board should not move more than 0.012", a more detailed testing of the clamp rigidity were not tested due to the lack of time.

Electronics Temperature - The electronics temperature was not measured due to the lack of time and material. Maintaining the electronics temperature to 60°C is not a main concern because the motor boards are designed to work under high temperatures as high as 90°C. Also, a 12V fan is installed into the impact case to increase airflow within the electronics box.

Shutdown Time - The Forest Sign Maker did not shut down within 0.5 seconds. There were two main reasons that led to the failure of this specification. When the emergency button switch is triggered, the capacitor within the power supply will drain all of its power before it finally shuts down. With the capacitor in the power supply, the motors will still be running and there was inadequate testing to check how long it takes for each motor to stop. Also, the Bosch Palm Router takes approximately five seconds to come to a complete stop. With the listed specifications, the machine will always fail.

13 Recommendations

Upon completion of the Multidisciplinary Senior Project effort, it is clear that there is more work that can be done to improve the current state of the prototype. The following recommendations relate to all fields of engineering involved in this project:

1. **Replace the existing ATmega128 microcontroller with the ATmega1281 variation.**

The current microcontroller does not support as many toggle interrupt pins as the Forest Sign Maker requires for proper operation. The upgraded version, ATmega1281, has a sufficient number of toggle interrupt pins to accommodate all three encoder modules that provide closed-loop feedback information.

2. **Troubleshoot or repair the Vcc input and USB serial on current motor controller board.**

In its current state, the input connection for microcontroller power, Vcc, and the USB serial port do not function properly. Due to time constraints, these issues were not directly resolved, rather a temporary solution was implemented. Future efforts should focus on fixing these problems for proper user operation and data communication.

3. **Replace temporary Delrin sleeve bushings with fixed-alignment linear ball bearings.**

In order to remedy the lack of stiffness in the cutting module, replacement Delrin bushings were designed and manufactured. These replacement bushings greatly increased the overall stiffness of the y- and z-axes, however, they also increase the amount of axial friction in the system and exert more wear on the mechanism. Long-term operation is not advised with these replacement bushings installed.

4. **Add compliance to guide rod shaft supports.**

The current design of the Forest Sign Maker shaft supports does not allow for any adjustment in the guide rod locations. Therefore, if the supports were not located within tolerance, there is no alternative method to aligning the guide rods. One possible solution is to drill oversized holes in the endplates, and then add mounting holes so that a flanged guide rod support can be installed. By adding this intermediate part, the final location of the guide rod can be adjusted upon assembly.

5. **Remanufacture the z-module top and bottom endplates.**

Due to time constraints and situational circumstances, the z-module endplates were not machined with sufficient accuracy. Primarily, the guide rod and lead screw holes were severely misaligned. The result is a large amount of misalignment in the lead screw, and large displacements in the helical shaft couplings that support the screw itself. These components will wear quickly in their current state.

6. **Install a power switch in the electronics region.**

One oversight in the design of the electronics region includes the lack of a power switch. Aside from plugging and unplugging the AC power cord, the only way to turn off power is to press the EMO switch. It would be ideal to include a power switch.

7. **Use Chrome web browser to load the web GUI.**

Exhaustive testing of the web GUI has been conducted on the Chrome browser, therefore, it is sure to perform smoothly on that browser. There should not be any performance concern if other browsers are used, such as Firefox, however the display of the GUI may be compromised.

8. **Add larger access holes or slots for wiring harness.**

By the time the Forest Sign Maker prototype was prepared for wiring all the electrical components, it became clear that the wiring access holes were too small and that there were too few of them. Future prototyping efforts should include adding more access holes, or converting the current holes into larger slots, for ease of cable routing. Also, larger access holes would mitigate the chance of contact vibrations cutting through the wire insulation and exposing the bare metal.

9. **Redesign impact cover assembly.**

There are a few issues with the current impact cover design. First, the continuous hinge holes should be repositioned so that they match the foundation subassembly endplate holes. Second, the case fan location should be adjusted so that the fan is not located directly adjacent to the x-axis motor; the motor severely impedes the overall airflow. Third, with regard to airflow, the enclosure edges need to be air-tight, whereas they currently have a gap. Fourth, the solvent-welded joints are not sufficiently strong due to the tapered cut that was a product of the laser cutter; the edges should be routed flat after the panel is cut on the laser cutter to ensure a perfect joint.

14 Acknowledgements

Despite the efforts made by the Cal Poly Forest Friends, this Forest Sign Maker Project could not have been assembled within the set timeframe without the assistance of three important people: Dr. John Ridgely, Mr. Lee McFarland, and Mr. Darren Chan.

Dr. Ridgely served as the senior project advisor, and was integral in the design development of the Forest Sign Maker. The knowledge and experience he bestowed upon the team guided them in the correct direction, while allowing the team to make design decisions on their own.

Mr. Lee McFarland was the senior project sponsor, and served as a great facilitator for the project. Not only did Mr. McFarland sponsor the project, he was courteous enough to build the wooden components in the Forest Sign Maker.

Mr. Darren Chan provided critical electrical hardware feedback in addition to providing the motor controller board.

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The references that are boxed have attached PDF copies for your convenience.

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16 Appendices

16.1 Appendix A – Design Development Tools

16.1.1 QFD Table

The QFD Table provides a tangible approach to translating the customer requirements into concrete, testable engineering specifications. Furthermore, the QFD table provides reassurance that the current market solutions do not satisfy the customer's needs better than the future design created by the Cal Poly Forest Friends.

Table 9. QFD Table for the Forest Sign Maker.

Forest Sign Maker for Friends of the Inyo Paul McFarland & Lee McFarland	Engineering Specifications														Benchmarks		
Customer Requirements	Weighting (1 to 5)	200 lb	3.5' x 6' x 4' Size	Budget $3500	2 hour cutting time	3/16" Cutting Depth	Design GUI	Vacuums 50% of debris	Slotted Bed	Emergency off button	Positional Accuracy: ±1/16"	Holds Bosch Palm Router	Table-top Mounting Feature	Shutdown Time of 0.5 seconds	Rockler CNC Shark	Epilog Laser Cutter	Laguna Swift CNC Router
Maximum 2' x 4' x 1.5" board size	5		9												1	1	5
Minimum 1' x 1' x 0.75" board size	2		1												5	5	5
Handle knots	2											9			3	5	3
Route faster than human	5			1	9						1			1	5	5	5
Workbench mountable	3	3											9	1	5	1	1
Operate in hot or cold temperatures	2											1		3	4	3	4
Low Maintenance	2							1	1						3	2	3
Easy to Clean	3							9							3	4	3
Easy to load blank	3								9						2	4	2
Adhere to USFS guidelines	5					3									1	5	1
Adhere to OSHA guidelines	2									3					3	3	3
Local Computer	2														4	4	4
Easy to Use	2				1		3		1			1			3	1	2
Top left corner reference	3														3	3	3
Safety	4							1		9					3	4	3
Holds Bosch Colt Palm Router	5										9	9			2	1	1
Operate in work shed	5													9	5	5	5
Units		lb	ft	$	hr	in	--	%	--	--	in	--	--	sec			
Importance Scoring		9	47	5	47	15	6	33	31	42	50	67	27	59			
Importance Rating (%)		13	70	7.5	70	22	9	49	46	63	75	100	40	88			

Legend	
Engineering Specifications	Benchmarks
9 = Strong Correlation	1 = Does not meet requirements
3 = Medium Correlation	2 = Slightly meets requirements
1 = Small Correlation	3 = Somewhat meets requirements
Blank = No correlation	4 = Mostly meets requirements
	5 = Fully meets requirements

Referring back to Table 1 in Section 6 Engineering, the table utilizes a series of code letters to designate methods of compliance and levels of risk. The code letters are described below.

Risk is the likelihood that the parameter will not meet its target. A Low (L) risks means that there is little risk that it would not meet its target. A Medium (M) risk means that there's a higher chance that the parameter would not meet its target. A High (H) risks means that it will be difficult for the parameter to meet the target.

Compliance is the method of how each parameter will be tested. Analysis (A) will involve calculations of the properties of specs such that when the parts work together, the performance is theoretically proven. Test (T) will involve measurement the performance of a prototype or the final product. Similarity to Existing Designs (S) will involve comparing our performance with an already proven tested product. Inspection (I) will involve a visual and auditory check whether our parameter meets the specification.

16.1.2 Weighted Decision Matrix

The Design Development section provided individual weighted decision matrices for the concept selection of the various subsystems. Those tables were extrapolated from this complete weight decision matrix:

Table 10. Complete Weighted Decision Matrix for the Forest Sign Maker

Cal Poly Forest Friends Forest Sign Maker			Engineering Requirements															
Subsystems	Potential Options	Benchmark	200 lbs	3.5ft x 6ft x 4ft	$3500 Budget	2 Hr Cutting Time	3/16" Routing Depth	Design GUI	Debris Management	Slotted Bed	Positional Accuracy +/- 1/16"	Holds Bosch Palm Router	Table Top Mounting Feature	Shutdown Time: 0.5 sec	Weighted Sum +	Weighted Sum -	Weighted Sum S	Total Score
	Specification Weight		5	8	8	4	10	11	7	9	11	10	6	11				
Movement	**Gantry**	ShopBot Buddy	**S**	**S**	**+**	**S**	**S**				**S**	**S**	**S**		**8**	**0**	**54**	**24**
	Drawstring		S	S	-	-	-				-	-	-		0	49	13	-45
	Tower		S	S	+	S	S				S	-	-		8	16	38	3
	Strong-Arm		-	-	-	-	S				-	S	-		0	42	20	-36
User Interface	Tablet	PC			+			-							8	11	0	-3
	Personal Computer				**S**			**S**							**0**	**0**	**19**	**6**
	Custom Display				+			-							8	11	0	-3
Microcontrollers	**Raspberri Pi**	CNC Controller Kit			**+**			**+**							**19**	**0**	**0**	**19**
	Ardruino				+			-							8	11	0	-3
	Custom				+			S							8	0	11	11
	Beaglebone				-			+							11	8	0	3
Working Tool	**Router**	Bosch Router			**+**	**S**	**S**		**S**		**S**			**S**	**8**	**0**	**43**	**21**
	Laser				-	+	-		+		+			S	22	18	11	7
	Chemical				-	-	-		-		-			-	0	51	0	-51
	Print				-	+	-		+		-			S	11	29	11	-15
Actuation	Belts and Pulley	ShopBot Buddy	+		S				+		-				12	11	8	3
	Power Screw		**S**		**S**				**S**		**+**				**11**	**0**	**20**	**17**
	Rack and Pinion		-		S				-		S				0	12	19	-6
Foundation	**Wood w/ T-slots**	Prefabricated Slotted Bed	**+**	**S**	**+**				**S**	**S**					**13**	**0**	**24**	**20**
	Metal w/ T-slots		-	S	-				S	S					0	13	24	-6
	Prefabricated Bed		S	S	S				S	S					0	0	37	11
	Track Extrusions		S	+	-				-	-					8	24	5	-15
	Cast Aluminum		-	+	-				S	-					8	22	7	-12

16.1.3 FMEA Table

FMEA

16.2 Appendix B – Schematics

In order to facilitate fabrication and assembly of the Forest Sign Maker, many commodity were selected instead of designing many individual custom parts. The system design has been optimized by using a combination of commodity and custom parts. The commodity parts have a greater impact on the budget, however they save significant fabrication time, especially considering parts such as linear bearing housings. The parts that are better suited for custom machining have been designed for vertical milling. Each custom part has been modeled, and has a corresponding mechanical drawing.

All the drawings have been compiled into the following PDF. The order of drawings is structured by subassembly, akin to the structure of the Mechanical Assembly BOM found in Appendix D.

Click on the label to view the corresponding PDF.

Mechanical Drawings

Another element of the Forest Sign Maker that is customized, not a commodity part, is the microcontroller PCB design. The designer, Darren Chan, has provided the updated Eagle board and schematic files. The PDF versions are found below.

Microcontroller Drawings

16.2.1 Wiring

The wiring schematics for the default pin hookup values is given below. Some devices connected to the Forest Sign Maker are the 3 optical encoders, 6 limit switches, 3 current sensors, and a serial communications port. A description is also included below, and can also be found in **pinLayout.h** inside the Github repository.

Limit Switches

X Minimum	X Maximum	Y Minimum	Y Maximum	Z Minimum	Z Maximum
PA7	PA4	PA6	PA3	PA5	PA2

X Minimum is the switch that will be activated when the router moves to the lowest X coordinate. It is essentially the home position in the X axis.

X Maximum is the switch that will be activated when the router moves to the highest X coordinate. It is the farthest right the router is allowed to go.

Y Minimum is the switch that will be activated when the router moves to the lowest Y coordinate. It is essentially the home position in the Y axis.

Y Maximum is the switch that will be activated when the router moves to the highest Y coordinate. It is the lowest that the router is allowed to go.

Z Minimum is the switch that will be activated when the router moves to the lowest Z coordinate. It is the farthest vertically the router is allowed to go away from the work surface.

Z Maximum is the switch that will be activated when the router moves to the highest Z coordinate. It is the closest the router is allowed to go towards the work surface. This switch may seldom ever be activated because the there may not be enough vertical clearance for the router bit and the work surface.

Encoder Pins

Encoders are used to measure the rotation of a shaft. In this application, it will be used to measure linear movement of the router by monitoring the number of rotations the lead screw will perform. Each encoder has 2 pins, A, B, both of which will trigger high or low whenever the shaft rotates.

X.A Pin	X.B Pin	Y.A Pin	Y.B Pin	Z.A Pin	Z.B Pin
PE4	PE5 (INT)	PE6	PE7	PD0 (SCL)	PD1 (SDA)

X.A Is the A pin from the X axis encoder.

X.B is the B pin from the X axis encoder.

Y.A is the A pin from the Y axis encoder.

Y.B is the B pin from the Y axis encoder

Z.A is the A pin from the Z axis encoder.

Z.B is the B pin from the Z axis encoder.

PD0 and PD1 are interrupt pins that do not operate on toggle, making them not ideal for encoder pins. However, due to the lack of available toggle pins, PD0 and PD1 must be used.

Current Sensors

X Axis Power	X Axis Sensor	Y Axis Power	Y Axis Sensor	Z Axis Power	Z Axis Sensor
PF0	PF3	PF1	PF4	PF2	PF5

X Axis Power, Y Axis Power, and Z Axis Power are strictly used to provide 5V to the current sensors.

X Axis Sensor is the V_{out} from the current sensor of the X-Axis motor.

Y Axis Sensor is the V_{out} from the current sensor of the Y-Axis motor.

Z Axis Sensor is the V_{out} from the current sensor of the Z-Axis motor.

The current sensors requires the AREF pin on the motor board to be attached to the Vcc pin on the motor board. AREF is the analog voltage reference used for the analog to digital conversion.

Serial Port

From the FT232 breakout board, connect the RX line to the TX line of the Motor Controller Board and connect the TX line to the RX line of the Motor Controller Board. Finally, connect GROUND to the Motor Controller Board's GND. Then attach a USB cable from the FT232 breakout board to an empty USB port on the Raspberry Pi. This will serve as the serial communications bridge between the Raspberry Pi and the Motor Controller Board.

16.2.2 Operation

Upon startup, the machine first checks if any of the maximum limit switches are activated. If so, it will activate the motors to back the router away from the maximum limit switches until they are no longer activated. This check is performed on the X, then Y, then Z axis. After all 3 axis's maximum limit switches are no longer activated, then the system starts up the scheduler.

The coordinates are supplied through a serial port in the form of 3, unsigned 2-byte binary values, in the order of X, Y, then Z.

	Upper X coordinate	Lower X coordinate	Upper Y coordinate	Lower Y coordinate	Upper Z coordinate	Lower Z coordinate
Byte	0	1	2	3	4	5

The upper X coordinate contains the 8 more significant bits of the X coordinate, and the lower X coordinate contains the 8 less significant bits of the X axis. When combined, Upper X coordinate occupies bits [8:15] and lower X coordinate occupies bits [0:7].

The upper Y coordinate contains the 8 more significant bits of the Y coordinate, and the lower Y coordinate contains the 8 less significant bits of the Y axis. When combined, Upper Y coordinate occupies bits [8:15] and lower Y coordinate occupies bits [0:7].

The upper Z coordinate will contain 0, and the lower Z coordinate contains a height code corresponding to the height the router will plunge.

Z Code	Meaning
0	Hover ¼” above the board
1	Plunge ⅜” into the board
2	Hove ¼” above the board
3	Return home and set the board height to be ¾”
4	Return home and set the board height to be 1.5”

If the coordinates sent to the board is <0, 0, 0>, <0, 0, 3> or <0, 0, 4>, then the motor board will initiate HOME mode. The router will recalibrate itself to the home position by moving the router until engaging the x minimum limit switch, the y minimum limit switch, and z minimum limit switch. Upon completing the rehoming, the new relative home is set, and the machine is recalibrated. When the calibration is complete, the machine will exit HOME mode, and enter NORMAL mode.

If the coordinates sent is <0, 0, 3>, then the machine will enter HOME state and set the hover to plunge to ¼” above a ¾” tall the workpiece. If the coordinates sent is <0, 0, 4>, then the machine will enter HOME state and set the hover to plunge to ¼” above a 1.5” tall workpiece.

Normal Mode

Normal mode is when the motor board will take in coordinates as input and move the router to the given coordinates. Coordinate units are given in 1/128 inch units. For example <128, 128, 0> is to hover the router bit ¼” above the board 1 inch from the left border and 1 inch from the top border. <1, 1, 0> is to hover the router bit ¼” above the board 1/128 inch from the left border and 1/128 inch from the top border.

There is a 1/16” tolerance to the accuracy of the router position.

Z Axis

The Z axis takes priority over the X and Y axis because the height of the router needs to be positioned first. This is important of making sure the cuts on the board start and end at the right spot.

If at any time, any of the maximum limit switches have been activated, the machine will stop, and the motor controller board will have to be resetted.

Current Sensors

If at any time, any of the current sensors measure 9 amps, the machine will stop, and the motor controller board will have to be resetted.

Power

The board has to be supplied power by a 5v V_{cc} pin. Currently, the board is powered through the ISP programmer which is connected to a USB port.

16.3 Appendix C – Bills of Materials

The BOM outlines the completed mechanical assembly structure organized by component hierarchy and specifies the unit cost. For most commodity parts, McMaster-Carr is the primary vendor. For the major components of actuation, specialty vendors such as Pittman Motors and Roton. For raw materials such as aluminum plates and angle bars, Online Metals is the primary vendor. Included is the outline of the completed electronics parts list required to populate the custom microcontroller that Darren Chan, an Electrical Engineering graduate student and faculty member, designed and tested. All components can be purchased from Digikey using the listed part numbers.

Click on the label to view the BOM:

Forest Sign Maker BOM

16.4 Appendix D – Vendor Datasheets

Click on the part label to view the corresponding datasheet.

Gearmotor	Microcontroller	Incremental Encoder
Linear Ball Bearings	Current Sensor	Limit Switch
Roller Chain	Chain Sprocket	Chain Tensioner
Feet Bracket	Large Angle Bracket	Small Angle Bracket
T-Slot Extrusion	Tee Bracket	Helical Coupling
Universal T-Track	Shaft Collar	Gearmotor Spacer
Power Supply	Motor Driver	Raspberry Pi B+
Touchscreen	Voltage Regulator	

16.5 Appendix E – Supporting Analysis

The supporting analysis conducted by the Cal Poly Forest Friends is critical to the integrity of the Forest Sign Maker final design. The following analysis is organized into two categories: written hand calculations and computer simulations.

The following links refer to scanned copies of hand calculations that sets the foundation, or optimized baseline, for several various system elements, such as guide rod diameter, torque calculations, feed speed considerations, etc. The original copies of the analysis provided here can be viewed in the project logbooks that the Cal Poly Forest Friends maintain.

Click on the desired label to view the corresponding PDF.

Guide Rod Sizing

Vertical Member Thickness

Feed Speed Estimation

Preliminary Controller Calcs

Motor Selection

Encoder Selection

16.6 Appendix F – Project Management Tools

The following Figure 36 depicts the timeline for the rest of the project.

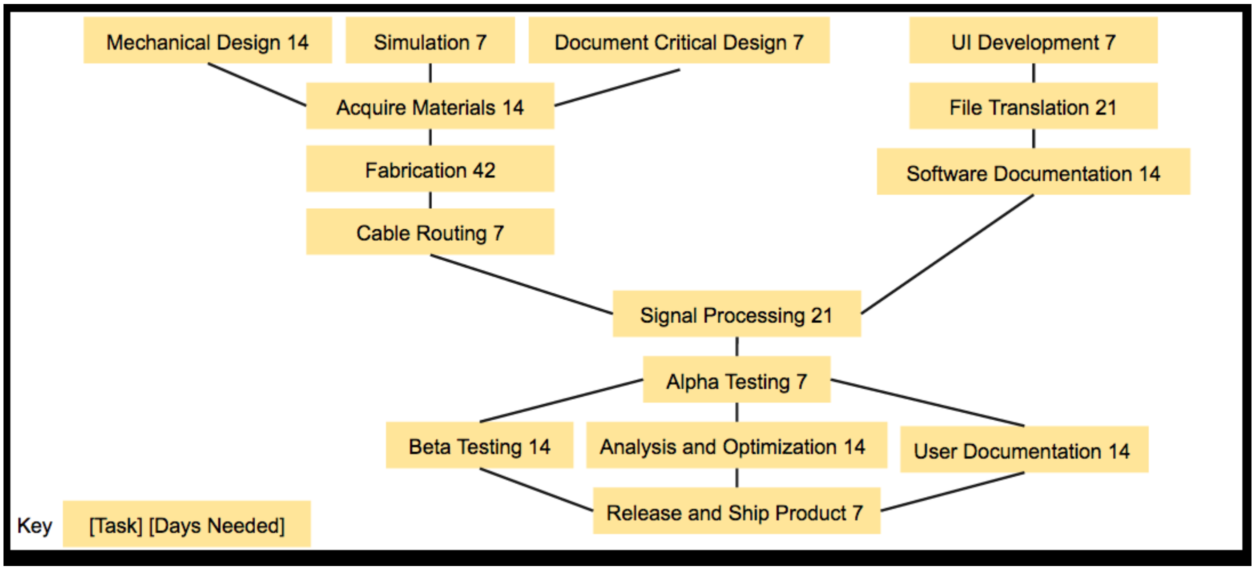

Figure 37. Forest Sign Maker timeline.

The Gantt scheduling chart developed for this project can be found using the following link:

Gantt Chart

16.7 Appendix G – Testing Plans

NOTE: Consult all provided test plans prior to testing. Some tests are designed to be conducted in parallel with each other.

Table 11. Copy of the Formal Engineering Requirements Table 1, but has been hyperlinked to the test plans.

Index	Parameter Description	Requirement or Targets	Tolerance	Risk	Compliance
1	System Weight	200 lb	Max	H	T
2	Width	3.5 ft	Max	H	T
3	Length	6 ft	Max	L	T
4	Height	4 ft	Max	L	T
5	Cost	$3,500	Max	H	A
6	Sign Production Time	2 hrs	Max	L	T
7	Max Blank Size	2 ft x 4 ft	± 1/4"	L	T, I
8	Positional Accuracy	Target dimension	±1/16"	H	T
9	Cutting Depth	3/16 in	± 1/16"	L	T
10	Graphical User Interface	Web Application	--	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

Click on the desired specification to view its testing plan, if available. Only specifications with a *"T"* in the Compliance column will have a testing plan.

16.8 Appendix H – User Manual

User Manual